Key Message 10.3

Our Future Ocean Depends on Decisions Today

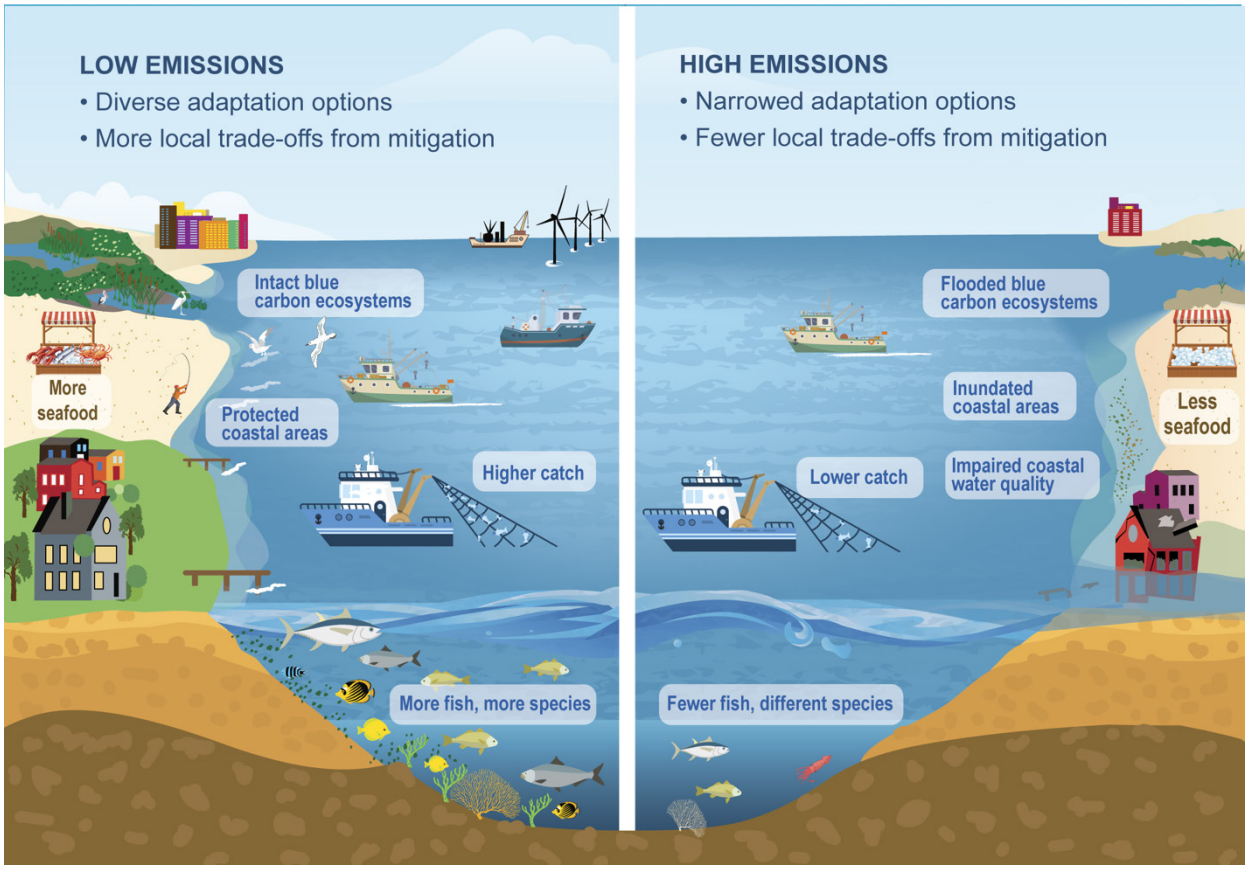
Future risks to marine ecosystems, ocean resources, and people will be substantially reduced by implementing adaptation and mitigation actions now (*very high confidence*). Responding swiftly to climate change will improve outcomes, reduce costs, promote resilience and equity, and allow the widest possible 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.

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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.

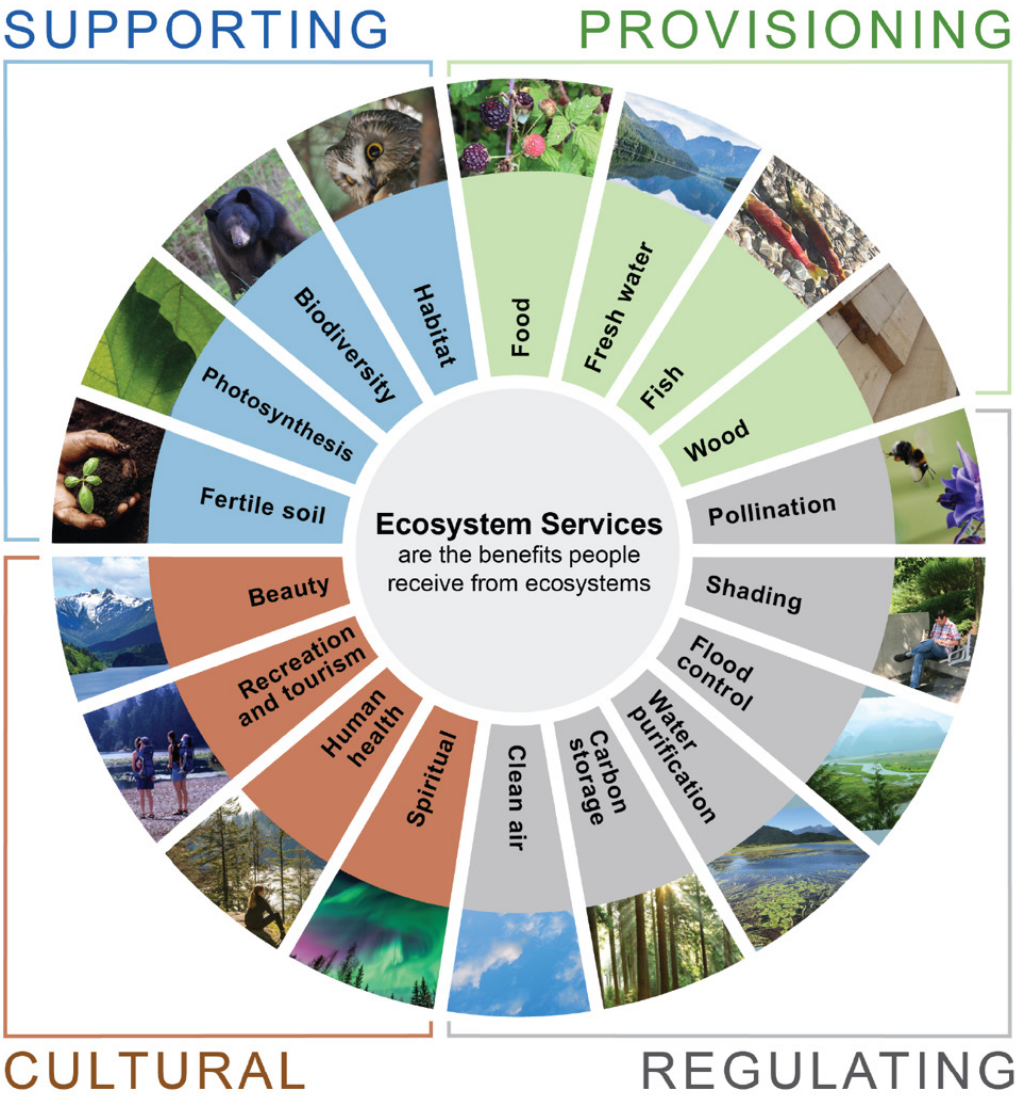
Key Message 11.1

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

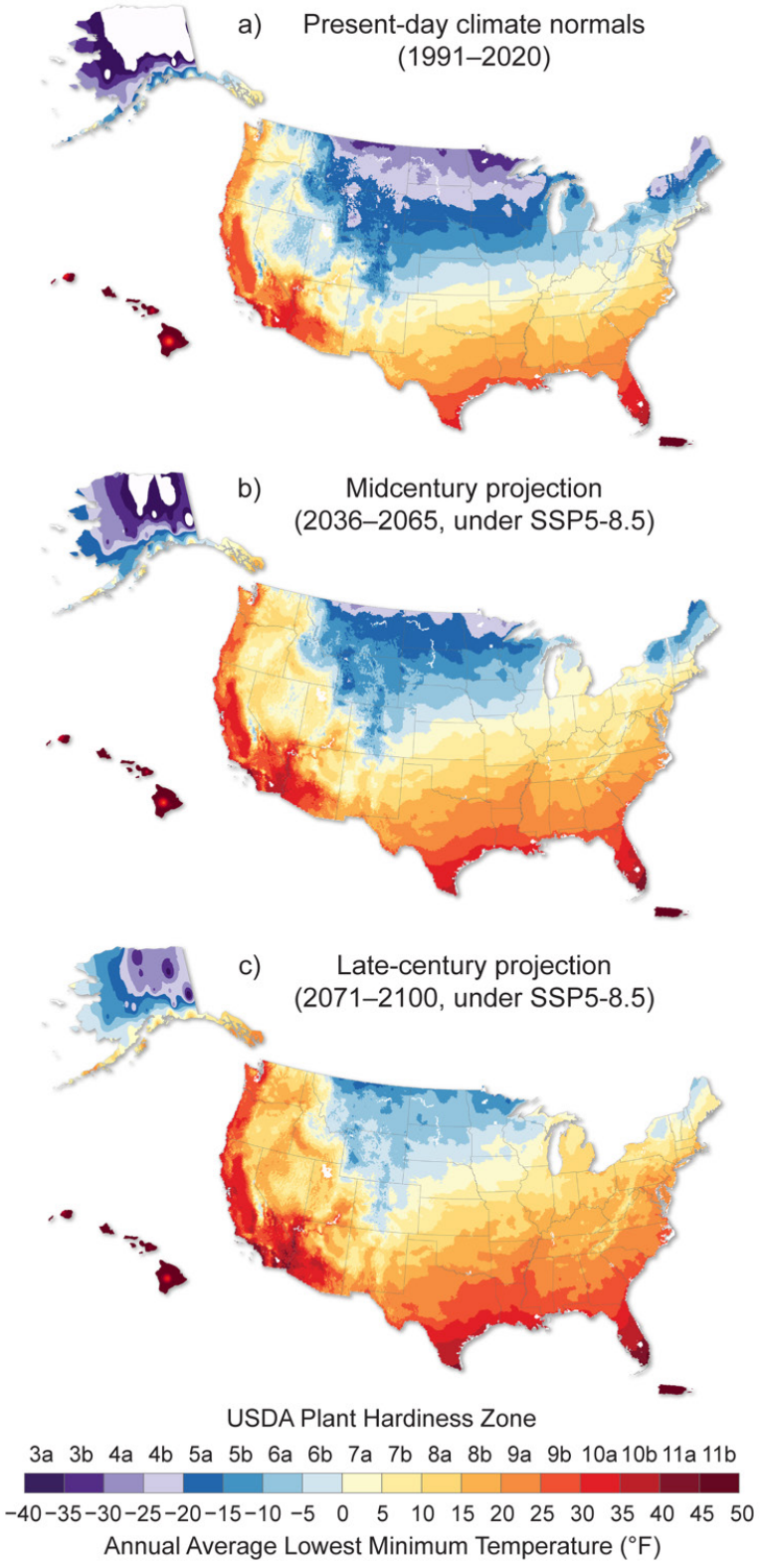


Ecosystem services have wide-ranging benefits for plants, animals, and human well-being.

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

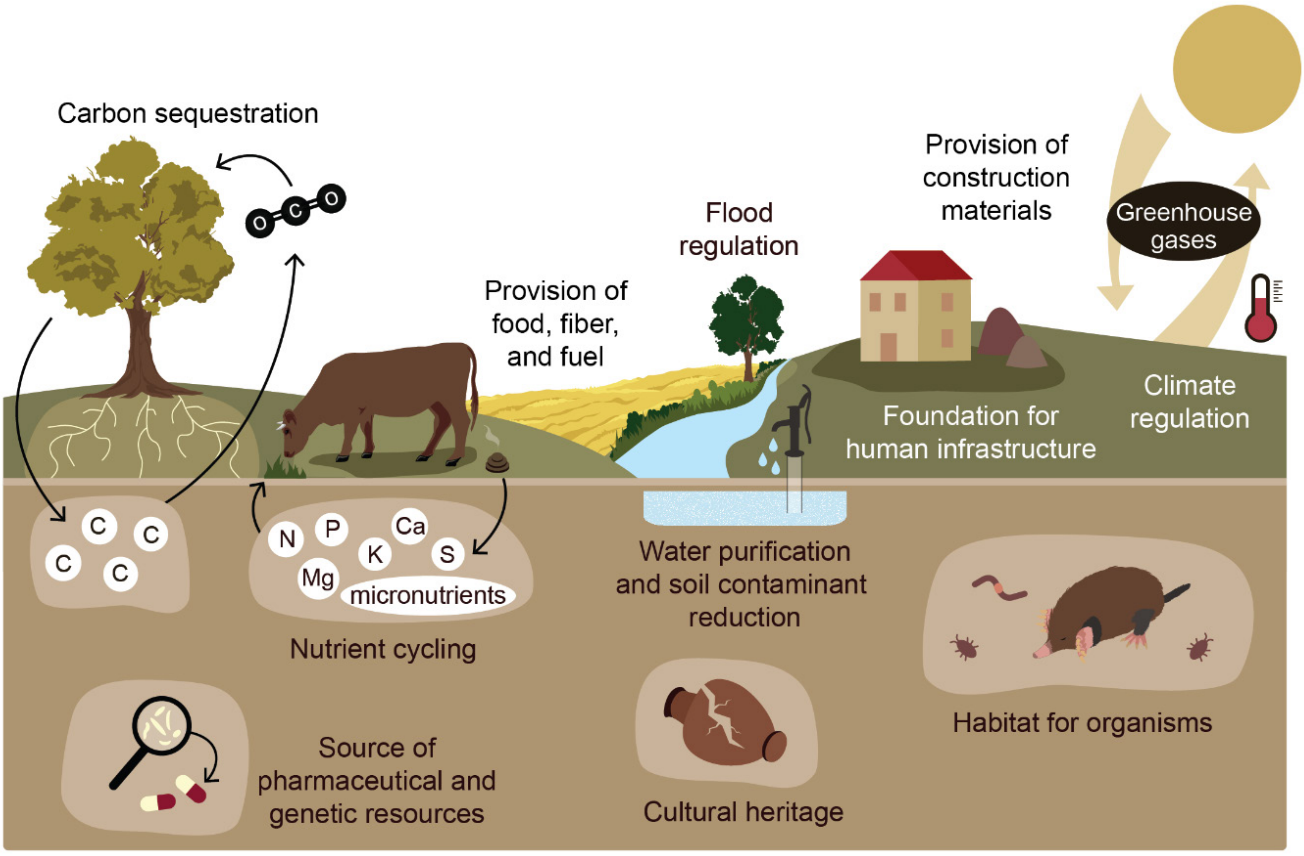


Plant hardiness zones are projected to shift northward throughout this century.

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.

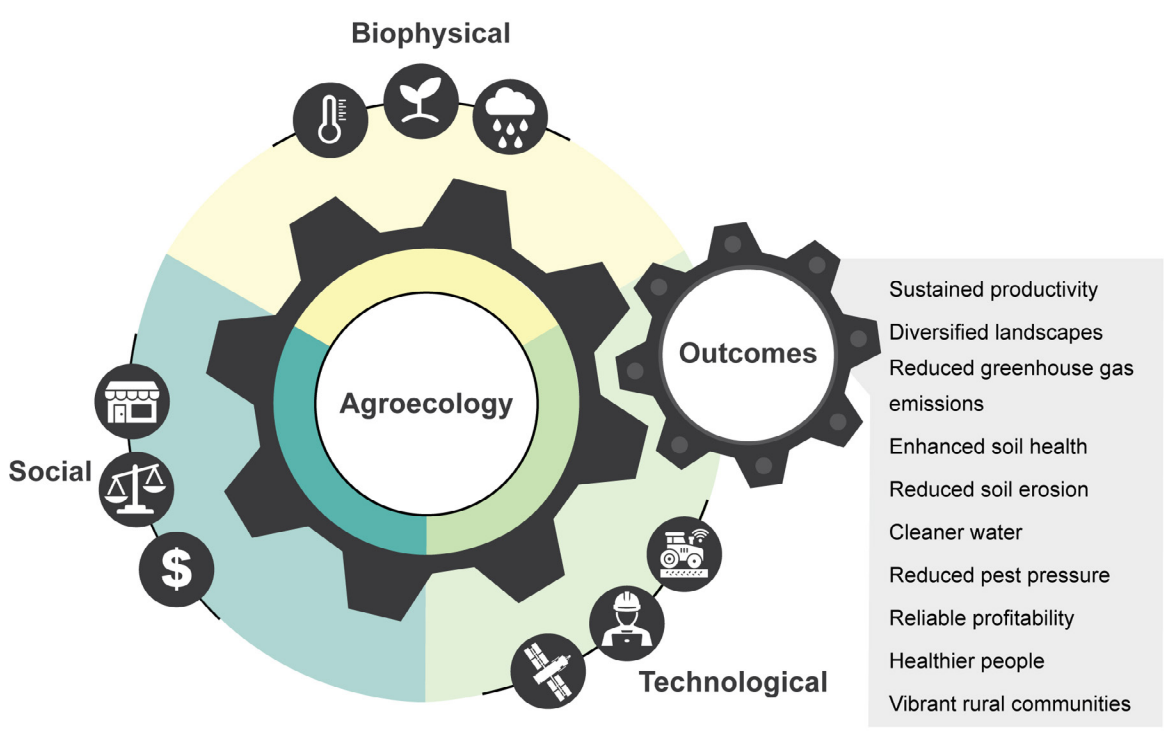
Figure 11.4. Healthy soil provides the foundation for many agricultural, ecological, microbiological, societal, and cultural activities. Climate change can negatively affect soil health, thus weakening its foundational role. Adapted from Baveye et al. 2016[31] [CC BY 4.0].

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



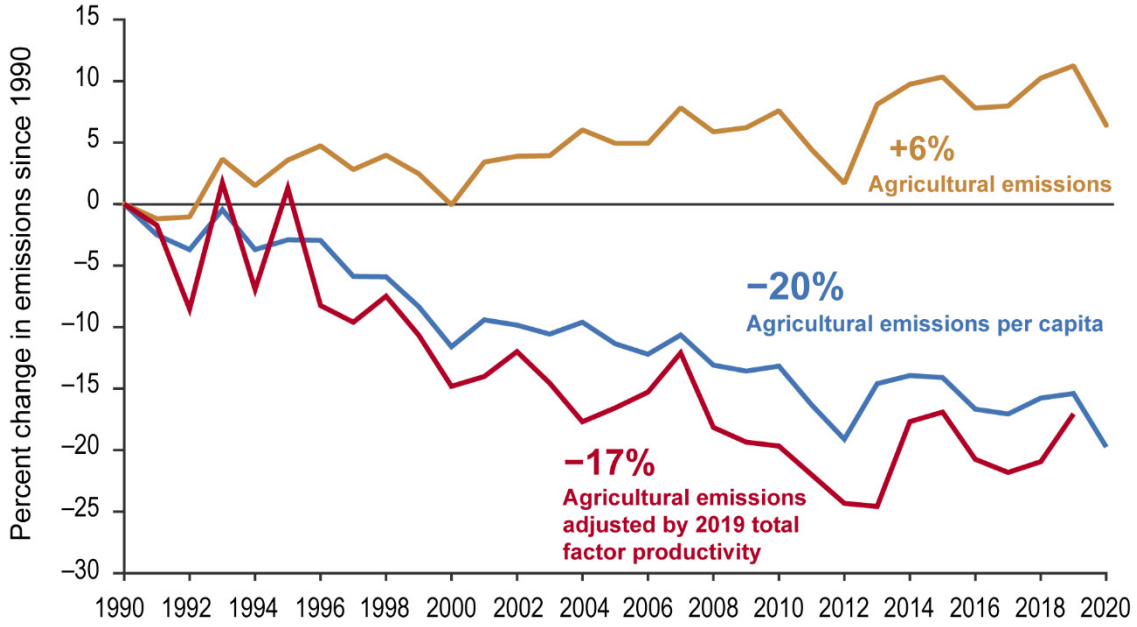
Agroecological approaches seek to achieve beneficial agricultural outcomes while promoting ecosystem services and rural livelihoods.

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.

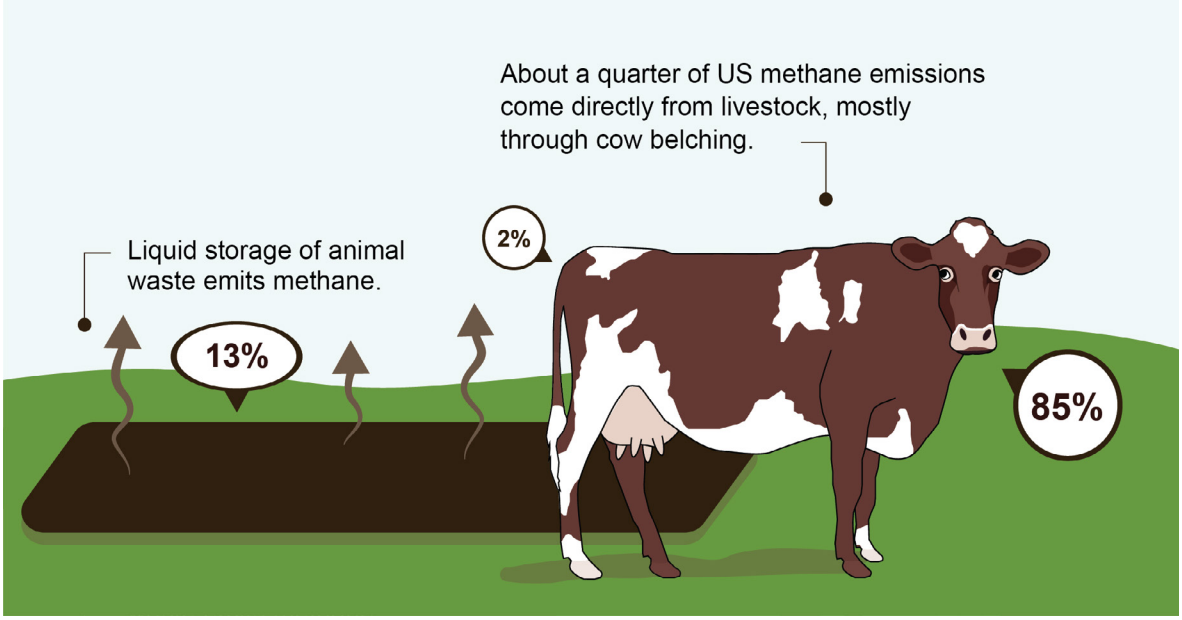
Figure 11.6. Over the last 30 years, declines in US agricultural emissions per capita (blue line) and per unit of agricultural productivity (red line) reflect an increasingly efficient US agriculture sector that produces more food, fiber, and renewable fuel with fewer resources. Despite per capita and 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.

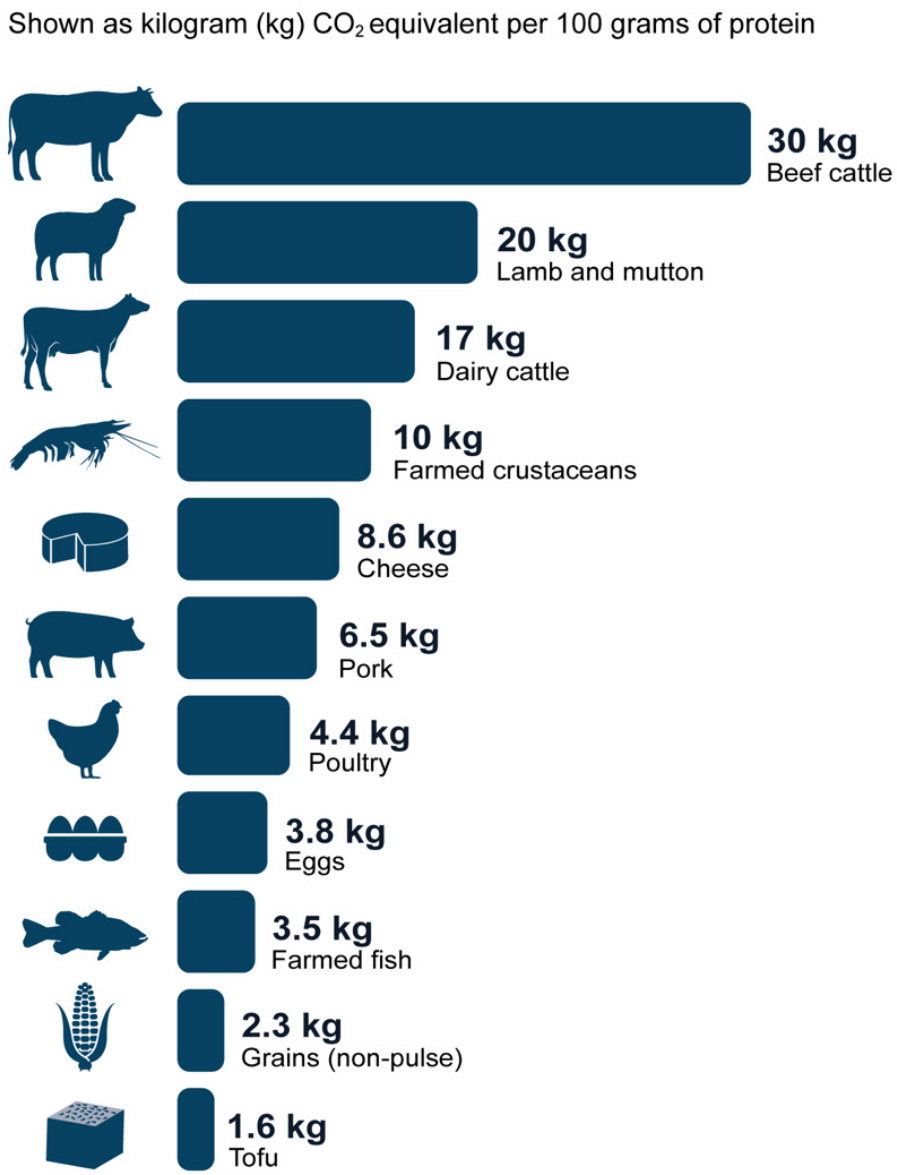
The complexity of climate-related threats and the diversity of agricultural environments in the United States require an array of management approaches. Matching unique regional combinations of plant and animal genetics with regionally relevant management practices can optimize soil carbon sequestration, 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

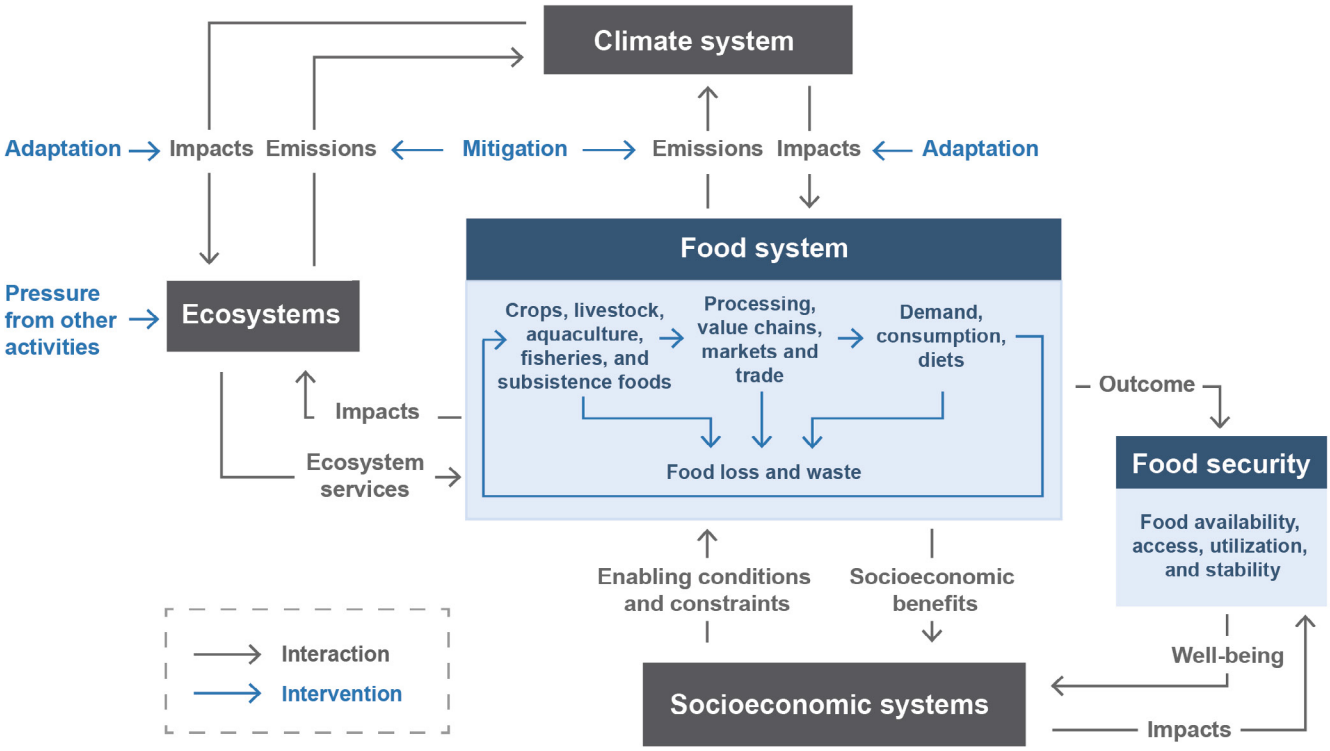
All dimensions of food security—availability, accessibility, utilization (or usability), and stability[71]—are expected to be affected by climate change through long-term changes in average climatic conditions (e.g., annual precipitation and temperature), as well as increases in climate variability and 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).

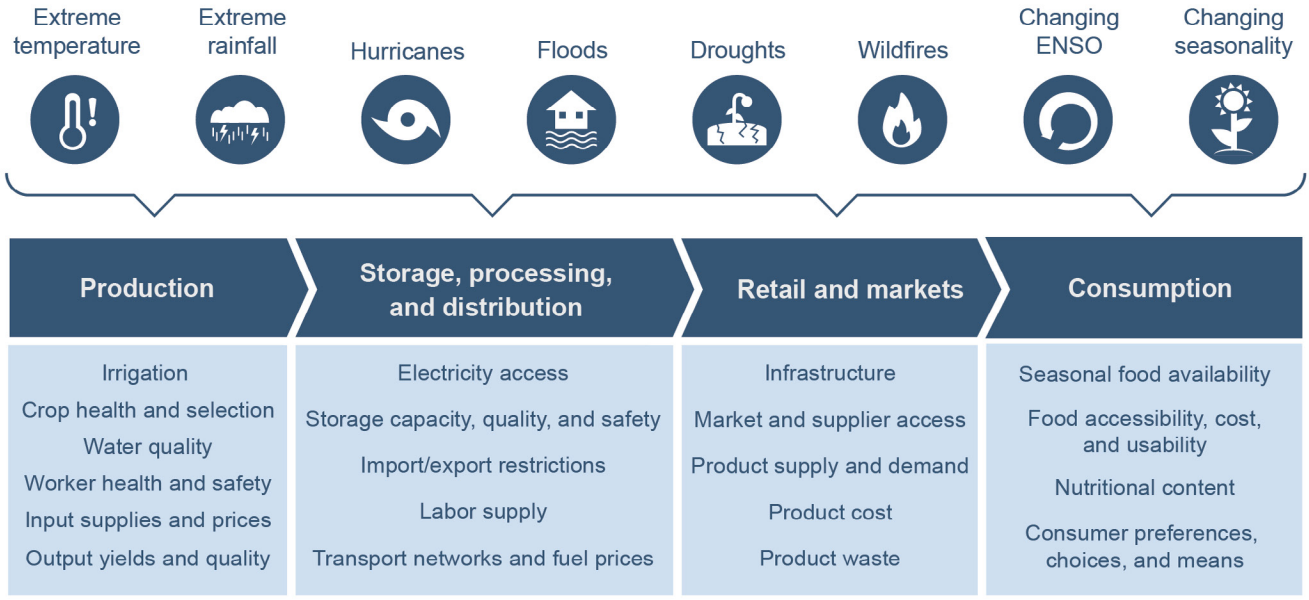
Connections Between Climate, Food, Ecosystem, and Socioeconomic Systems



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

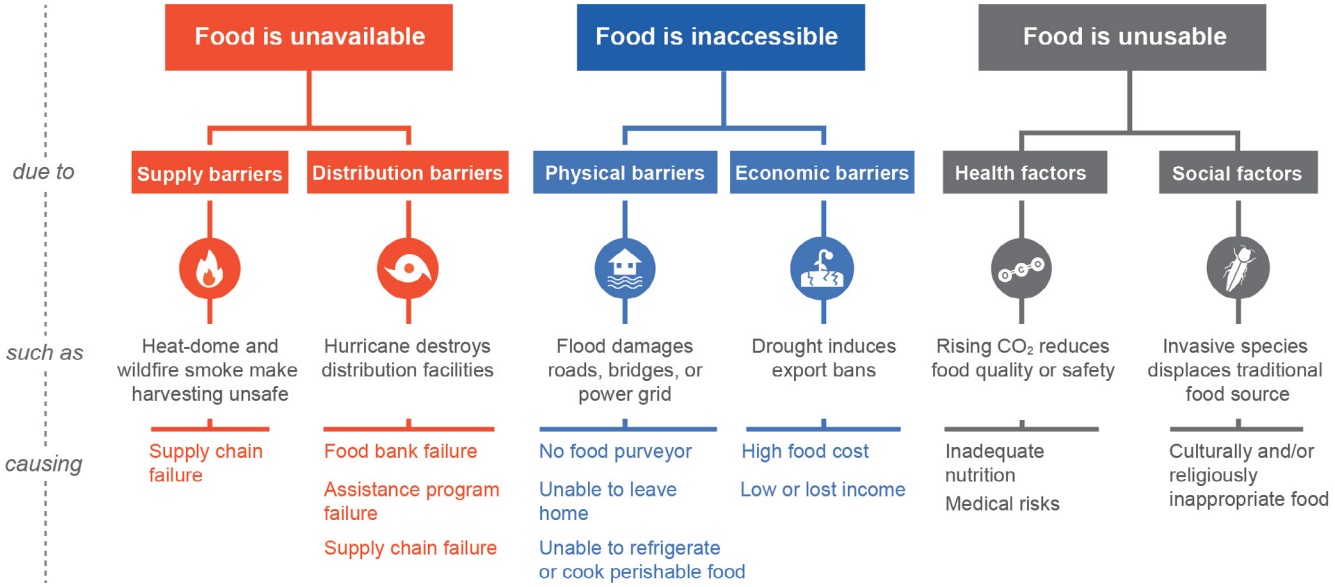
Food security risks from climate change impose socioeconomic costs that workers, producers, and consumers may feel but can be challenging to measure (Ch.15; KM 19.1). Climate change impacts on food production have been measured more comprehensively than impacts on food processing, distribution, marketing, 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]

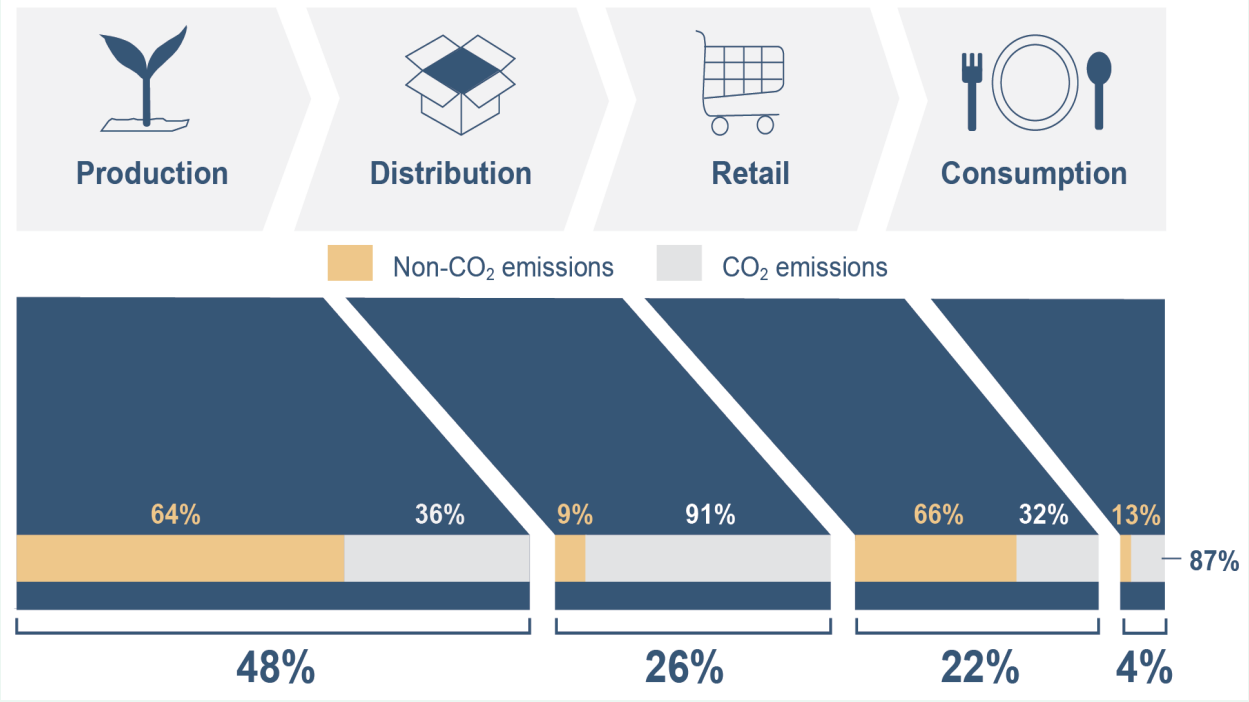
Subsistence-based people who forage for food (such as wild rice, beans, and mushrooms) may face unique challenges from climate change (KMs 16.1, 24.2).[111] Drought can reduce the availability of forest-based foods such as berries, nuts, and seeds. In Alaska, where subsistence hunting and fishing are 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.

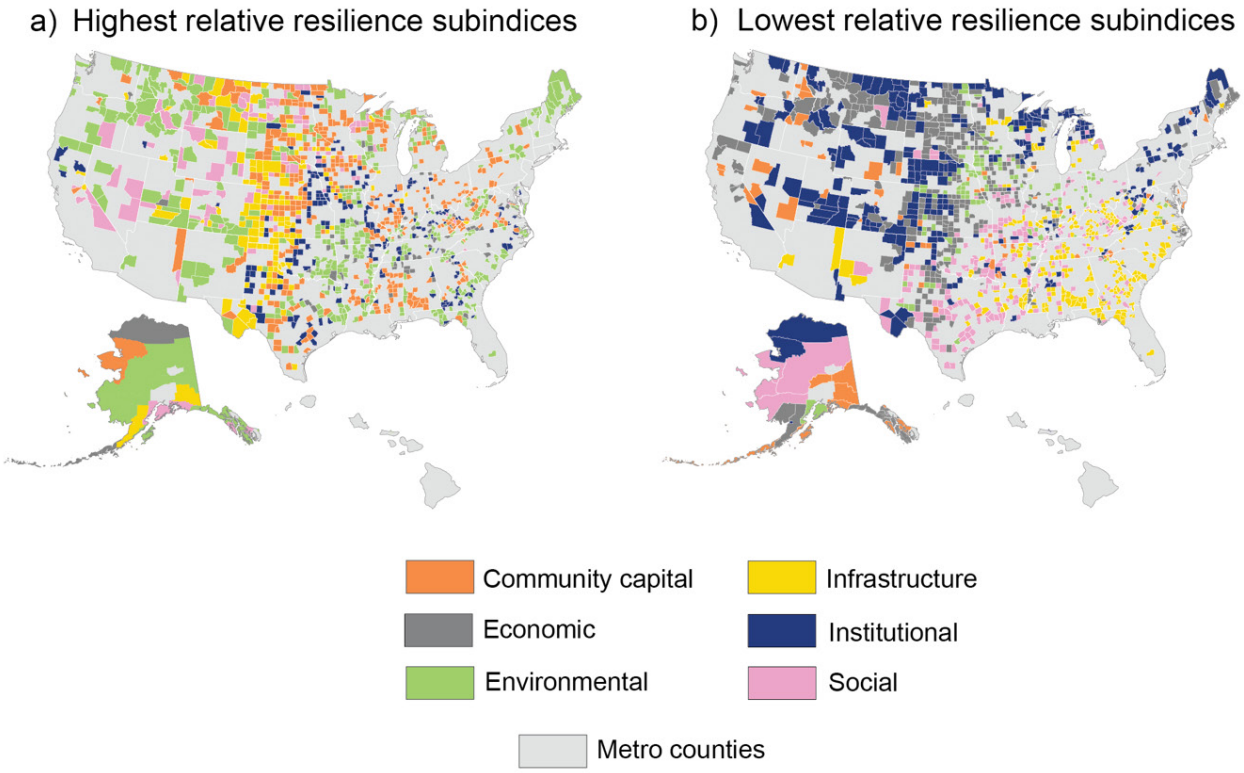
In recent years, there have been significant advances in analytic capabilities for identifying risk variation as influenced by a wide range of social (Ch. 20), economic (KM 22.3), and ecological factors (KM 24.5; Ch. 31). Measures that capture the ability of a community to prepare, adapt, and recover 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).

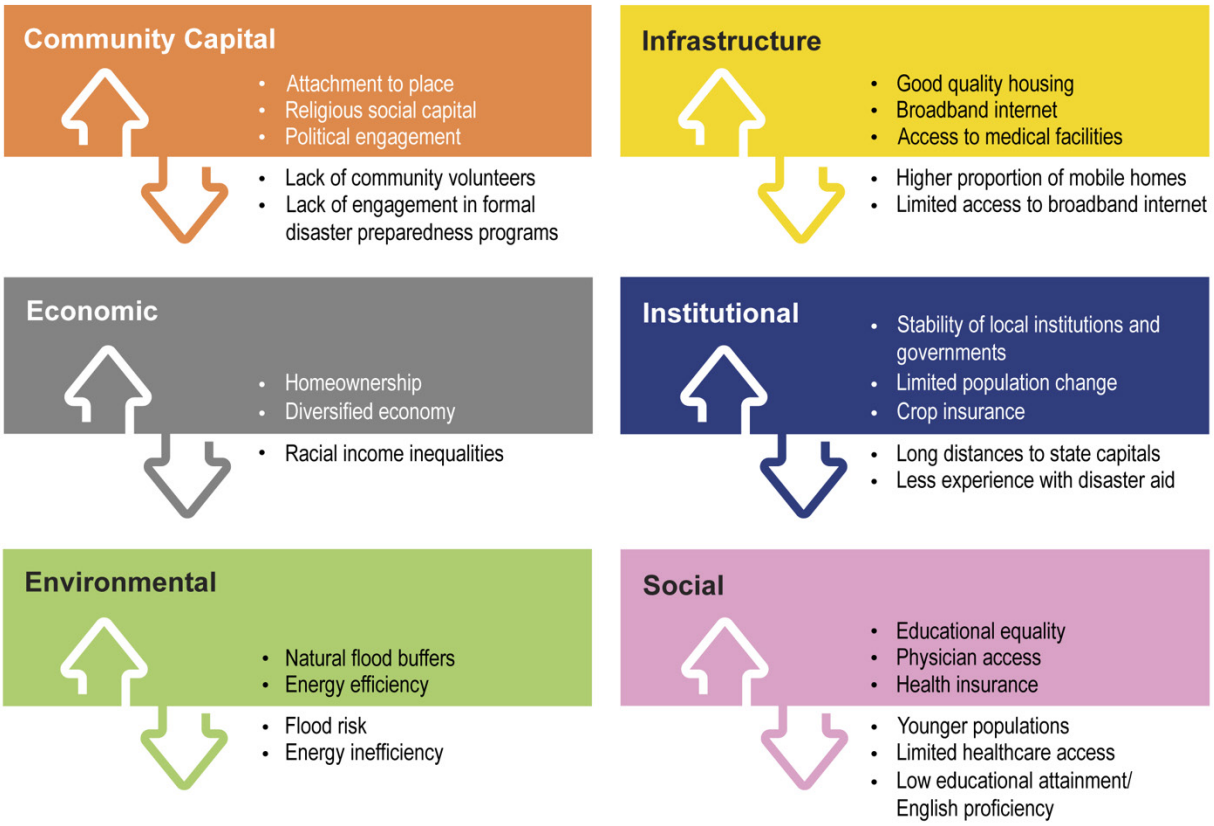
Community Resilience Index



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*.

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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

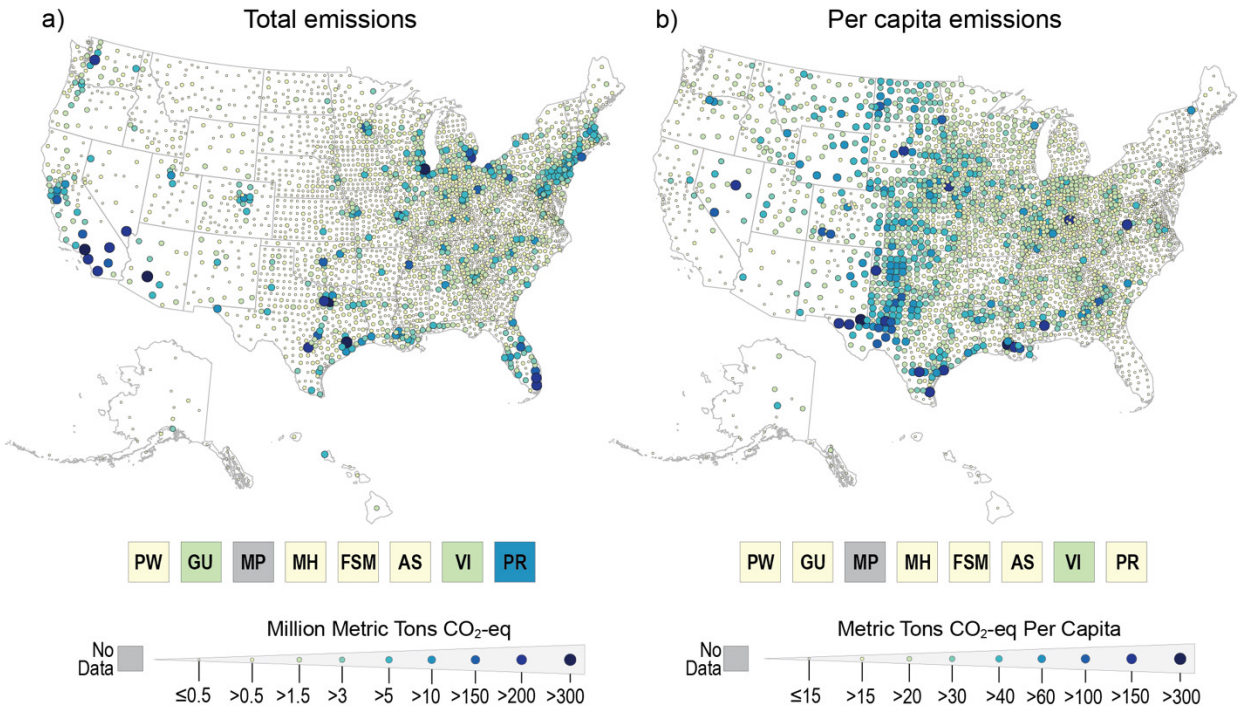
Urban Areas Are Major Drivers of Climate Change

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

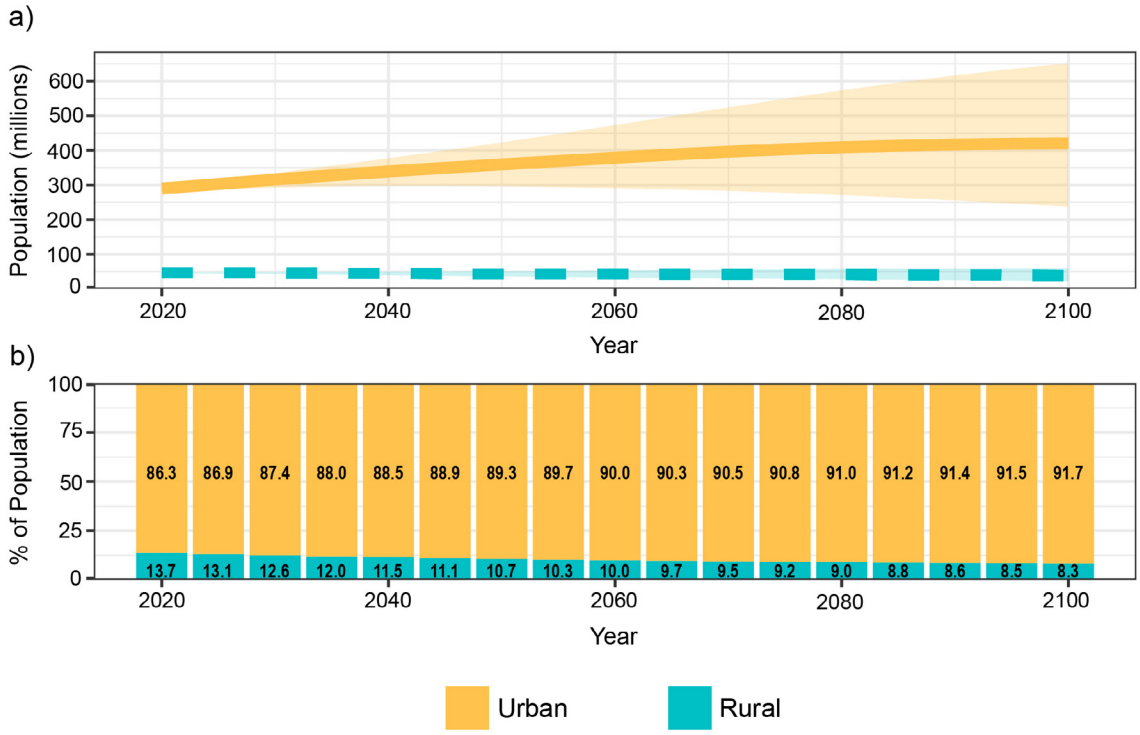


Urban and suburban areas contribute the majority of total greenhouse gas emissions through their consumption and populations.

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.

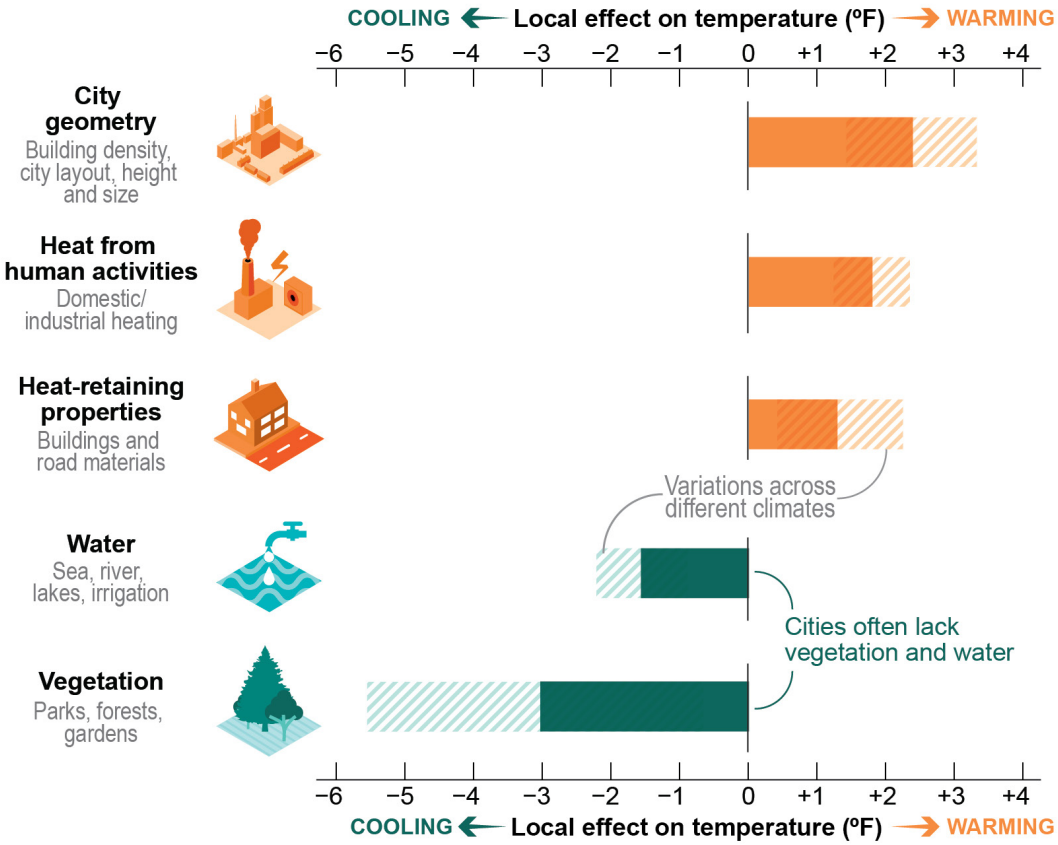
Examples of Built Environment Types Found in US Cities

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]

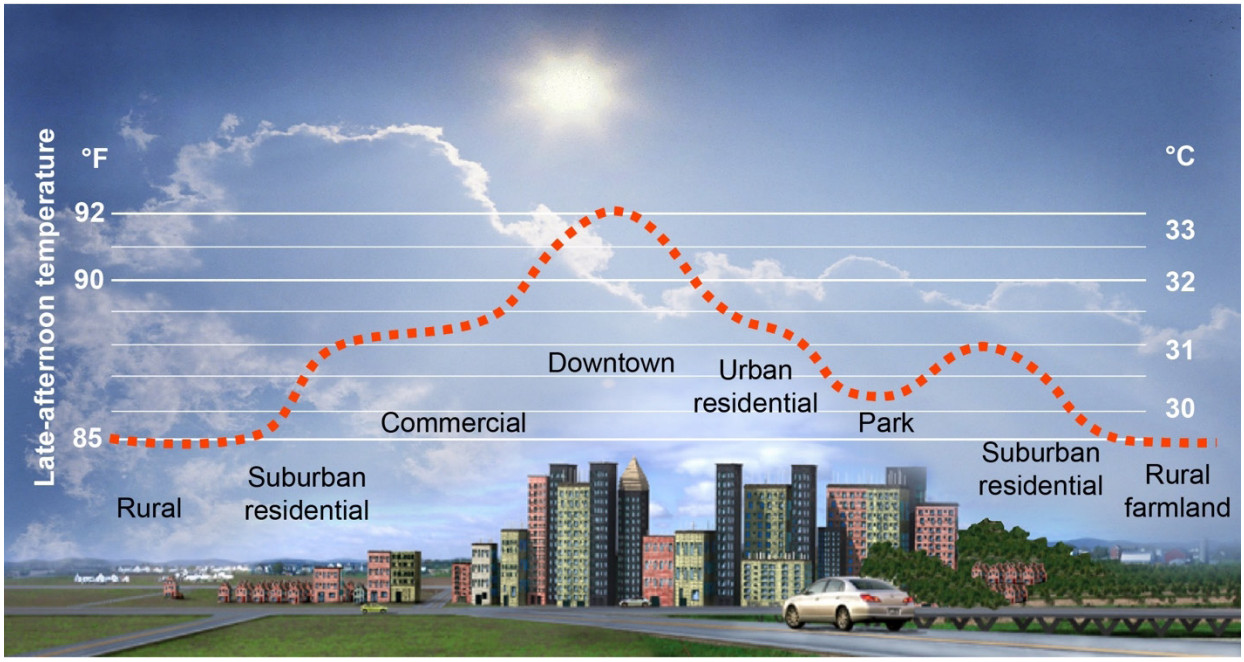
Effects of the Built Environment on Local Temperatures



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]

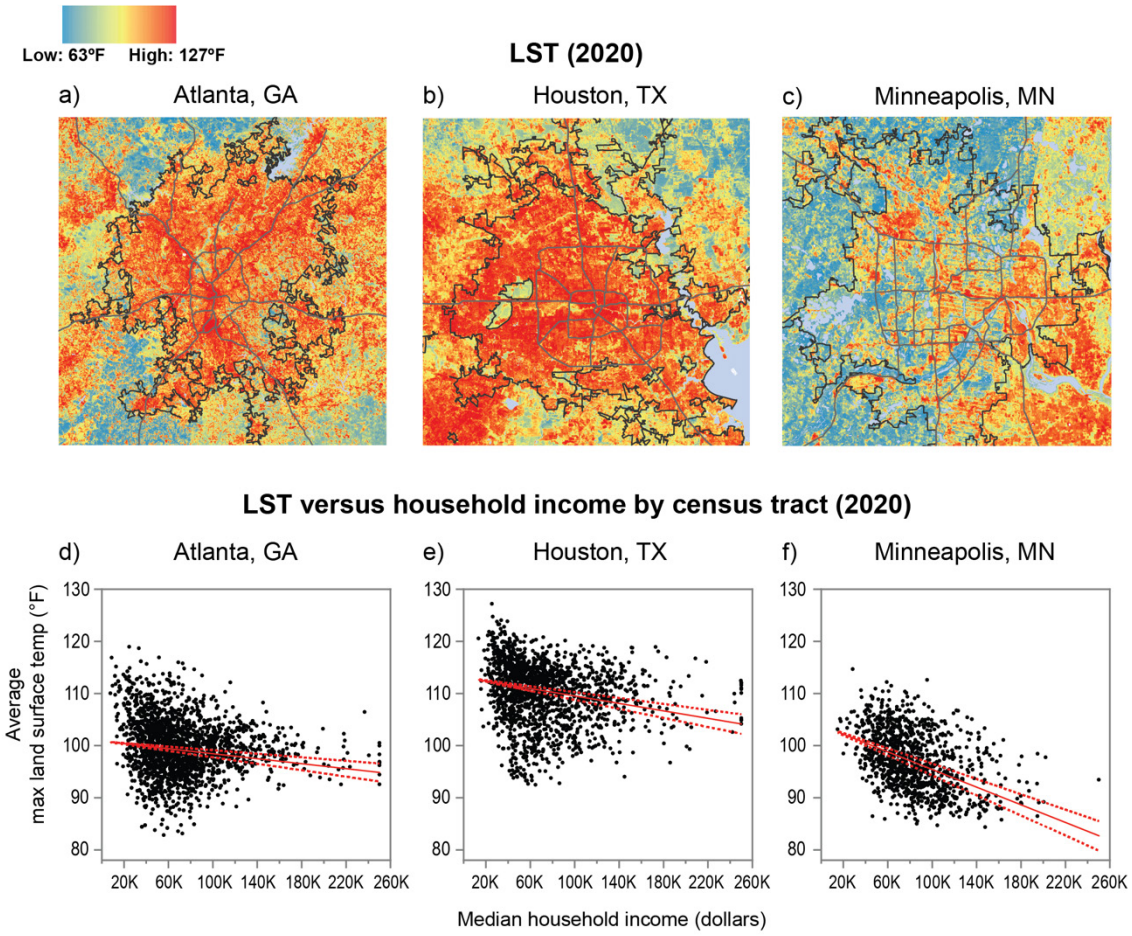
Long-term climate uncertainties will also affect future construction and maintenance of dams, levees, bridges, stormwater systems, electrical distribution systems, and building enclosures, as well as the protection of historic assets.[59,60,61,62,63] Impairment, damage, and failure across infrastructure 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

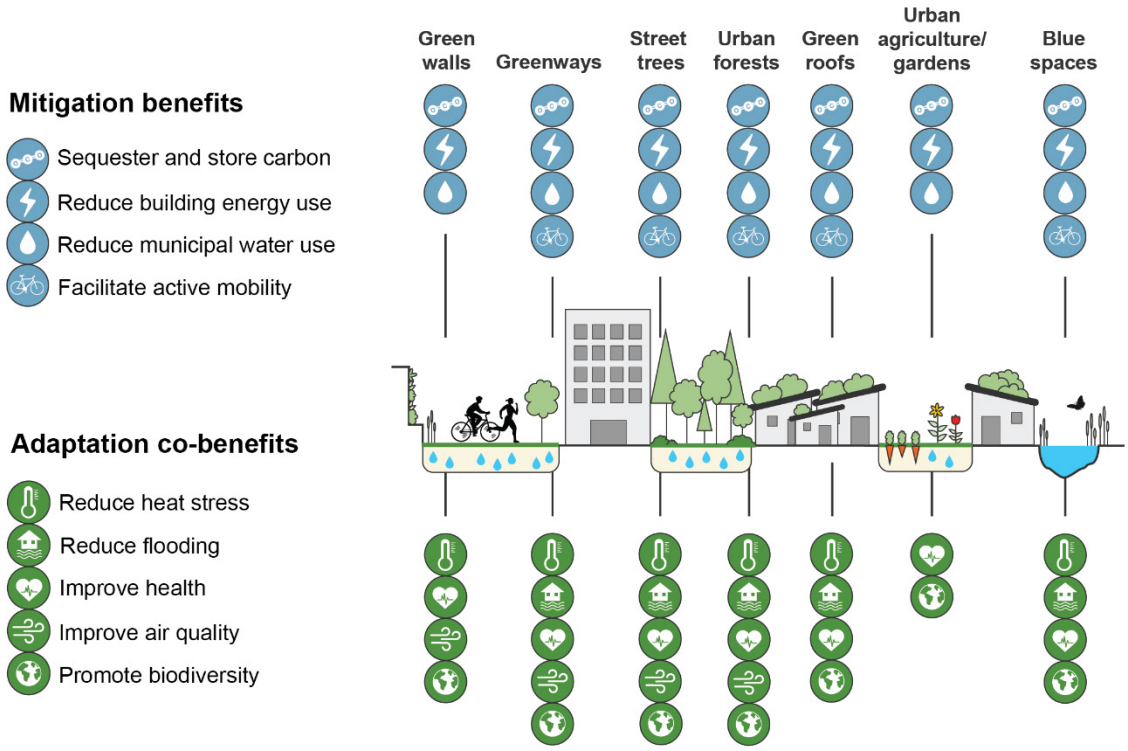
Building Options	Examples
Energy performance	Energy-efficient building retrofits, on- and off-site renewable energy production and use,[126] community/shared solar, energy-efficient lighting and appliances, monitoring and benchmarking,[127] grid-interactive buildings (see Ch. 5)
Codes and standards	Building 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.

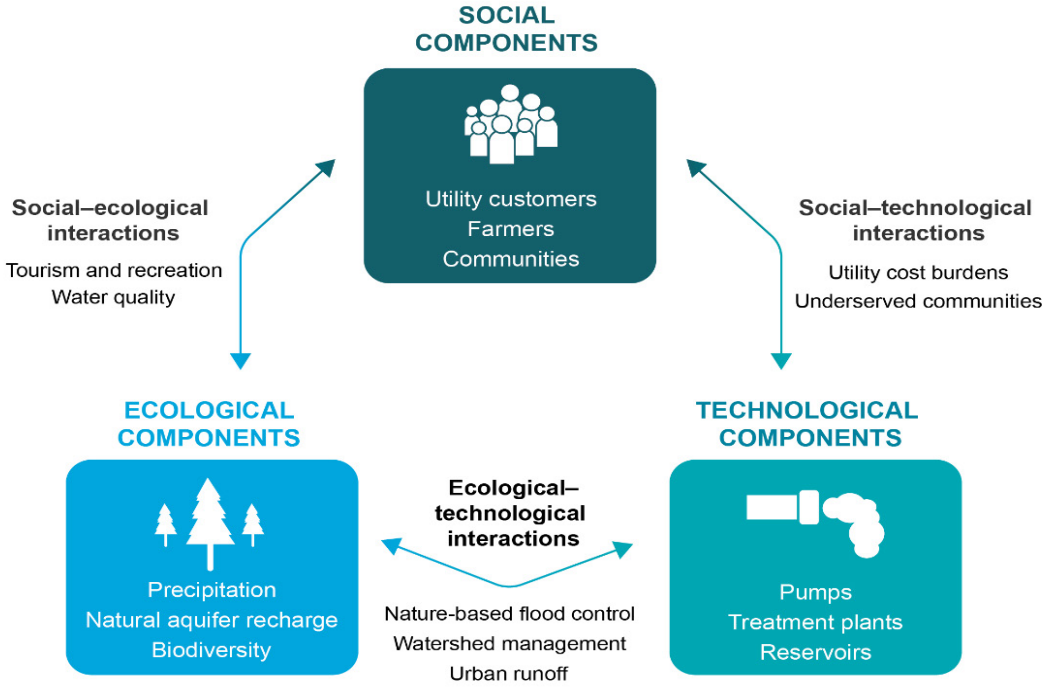
Green, Blue, and Nature-Based Solutions

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] • Neighborhood resilience hubs that support community development and resources for emergency response[221] • 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] • Plans with focus on youth, gender, and racial inclusion[169] • Reallocation of funds to support community engagement • Scenario planning,[112,223] games,[175,224] and future visioning[225]
Multilevel Collaboration	• Cross-Tribal networks[226] • Collaboration with nongovernmental organizations[227] • Creation of new leadership and coordinating roles[171] • 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.

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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.

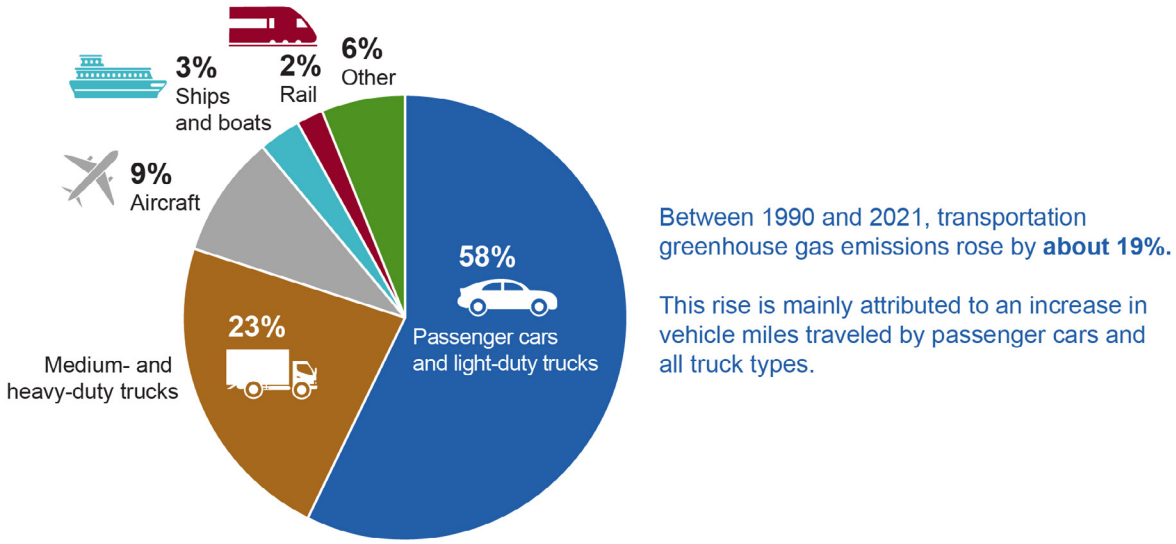
Key Message 13.1

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] • Adverse health impacts for walkers and cyclists (KM 15.1)[29]	• Shift from active transport to vehicle or public transport[30] • Obstructions and infra-structure 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] • Reduced active transport due to short- and long-term health impairments[32]
Aviation	• Runway damage from heat and thawing permafrost[33,34] • Altered flight schedules[35] • Increased insect activity and chance of bird strikes[36,37,38]	• Coastal airport water intrusion[34,39]	• Soil subsidence[40] • 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] • Unsafe working conditions (KM 15.1)[33] • Increased maintenance frequency[43,44,45]	• Damage from flooding, erosion, saturated soil, and sea level rise (Ch. 9)[34,40,43] • Increased risk of landslides[43] • Reduced life cycle from repeated runoff events[46] • 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] • Reduced slope stability due to decreased roadside seeding uptake[47] • Emergency bridge maintenance[48] • Reduced visibility and increased closures from dust storms[41]	• Road closures and reduced visibility[40] • Obstructions and debris flows (KM 6.1)[49] • Increased chance of runoff[26,43] • Reduced slope stability due to burn scar[50]
Rail	• Buckling of rails (KM 5.1)[34,40] • Reduced train speeds[51] • Catenary line sag[52]	• Flooding of bridges, tunnels, and low-lying rails[33,34] • Damage from landslides[52]	• Changes in soil stability affecting track geometry and integrity[53]	• Damaged equipment[54] • System disruption and rerouting[54]
Pipelines	• Structural damage due to permafrost thaw (KM 5.1)[55]	• Overloaded drainage systems[40] • Pipeline shifting, exposure, and fracture due to heavy precipi-tation[34]	• Broken pipelines due to ground subsidence[34]	• Fire-induced toxicity in plastic water systems[56] • Weakened pipelines due to increased runoff and debris flows[57]
Waterborne	• Reduced problems with ice accumula-tion and increased access to ports (Ch. 10)[34] • Longer shipping seasons[34]	• Port damage due to increased storm surges and tides[34] • River flooding[34]	• Reduced vessel carrying capacity due to lower water levels[34] • 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]

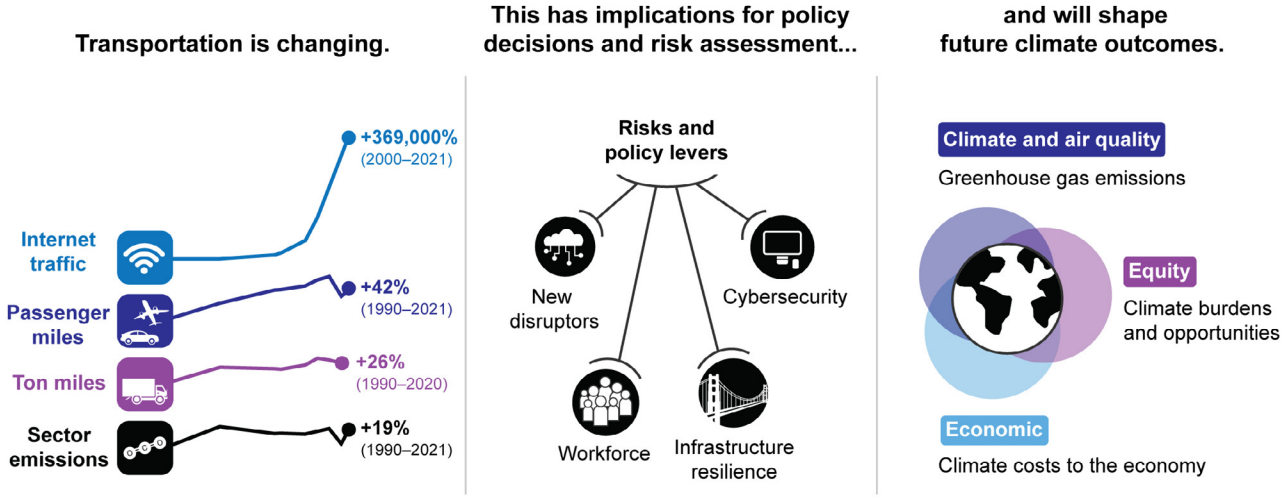
Key Message 13.2

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

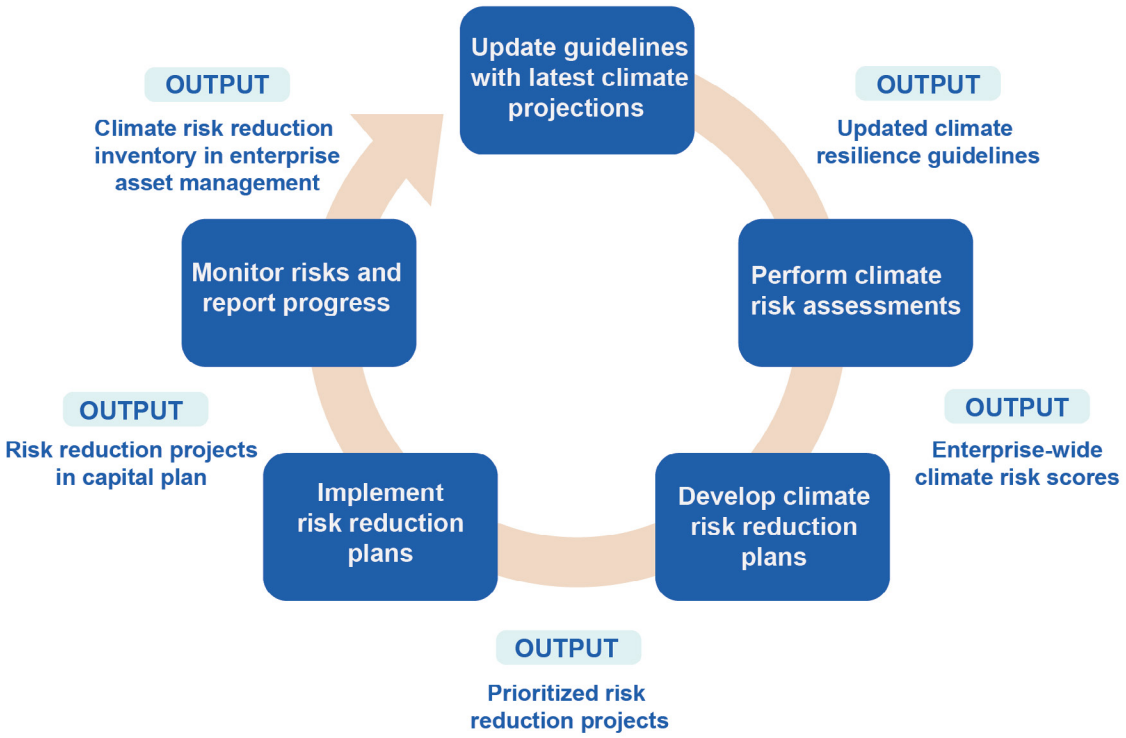


A shifting transportation landscape, and how we respond to it, will determine future climate outcomes.

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]

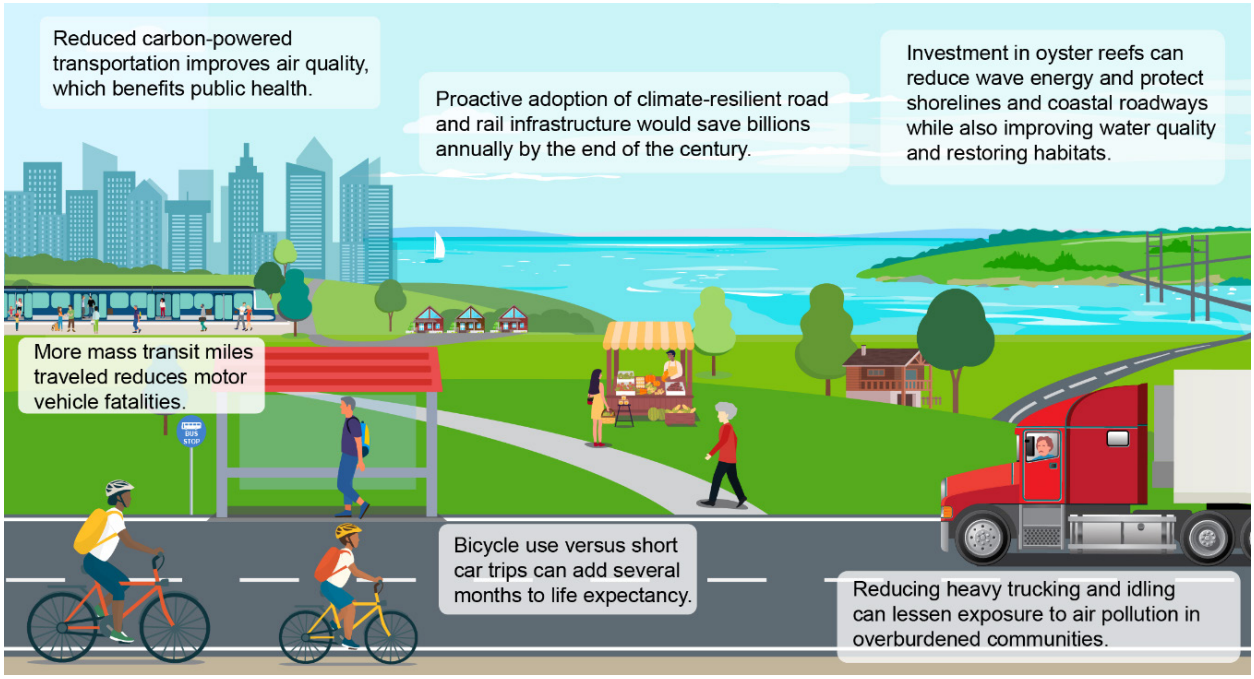
Key Message 13.3

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.

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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.

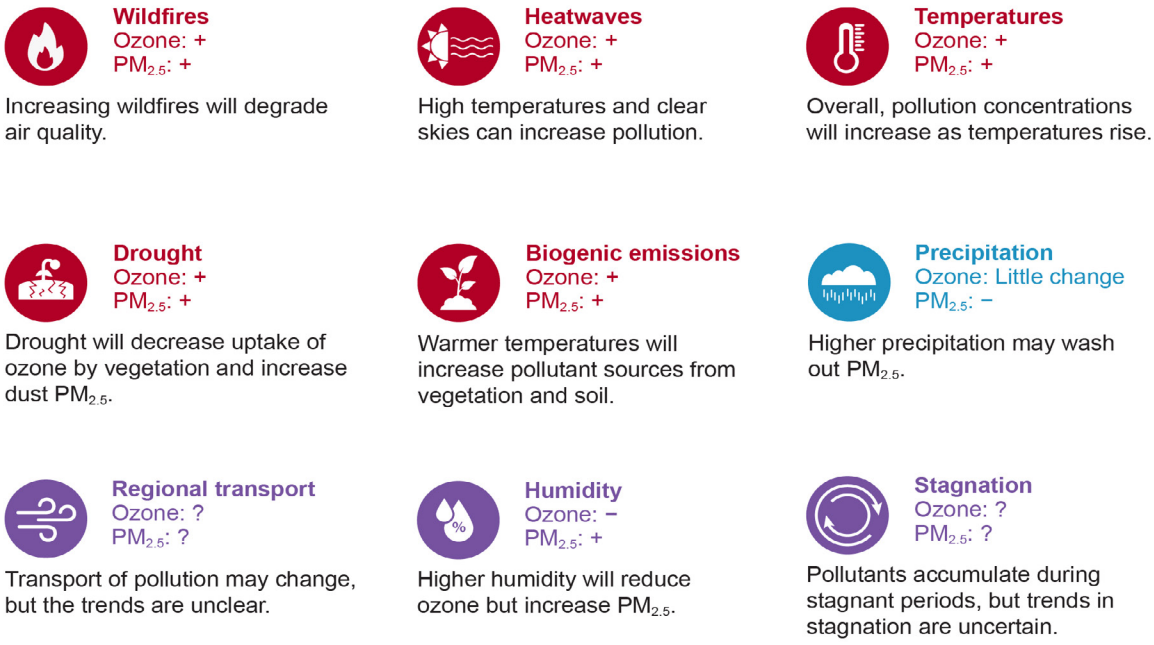
Climate change is expected to alter meteorology over the US in several ways that will directly degrade air quality (Figure 14.1). For example, ozone levels are higher on warm, sunny days because the chemical reactions that produce ozone speed up with temperature and sunlight. Exposure to these short-term 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

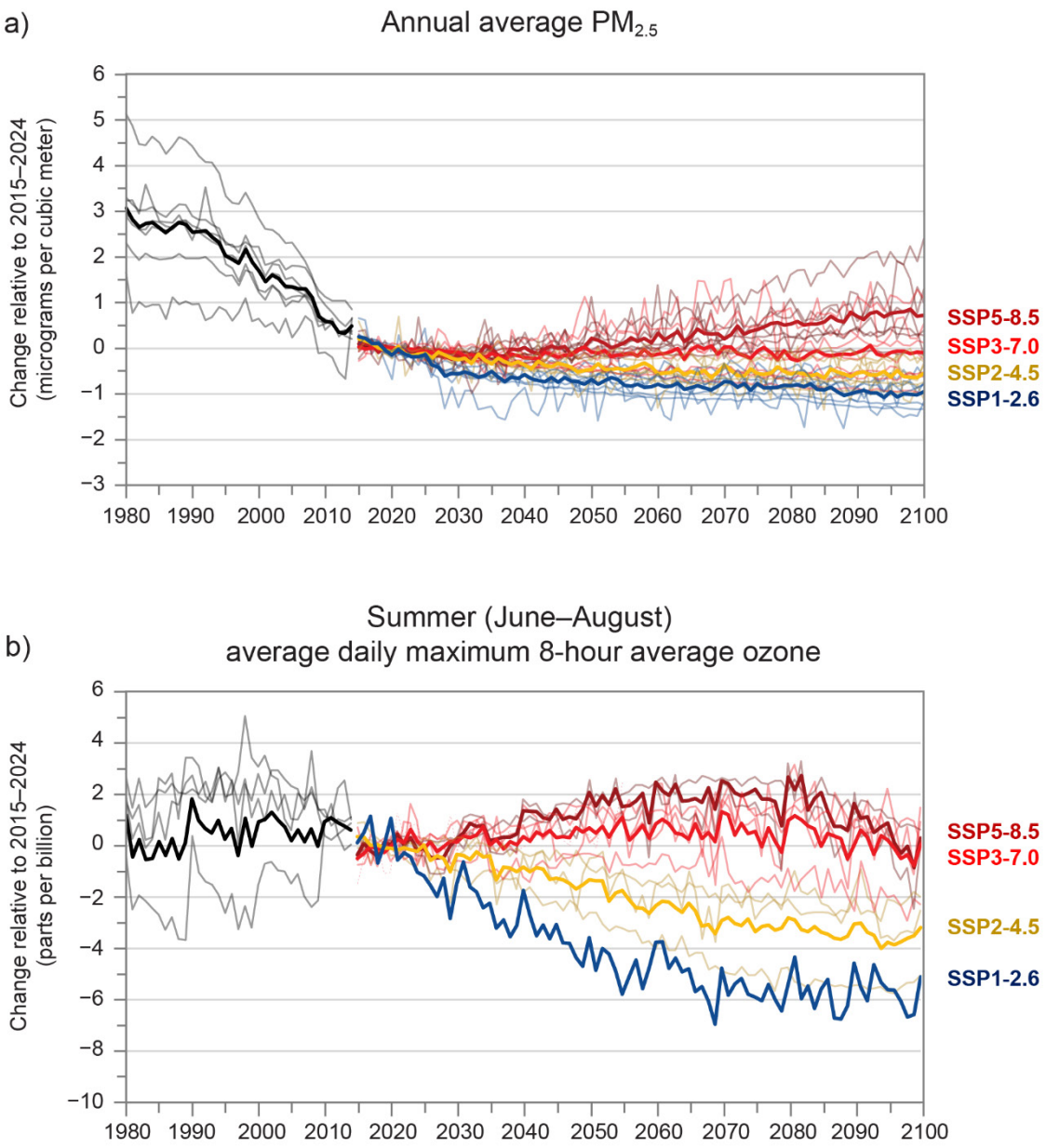


Climate change will have varying effects on ozone and fine particulate matter ($PM_{2.5}$) concentrations, including through impacts on weather-sensitive emissions.

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]

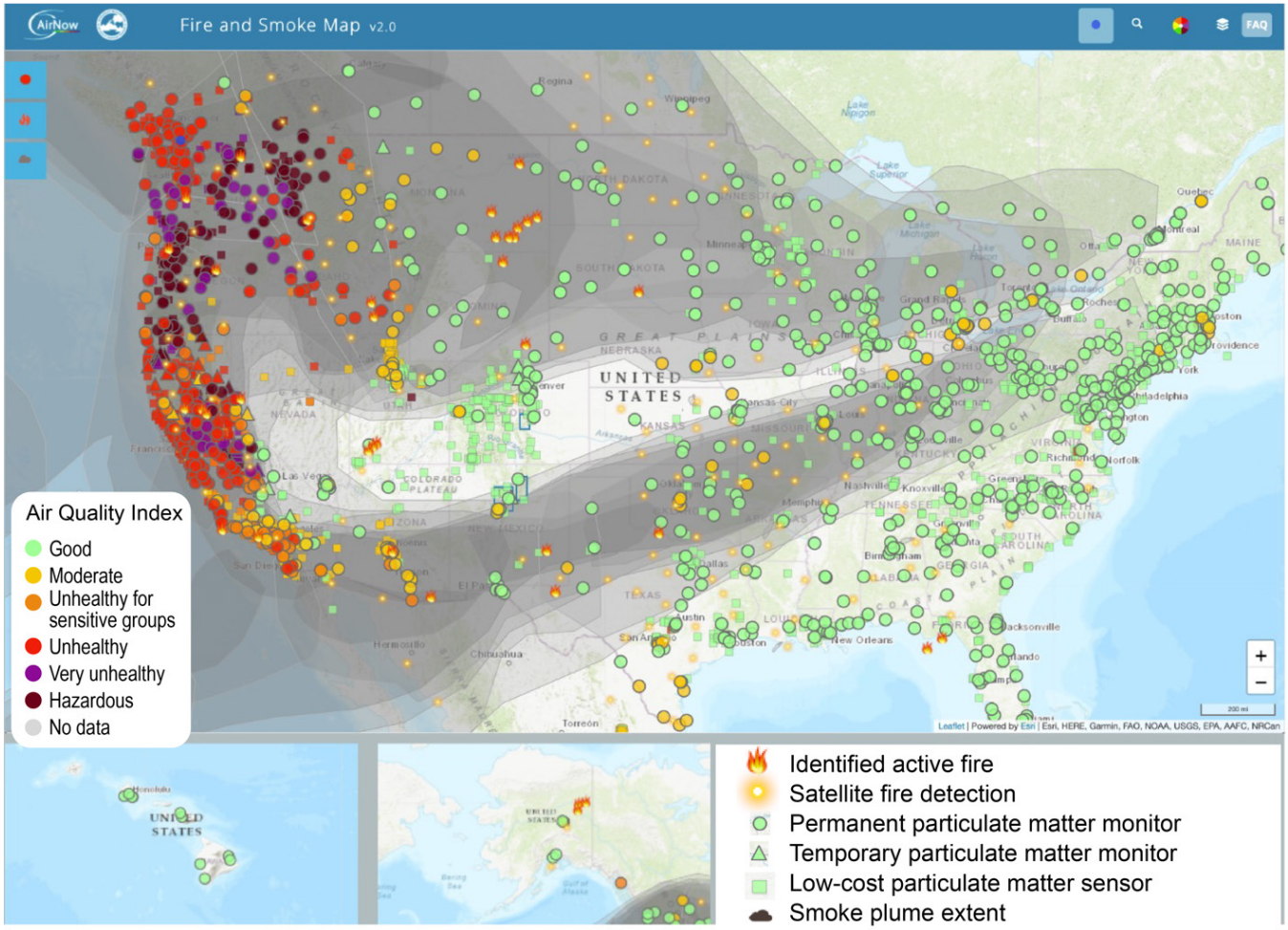
Wildfires emit $PM_{2.5}$ and other air pollutants, including volatile organic compounds (VOCs), nitrogen oxides (which contribute to ozone generation in plumes), and toxic gaseous and particulate species.[74,77] Since publication of the Fourth National Climate Assessment in 2018, studies have revealed 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

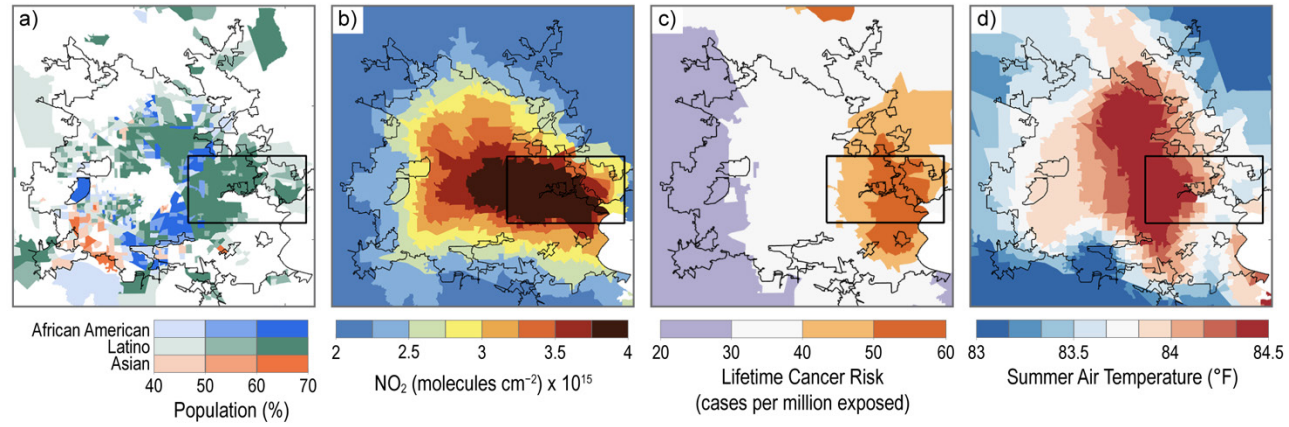
Houston's Ship Channel region is a patchwork of chemical refineries, freeways, homes, and playgrounds (Figure 14.4; Box 26.1). Air pollution levels along this busy industrial waterway, connecting downtown Houston to Galveston Bay, are among the highest in the city (Figure 14.5). Flares and odors are 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*).

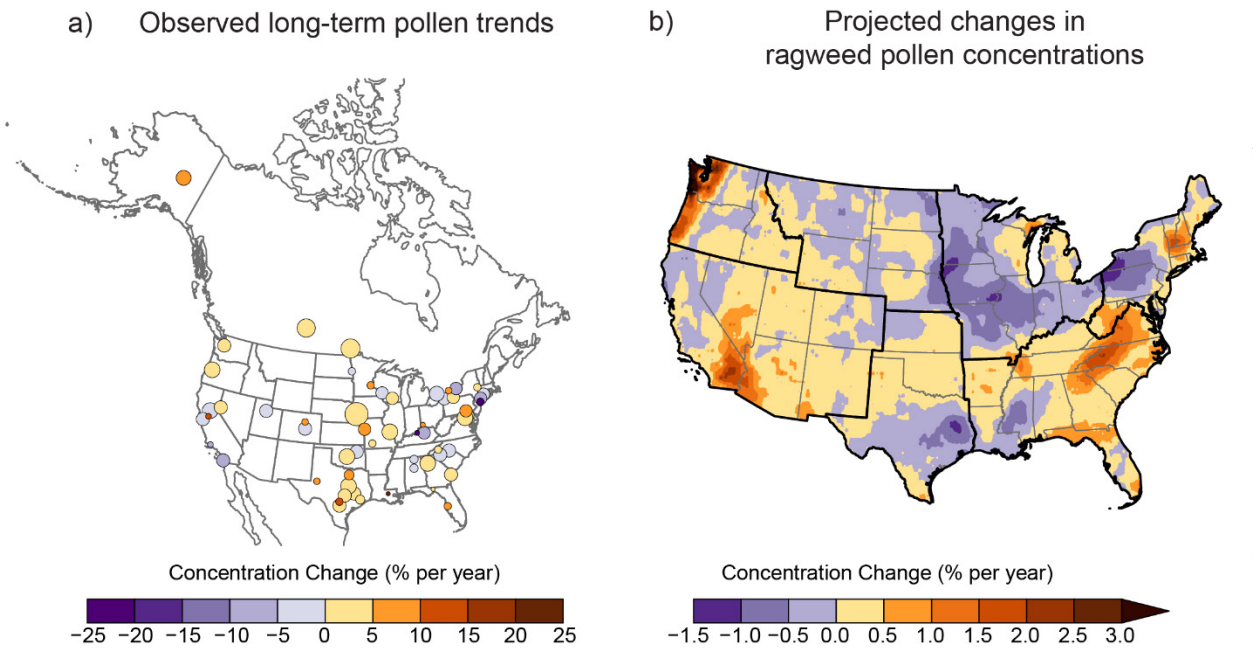
Allergic airway disease, including allergic rhinitis and asthma, is widespread in the US, is becoming more prevalent, and imposes a burden of several billion dollars in healthcare costs and lost productivity annually.[184] Exposure to allergenic pollens and molds (aeroallergens) triggers allergic disease 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

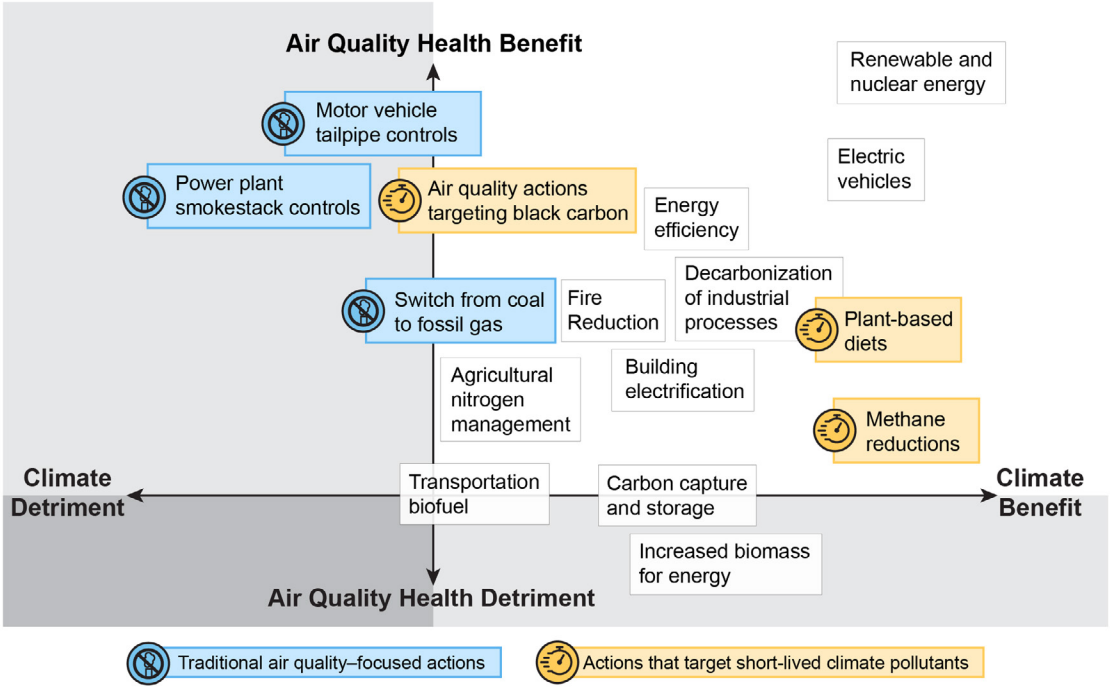
Substantial reductions in economy-wide greenhouse gas emissions would result in improved air quality and significant public health benefits (*very likely*, *high confidence*). For many actions, these benefits exceed the cost of greenhouse gas emission controls (*likely*, *high confidence*). Through coordinated 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

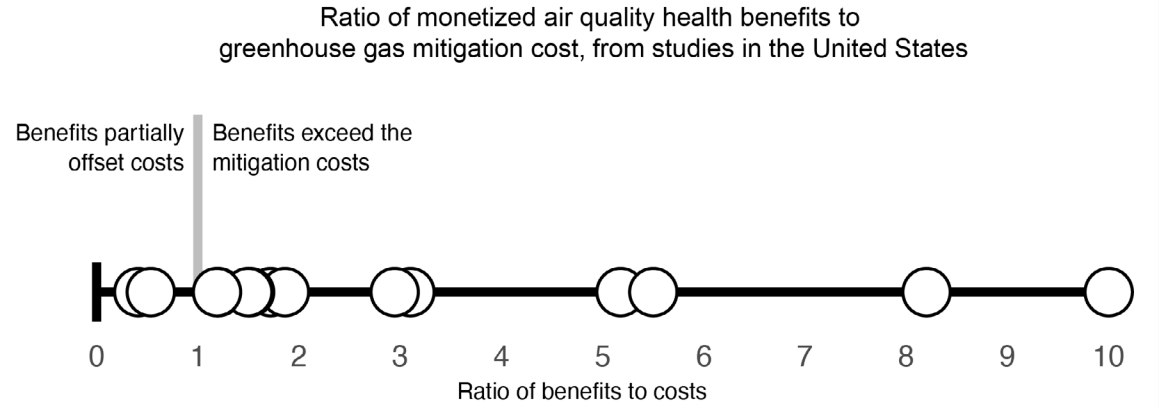


Many emissions-reduction actions can achieve multiple benefits for climate, air quality, and health.

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]

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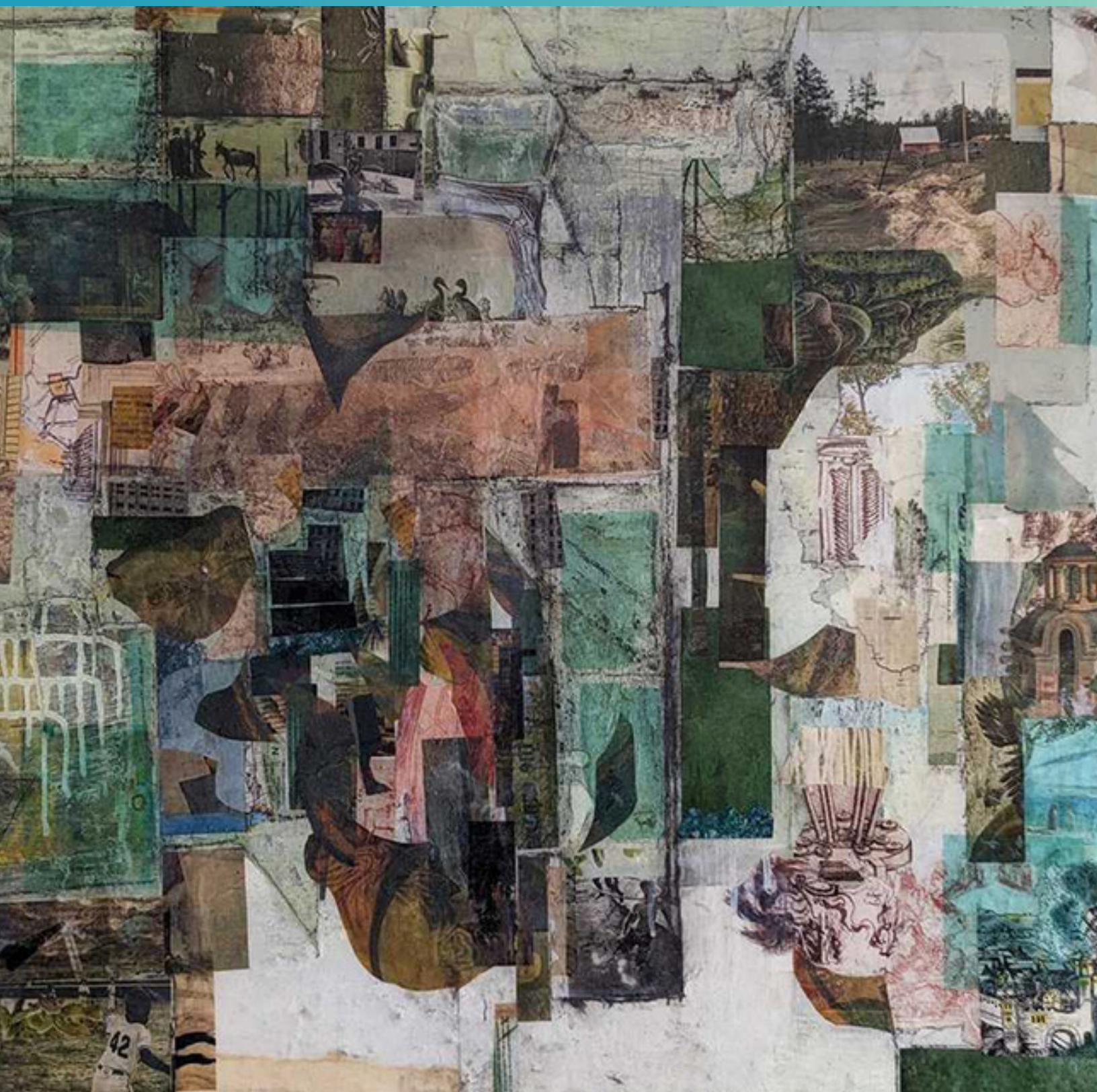
Fifth National Climate Assessment: Chapter 15

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]

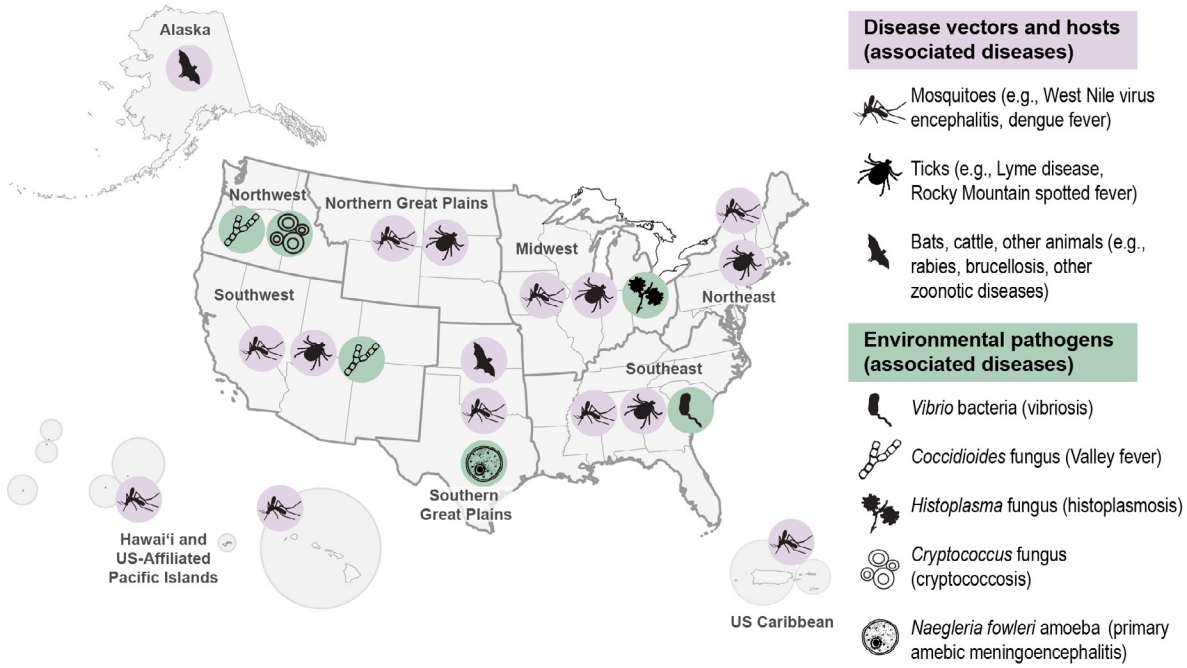
Infectious Diseases

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).

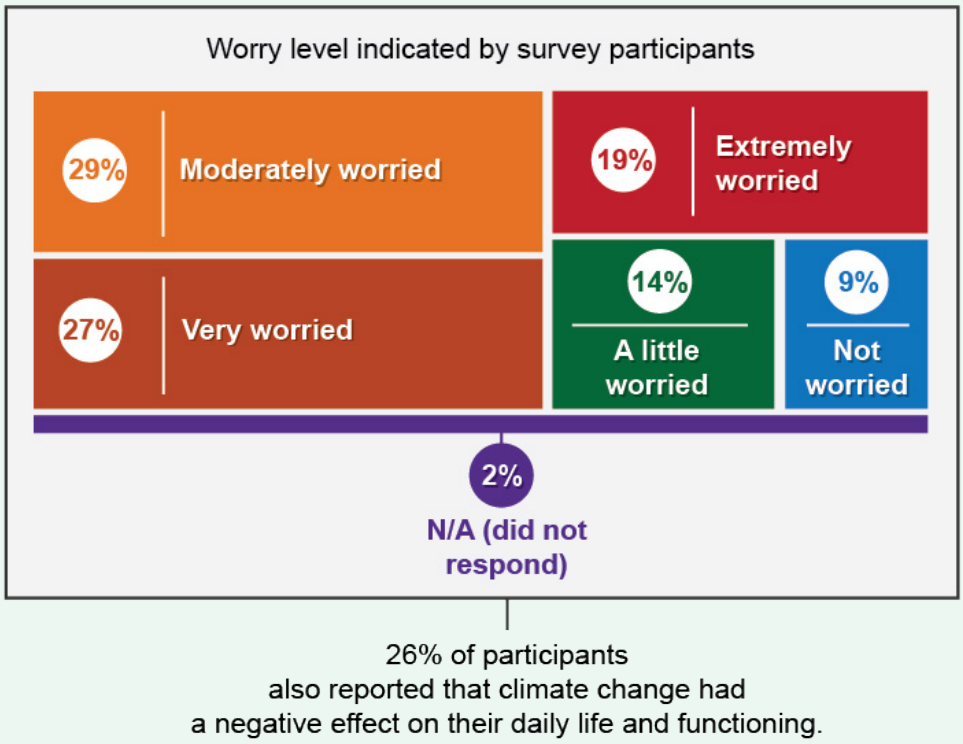
Mental health conditions including anxiety, depression, and suicide have become more prevalent in the US in the past decade, especially among adolescents.[119,120] Climate change may increase these mental health burdens.[55] Greater need for mental health services and psychiatric medications, as well 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

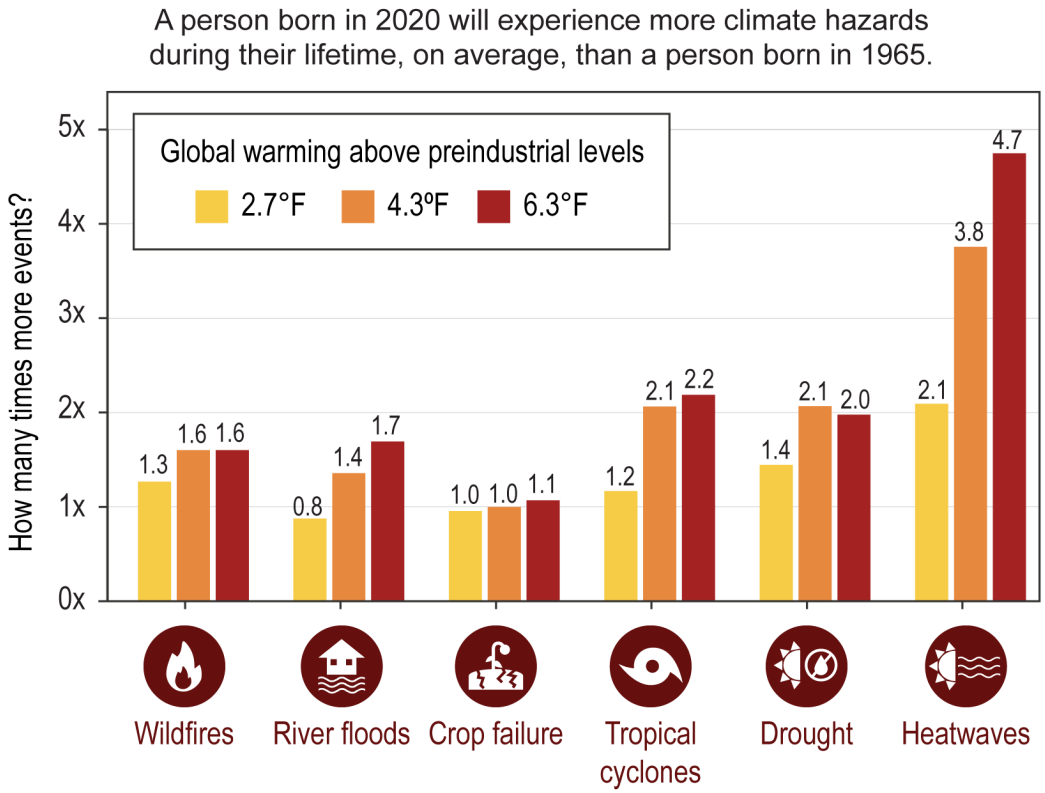
Climate change unequivocally worsens physical, mental, spiritual, and community health and well-being, as well as social inequities. It is an established fact that climate-related impacts disproportionately harm communities and people who have been marginalized. These include BIPOC (Black, Indigenous, 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

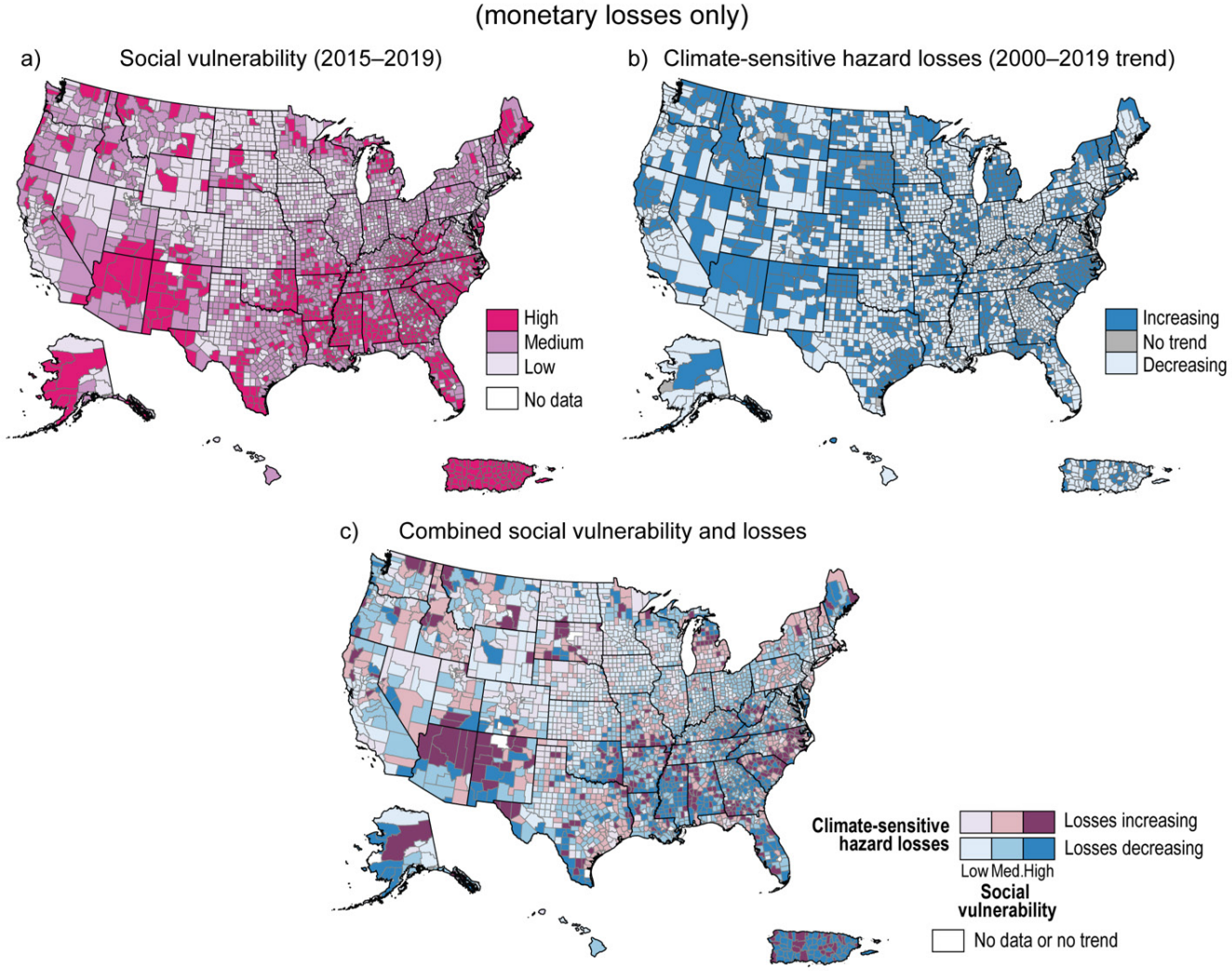
Women disproportionately experience the burden of climate change because of unique mental, sexual, and reproductive health needs that intersect with existing social, racial, and economic disparities. Women, and particularly women of color, are more likely to live in communities with low wealth,[190,191] 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.

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Fifth National Climate Assessment: Chapter 16

Tribes and Indigenous Peoples

Chapter 16. Tribes and Indigenous Peoples

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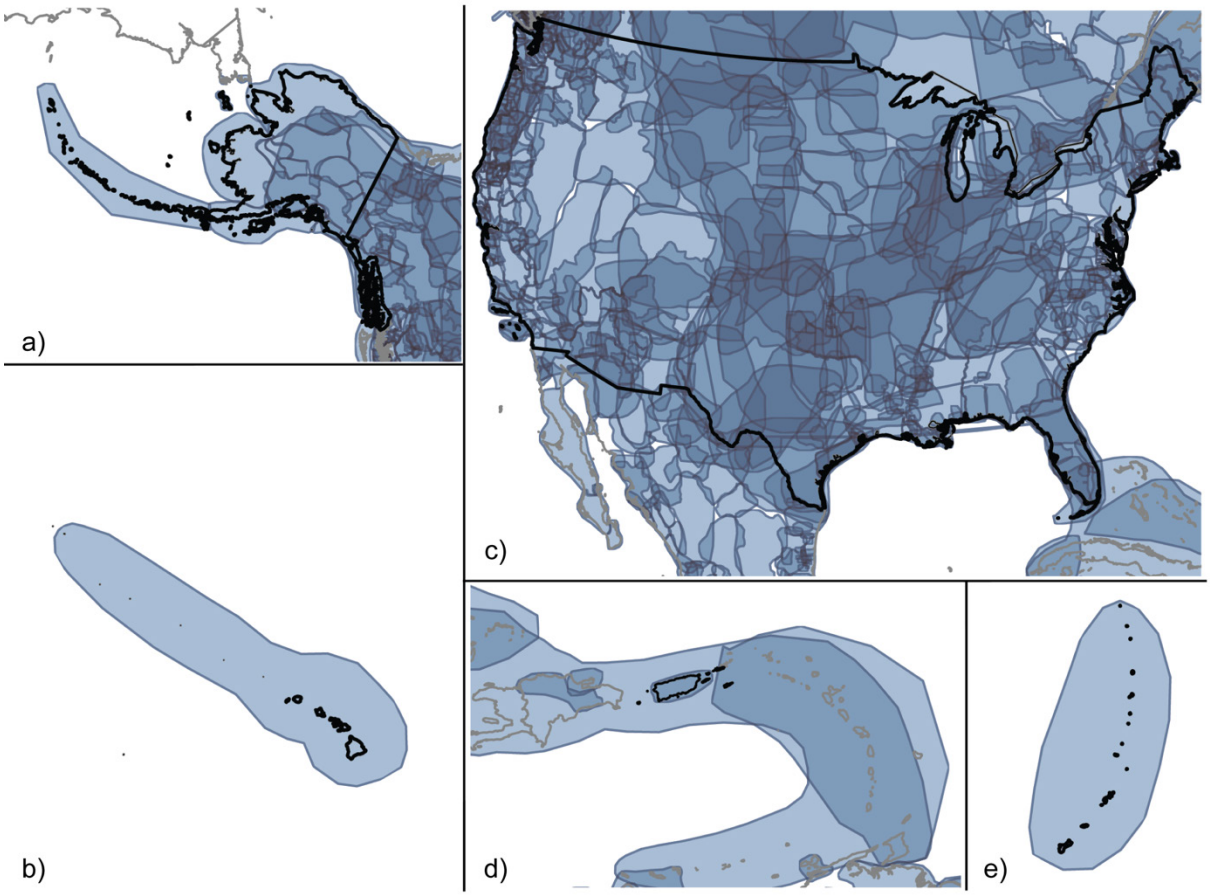
Introduction

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.

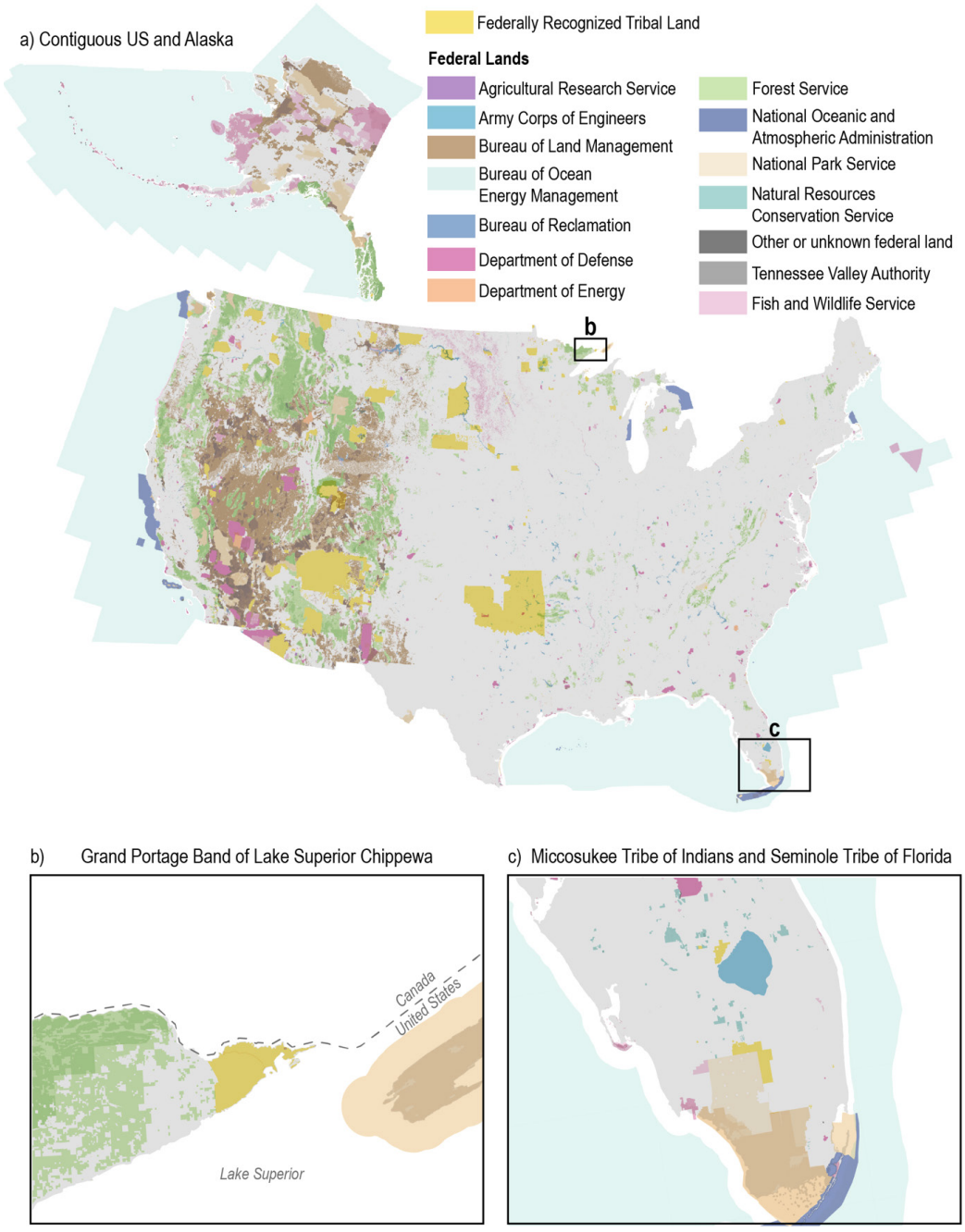
Representative Locations of Indigenous Peoples



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.

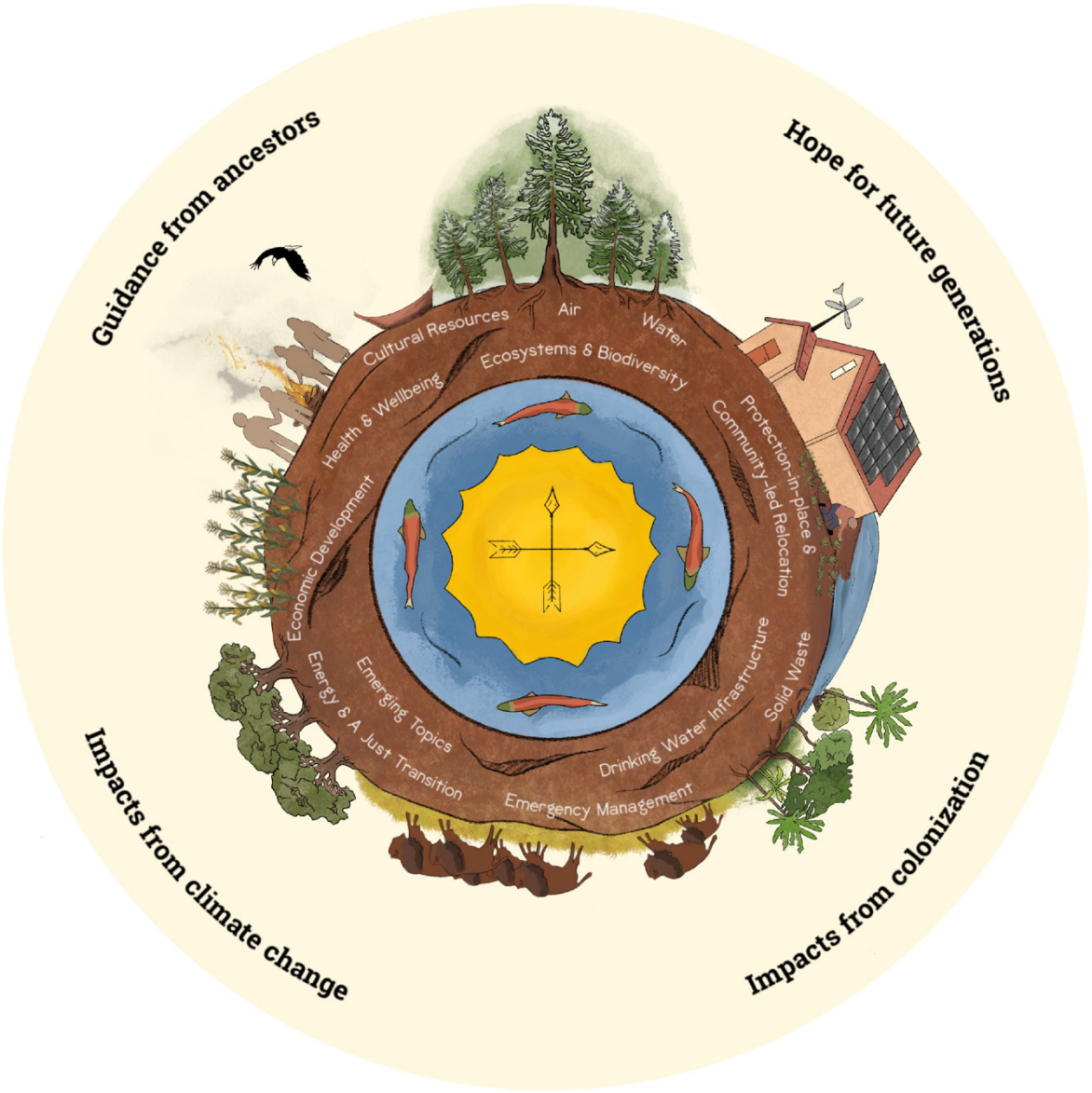
The Complexity of Land Tenure for Indigenous People



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]

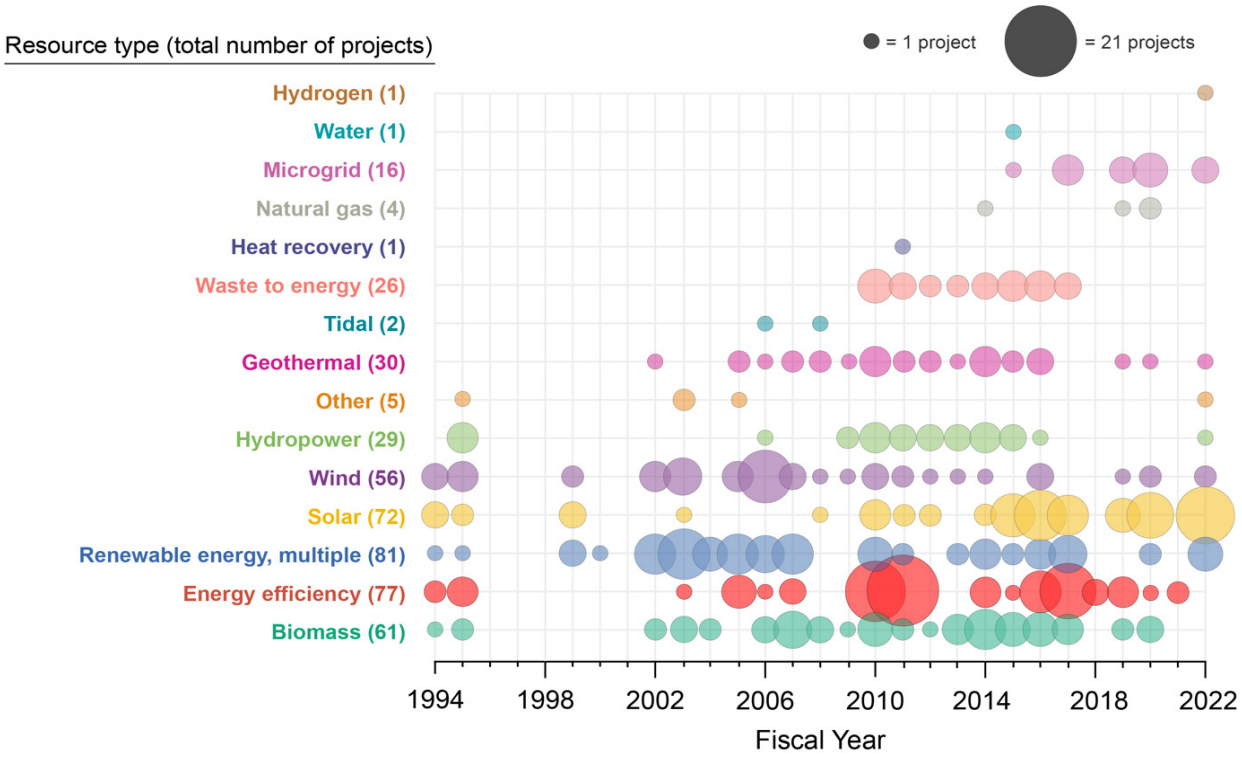
Climate change threatens to disrupt the conditions for critical Indigenous subsistence practices, including, but not limited to, planting, pollination, harvesting, the preparation and storage of food and medicines (i.e., medicinal plants), and subsistence-related travel (KMs 7.2, 10.2, 11.2, 21.3, 24.3, 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

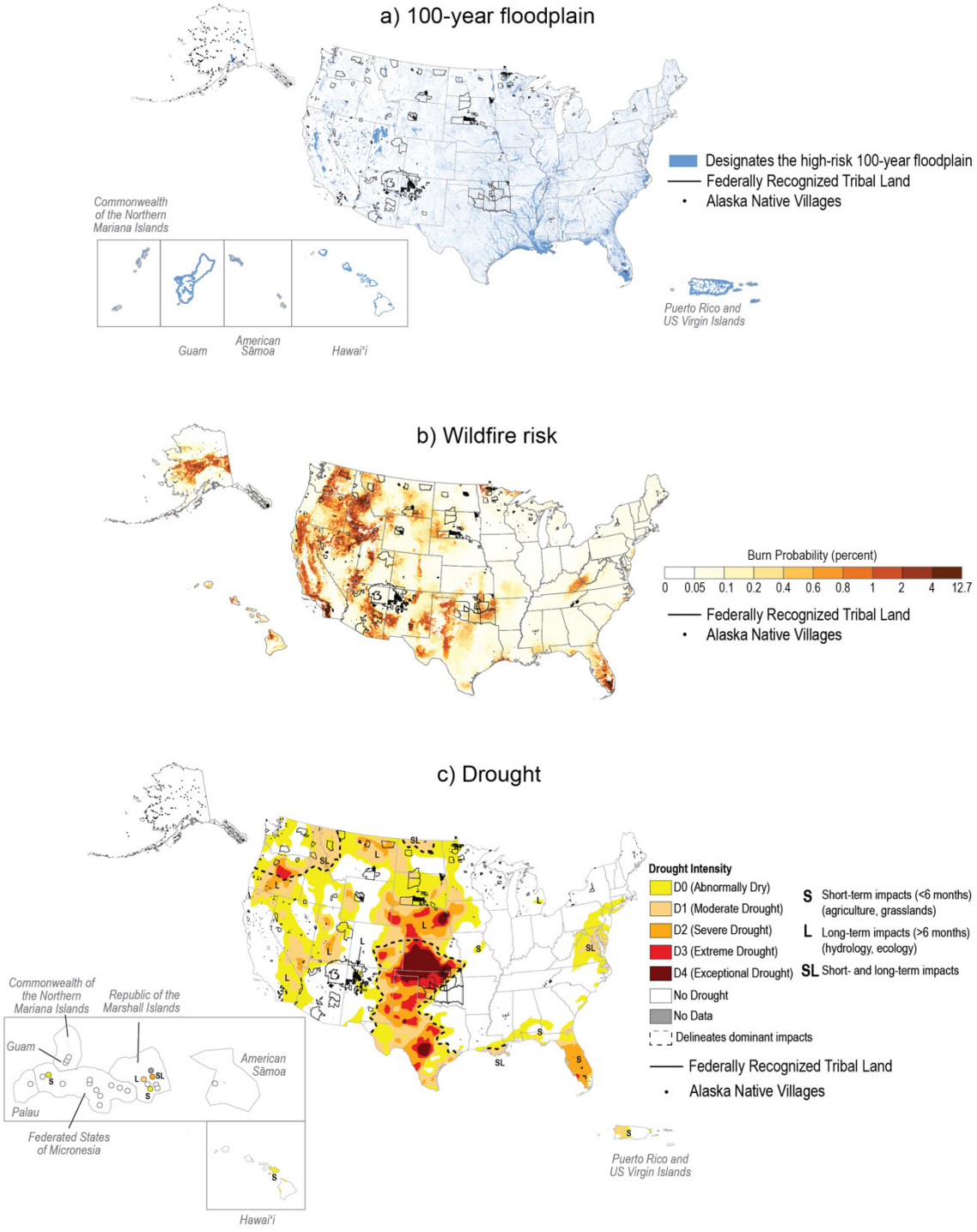
Indigenous Peoples, including Alaska Native villages, Pacific and Atlantic Coast Tribes, and Louisiana coastal Tribes, face unmet infrastructure needs and added stressors to culture and livelihoods as they relocate in response to increased erosion, more frequent flooding, increases in permafrost thaw, 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.

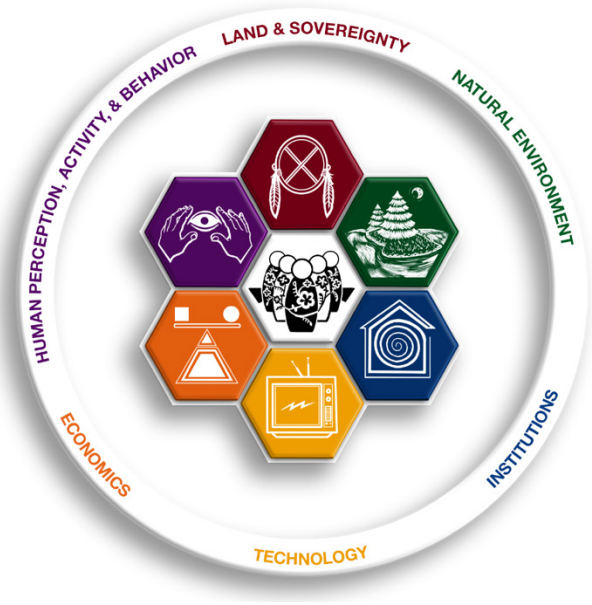
Figure 16.7. The firehouse was designed in collaboration with the community and reflects the Onondaga Nation's language and culture. Photo credits: © Kelsey Leonard, University of Waterloo.

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.

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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]

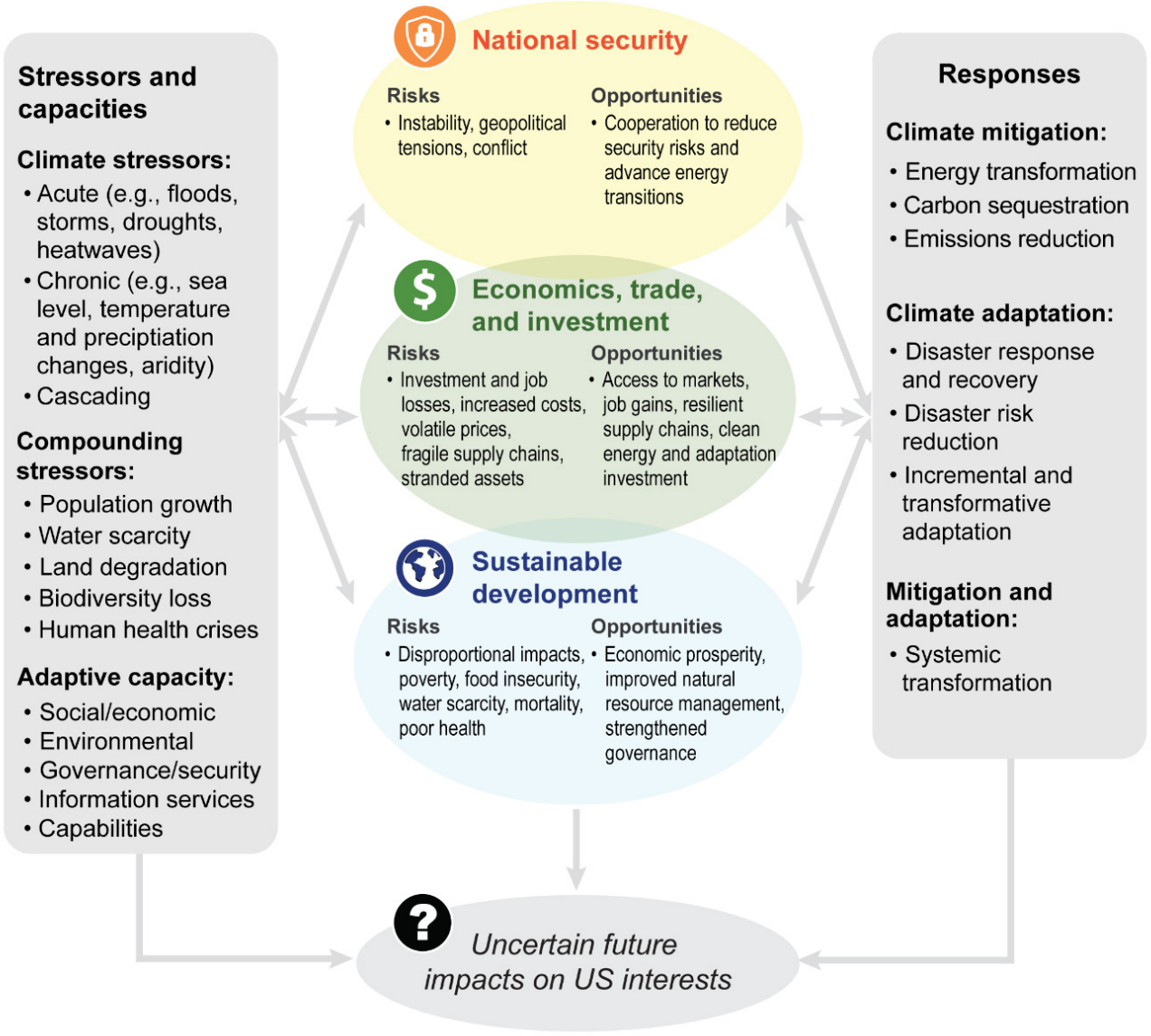
Climate change impacts affect the US's security, economy, and sustainable development interests by reducing local and global stability, disrupting livelihoods and economic growth, increasing poverty and global inequality[25,26] and compounding existing risks across US interests. For example, the Central 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

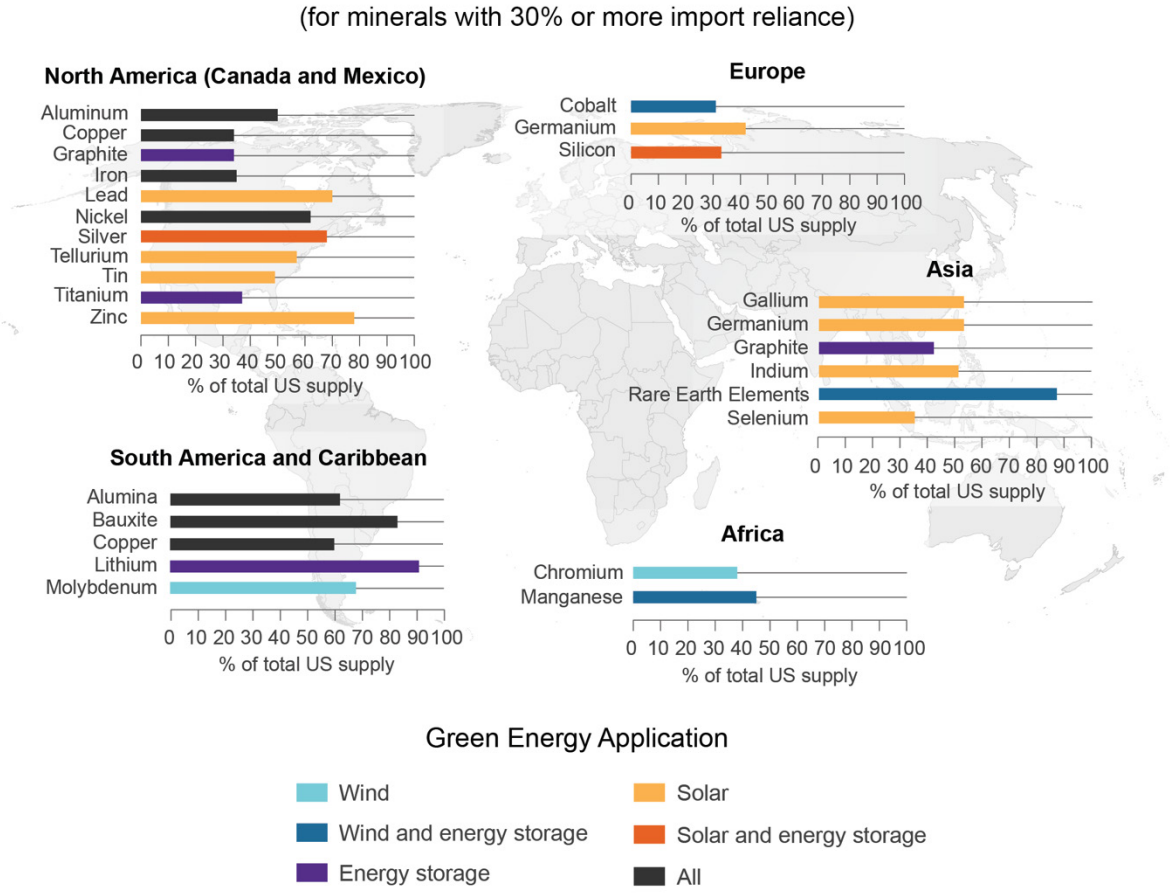
Mobility, both planned and forced, is a common adaptation response to a changing environment, contributing to displacement and migration that primarily occurs within countries and, at times, crosses national boundaries.[31,62,63] Climate change–related mobility, impacting both sending and receiving populations, 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).

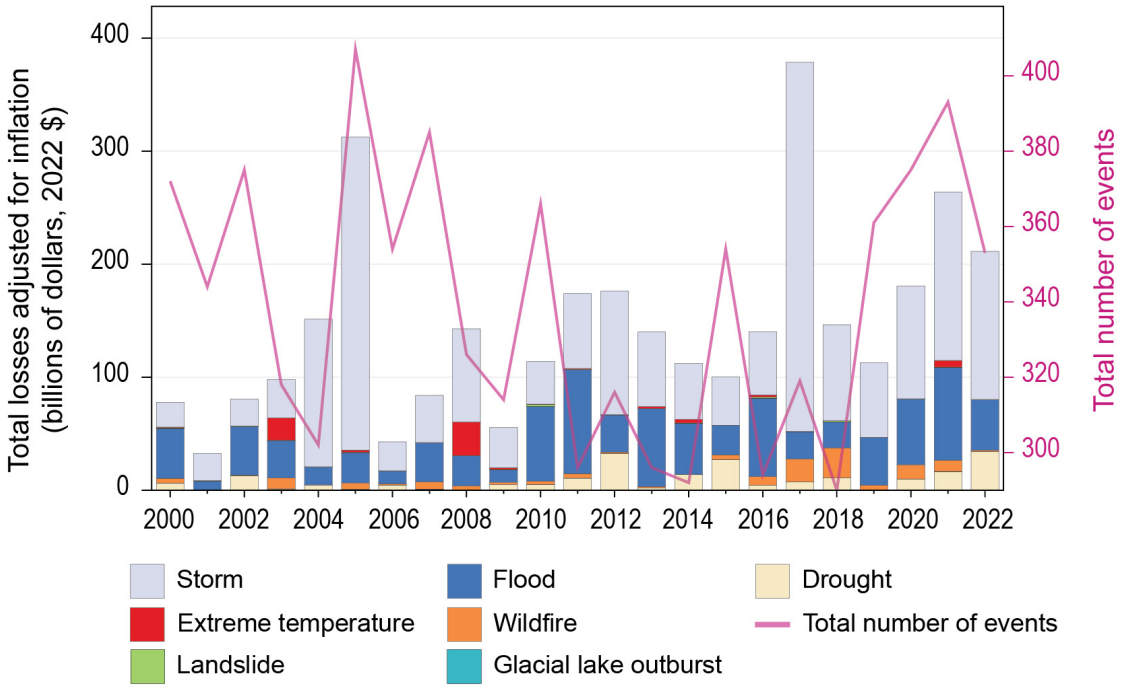
Key Message 17.3

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]

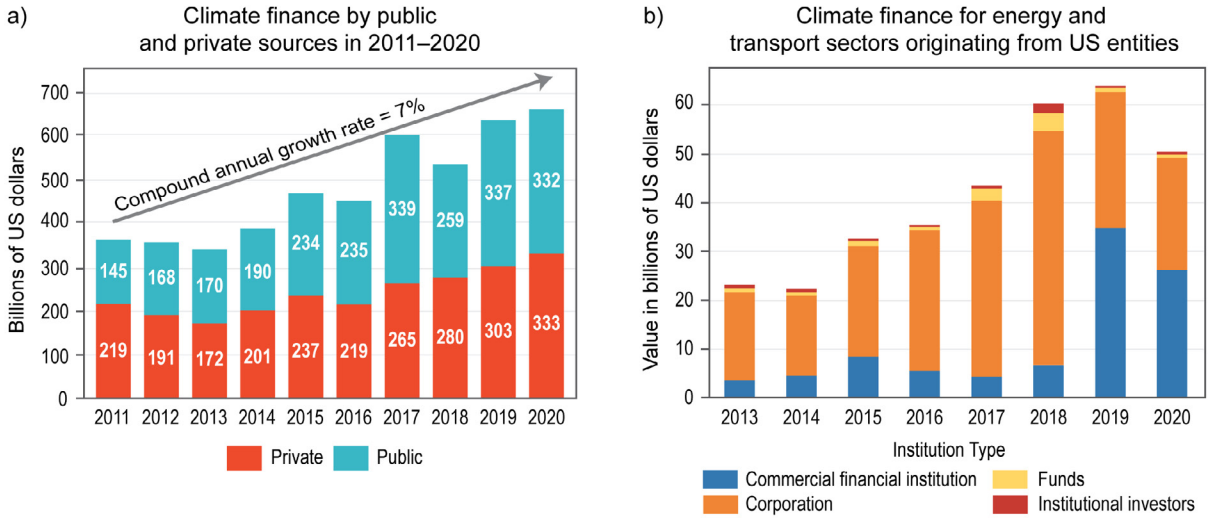
Global climate responses, including policy choices and market responses, present both risks and opportunities for US economic interests as other countries transition toward low-emissions, climate-resilient economies.[86,102] Transition risks include potential job losses, stranded assets, energy price 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

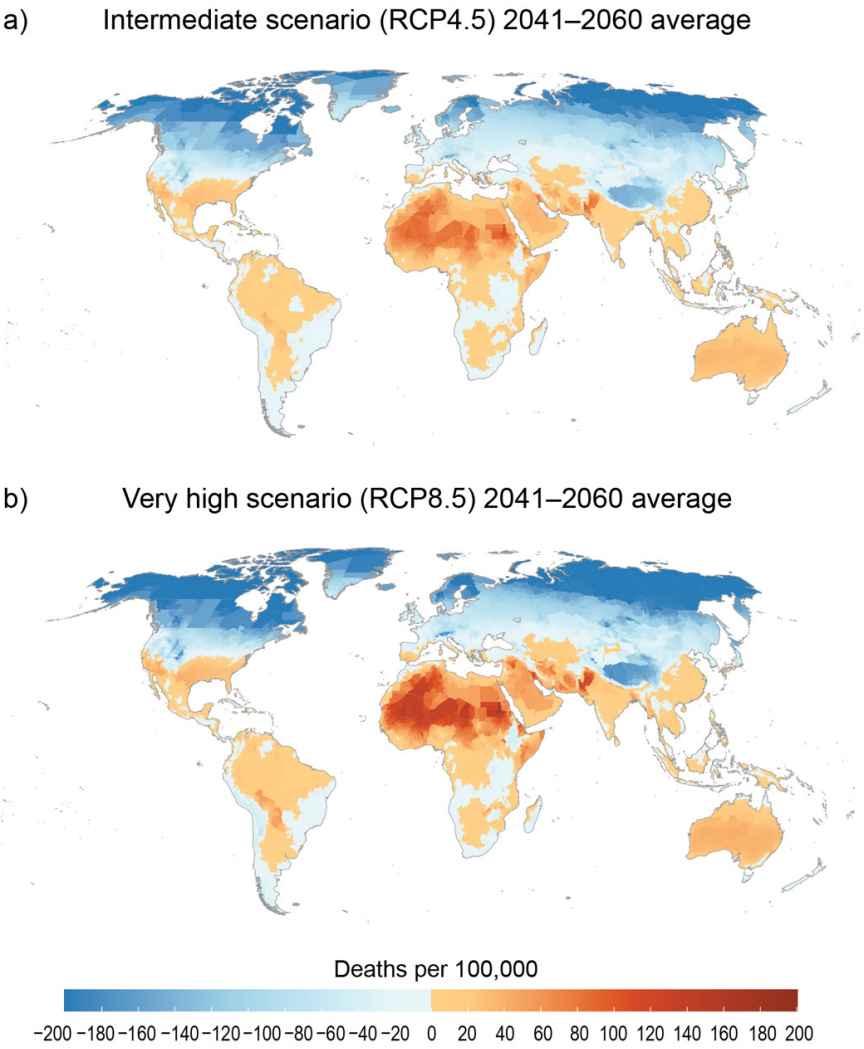
Climate change undermines the world's ability to develop sustainably, reverses development gains, and exacerbates inequities (*very likely*, *high confidence*). Climate finance is increasing, but global flows continue to fall short of needs (*likely*, *high confidence*). Accelerated deployment of adaptation 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.

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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.

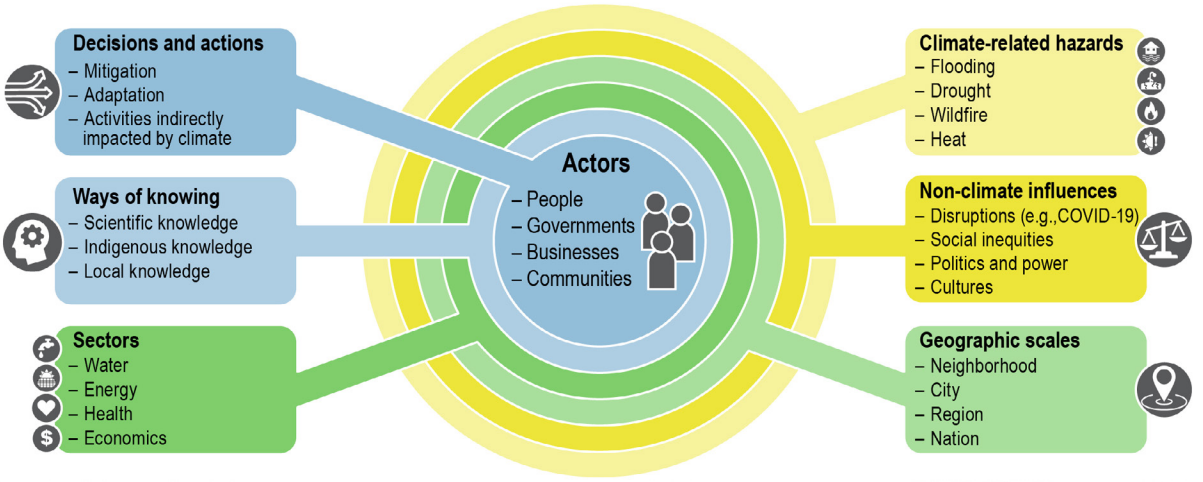
Climate change makes the existing interconnections between human and natural systems more important for two reasons. First, many human and natural systems have conditions in which a small shock or change can produce very large impacts, but these conditions are rarely known in advance.[7] For example, 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.

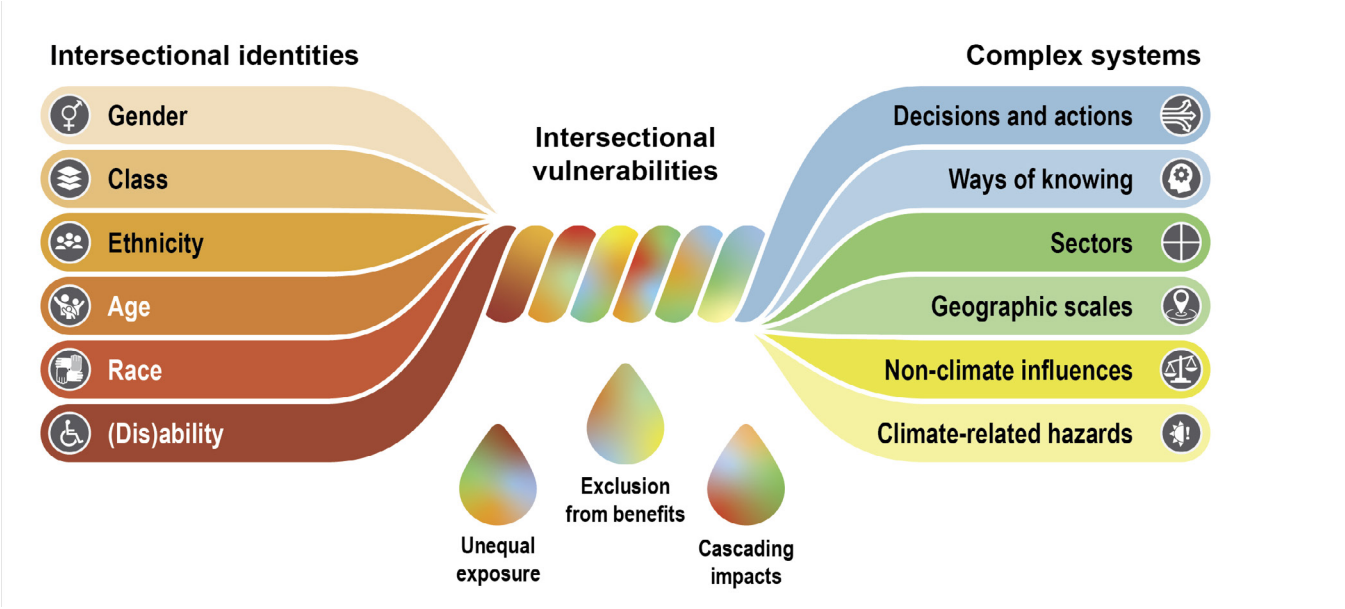
Box 18.2. Wildfire and COVID-19 Lead to Compounding and Cascading Impacts over Time

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]

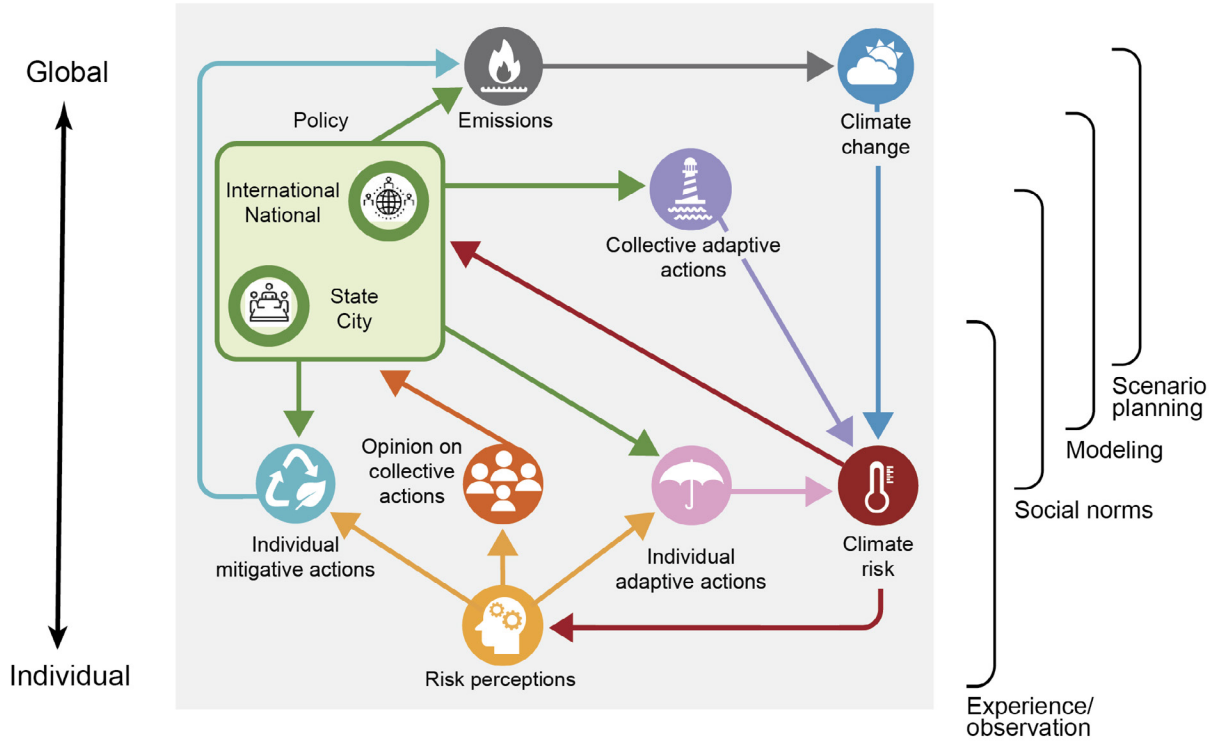
Connecting different knowledge holders and knowledges requires a different type of scientific practice that is more collaborative, participatory, or community-engaged.[116,146,147,148,149] Approaches such as coproduction, which bring together diverse knowledge holders with potential knowledge users, 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:

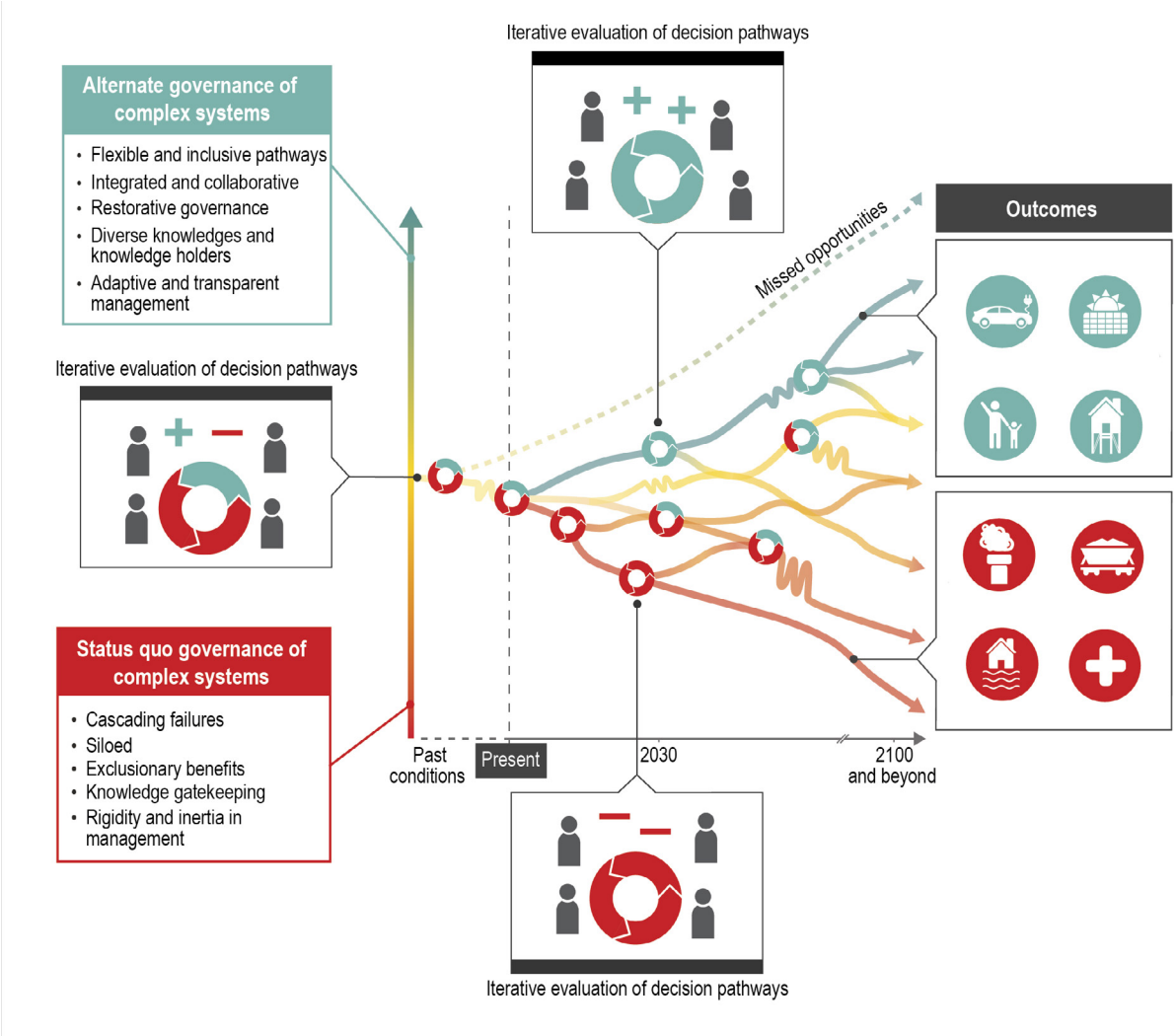
- Complex systems are often characterized by *deep uncertainty*—the presence of systemic structural uncertainties or unknowns without objective probabilities. Climate risks and possible scenarios exacerbate this uncertainty (KM 18.1). Stakeholders such as private-sector interests, public-sector officials, 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]

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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

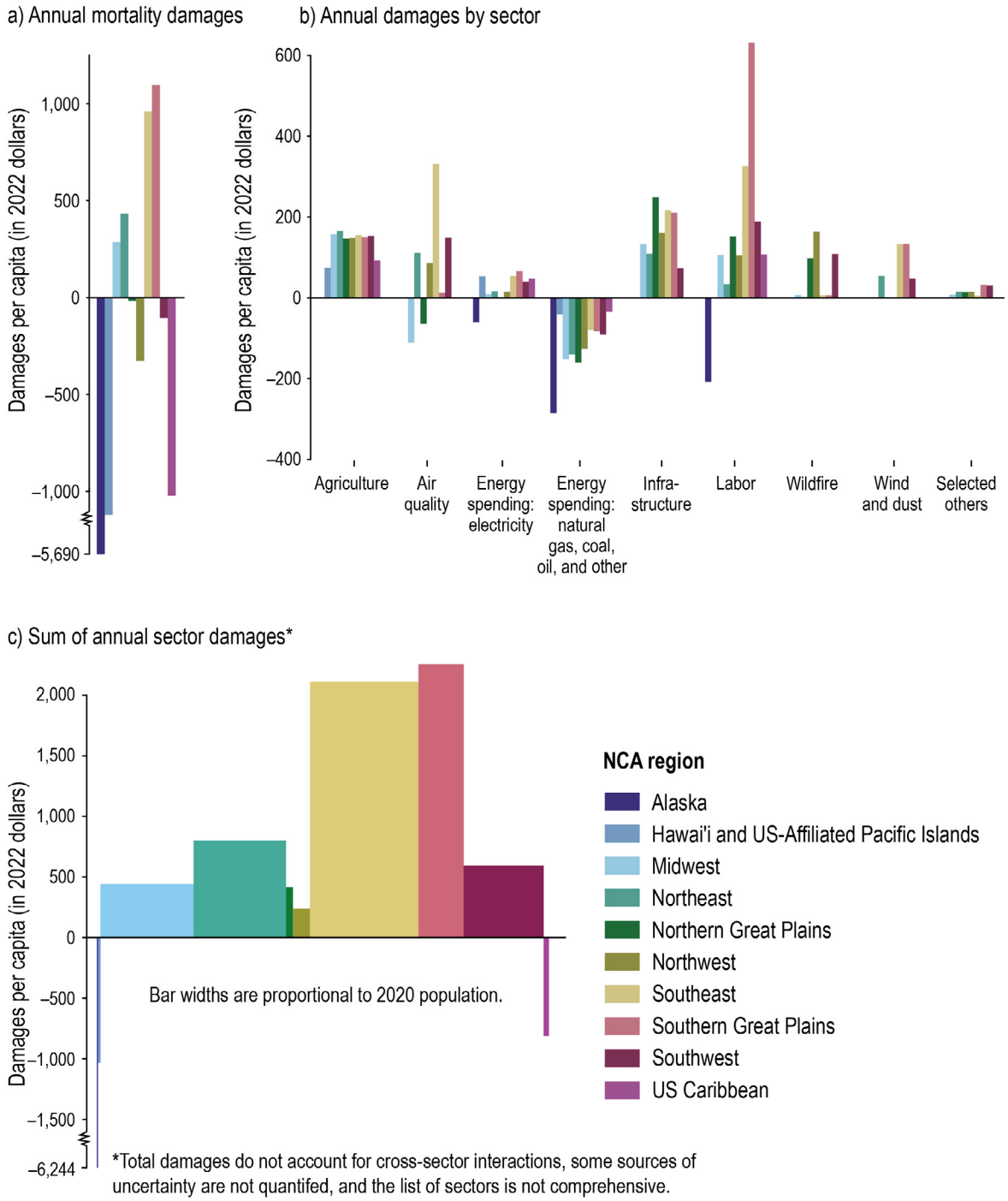
Sector	Impact Type	Climate Hazard	Economic Estimate
	Agricultural yields (maize, soybeans, winter wheat, spring wheat, cotton, and sorghum)	Temperature, moisture changes	12%–29%* decrease (2050–2100)[21] 20%–48%*** decrease (2050–2100)[21]
	Agricultural yields (maize, soybeans, and cotton)	Temperature, precipitation changes	30%–46%* decrease (2070–2099)[26] 63%–82%*** decrease (2070–2099)[26]
	Aggregate multisector impact	Temperature increases	−0.1%–1.7% GDP loss*[15] 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] +$36 billion*** (2050 annual expenditures)[66]
	National Flood Insurance Program	Flooding	+$3.9 billion annual losses (2050)*[66] +$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] +$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] +$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] +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.

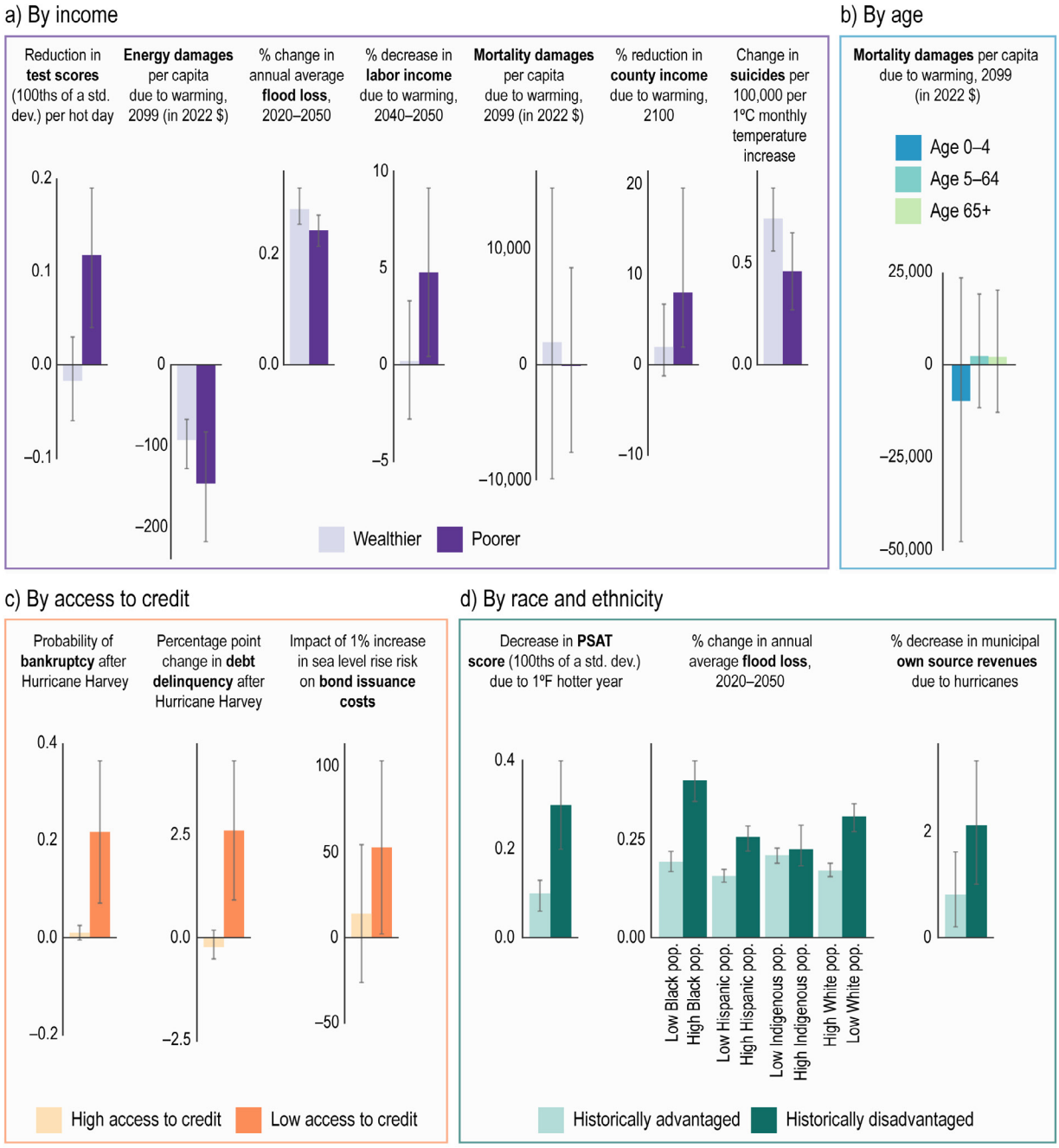
Adaptation

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*).

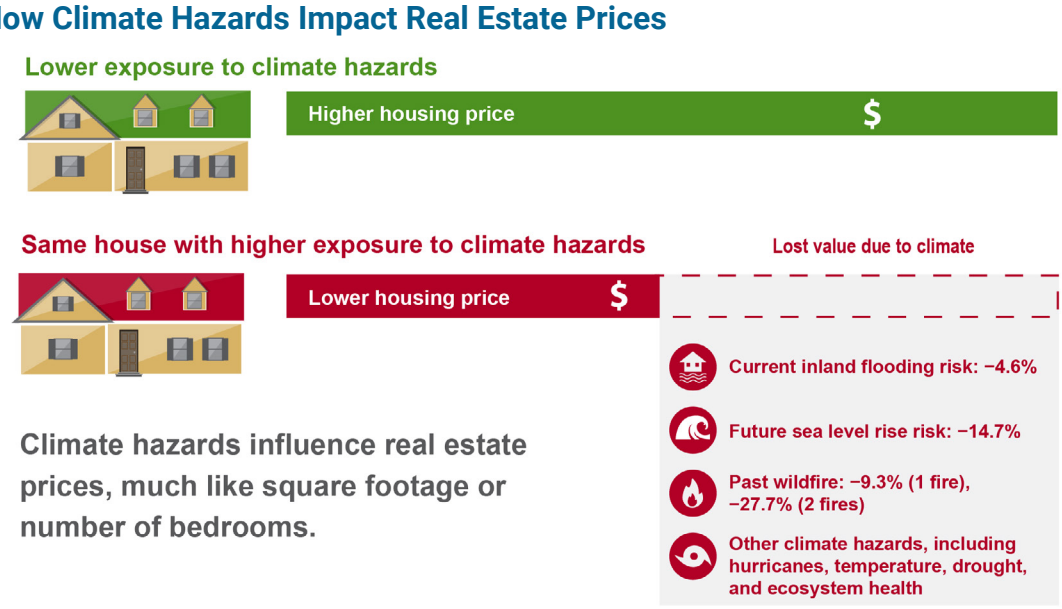
Markets

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]

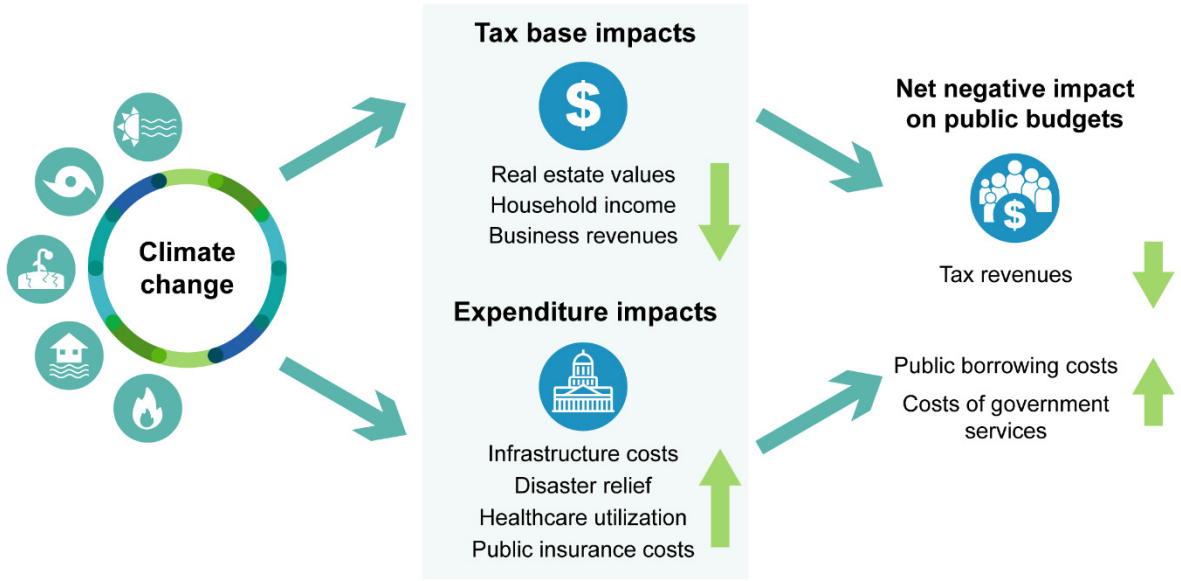
Global supply chains can transfer, amplify, or reduce the direct impacts of climate change (Focus on Risks to Supply Chains). Climatic events in other countries impact trade with the United States,[153] which in turn affects domestic markets (Ch. 17).[154] Climate impacts that affect multiple countries 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]

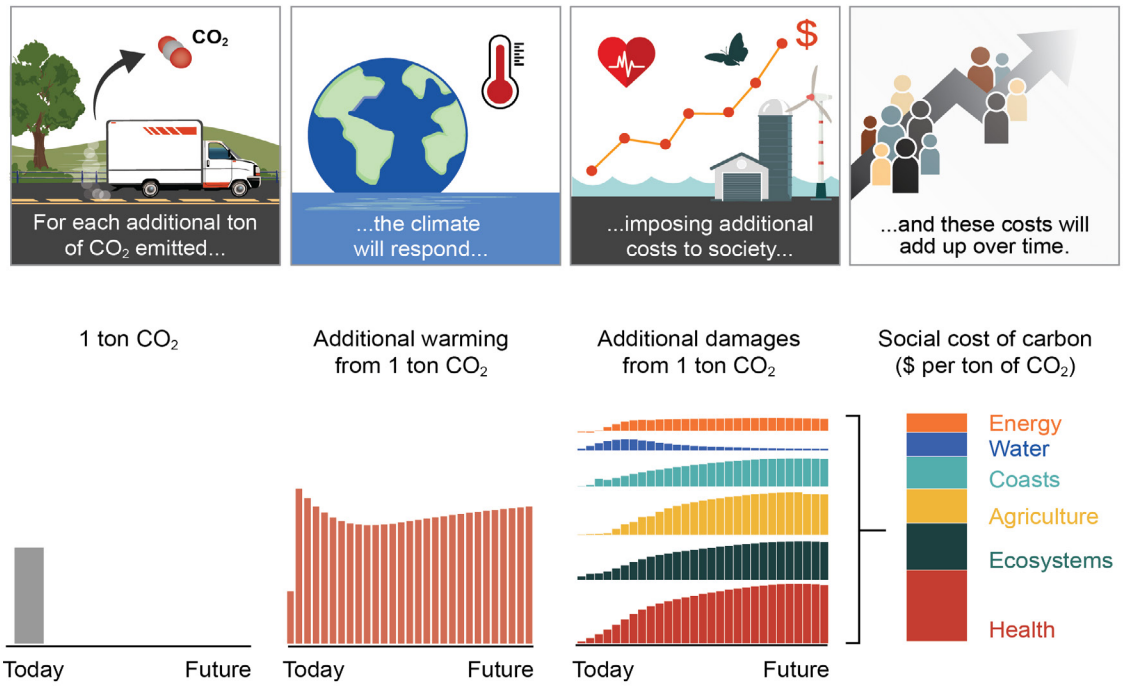
It is sometimes important for governments or institutions to quantify the overall economic impact of climate changes caused by certain current activities, for example, in analyses of whether the benefits of a new climate policy exceed its costs. A succinct summary description of the benefits of emissions 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*.

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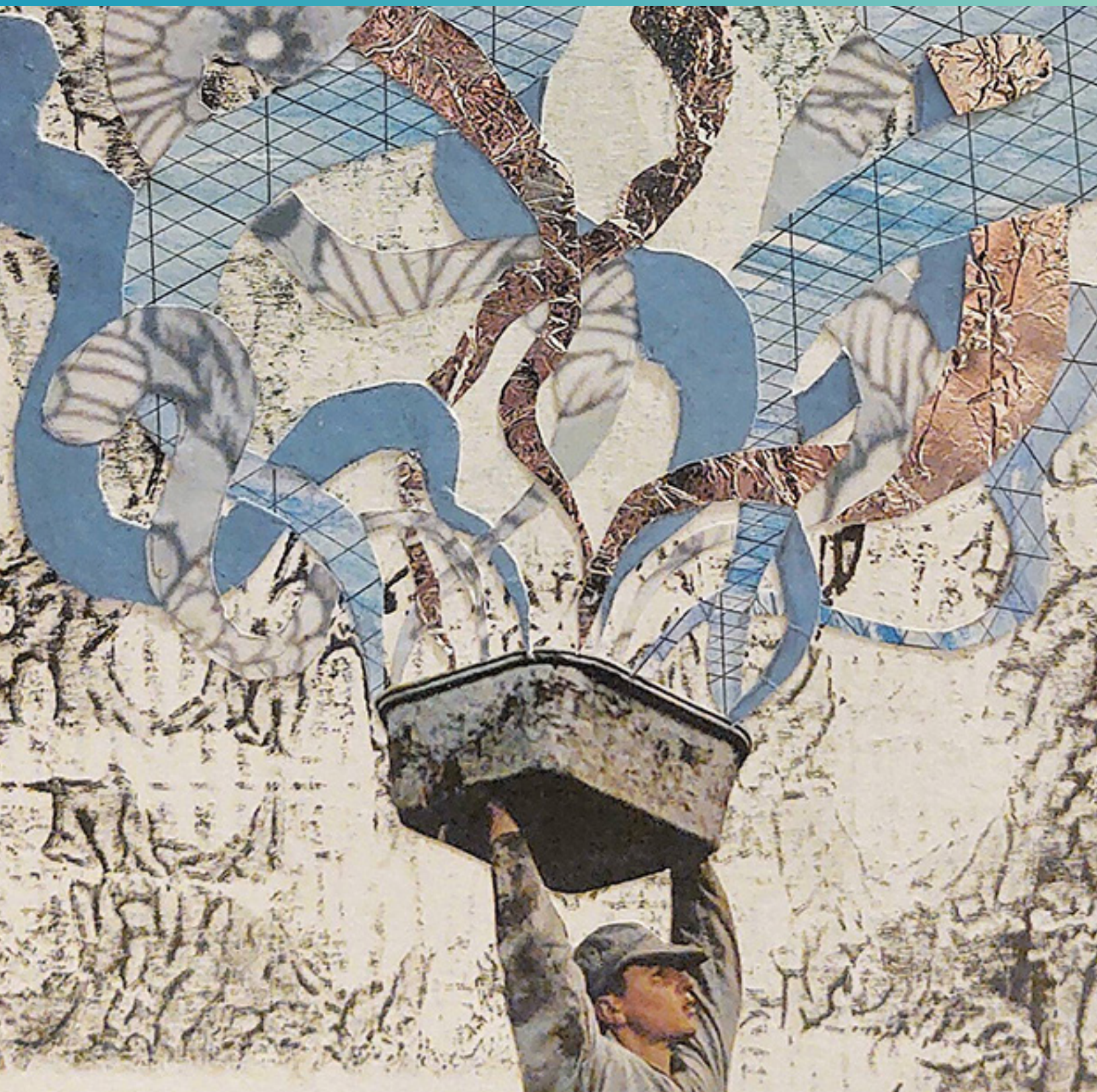
Fifth National Climate Assessment: Chapter 20

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.

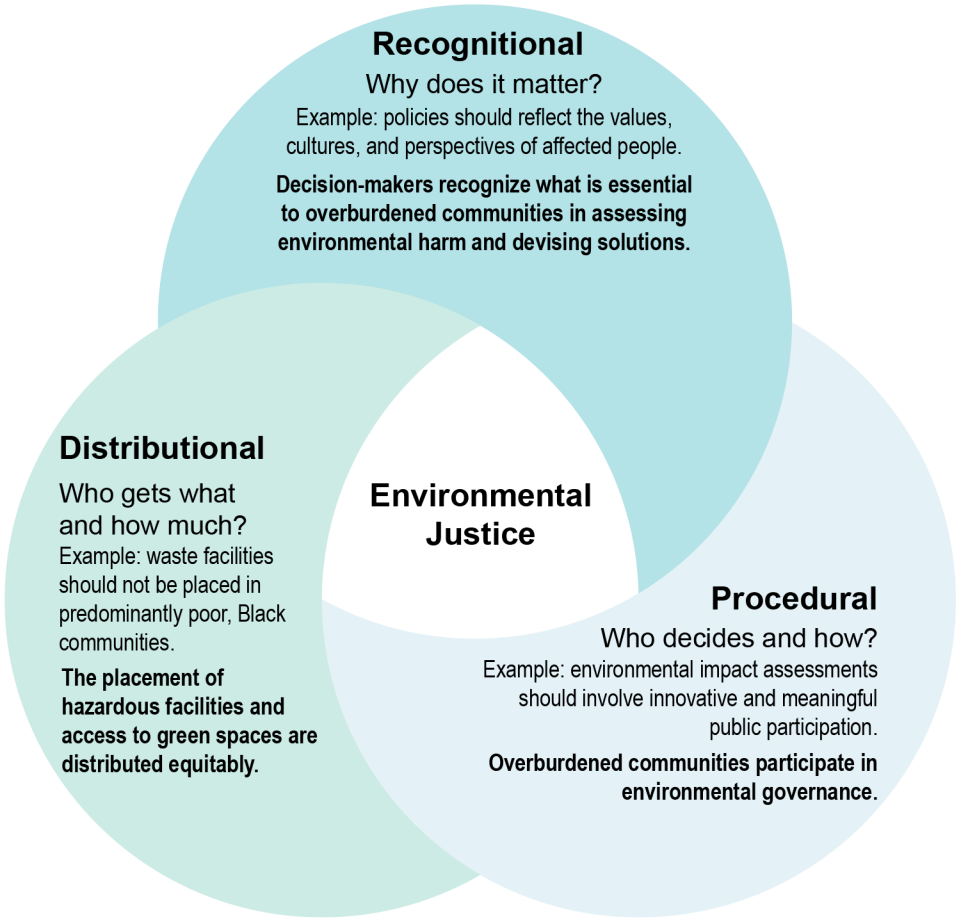
Social systems create and reproduce the assumptions that we—individuals and institutions—act on when making decisions about climate change over time and space. This might include what a given community considers sacred or taboo, or how we speak of and conceptualize environmental problems. Lack of rain, 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

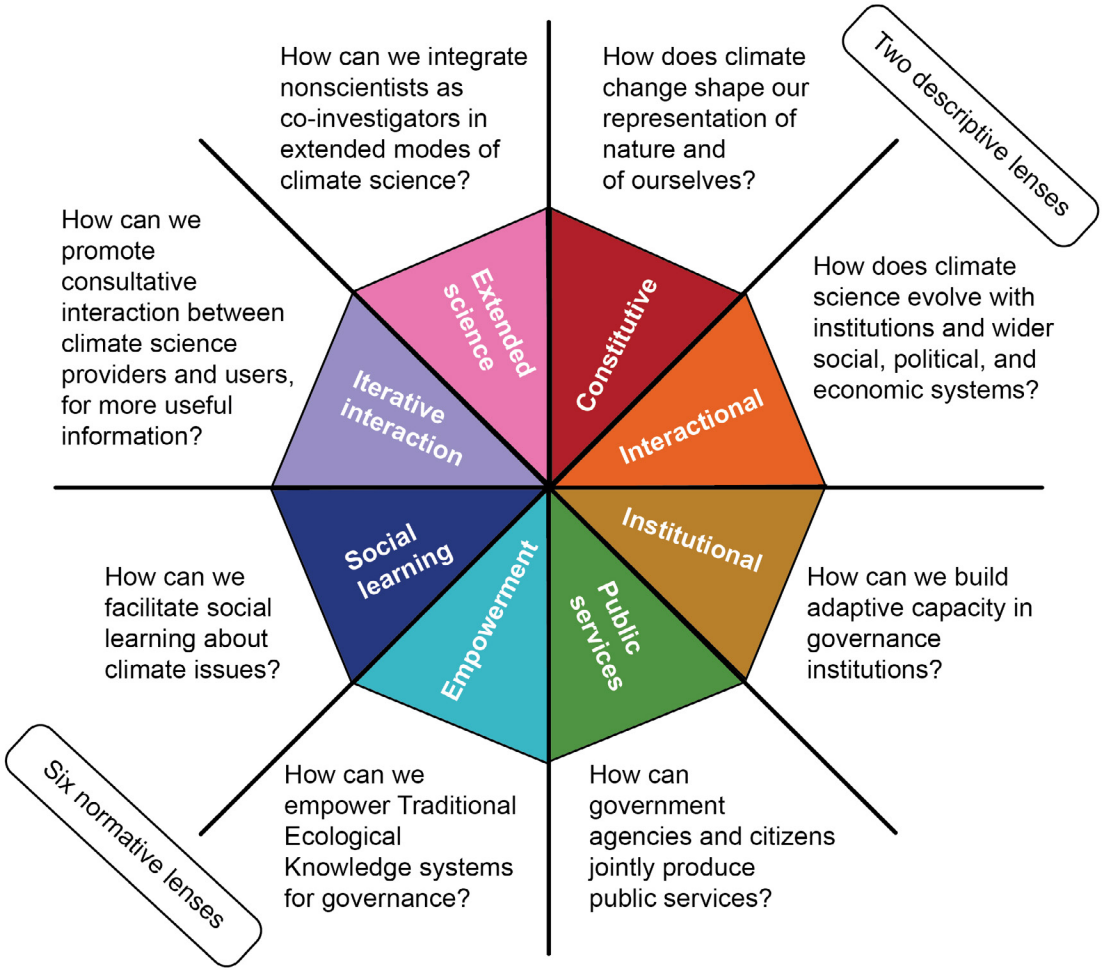
Researchers in the social sciences and humanities have studied the ways in which people and groups learn about and understand human–nature interactions, including climate change.[102,103,104] Epistemology is the name for the study of how people develop knowledge. For both scientists and nonscientists, 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]

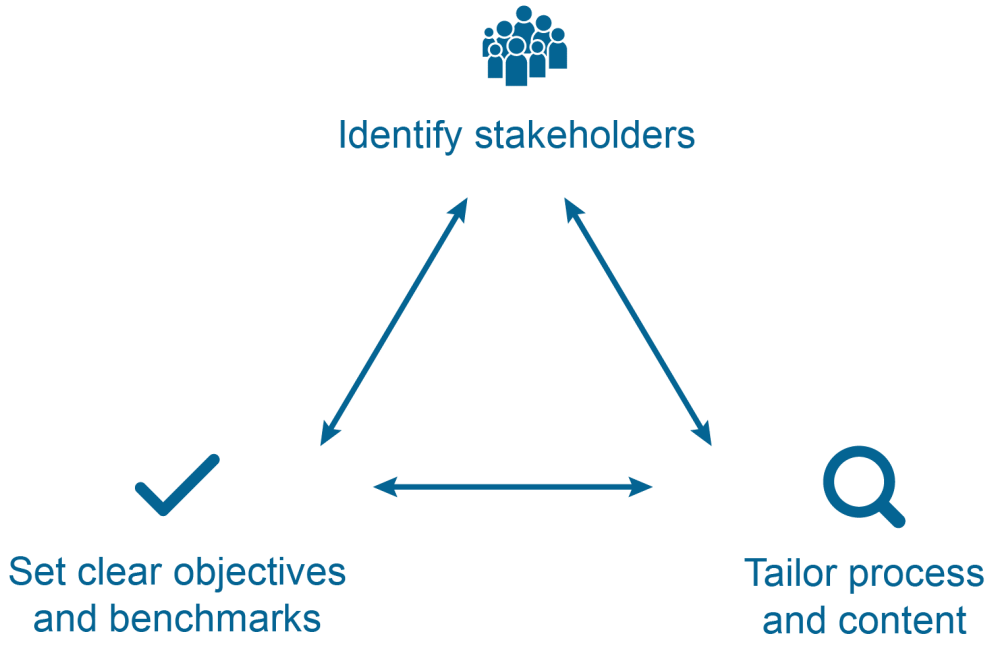
Processes for Promoting More Effective Climate Change Engagement Efforts

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).

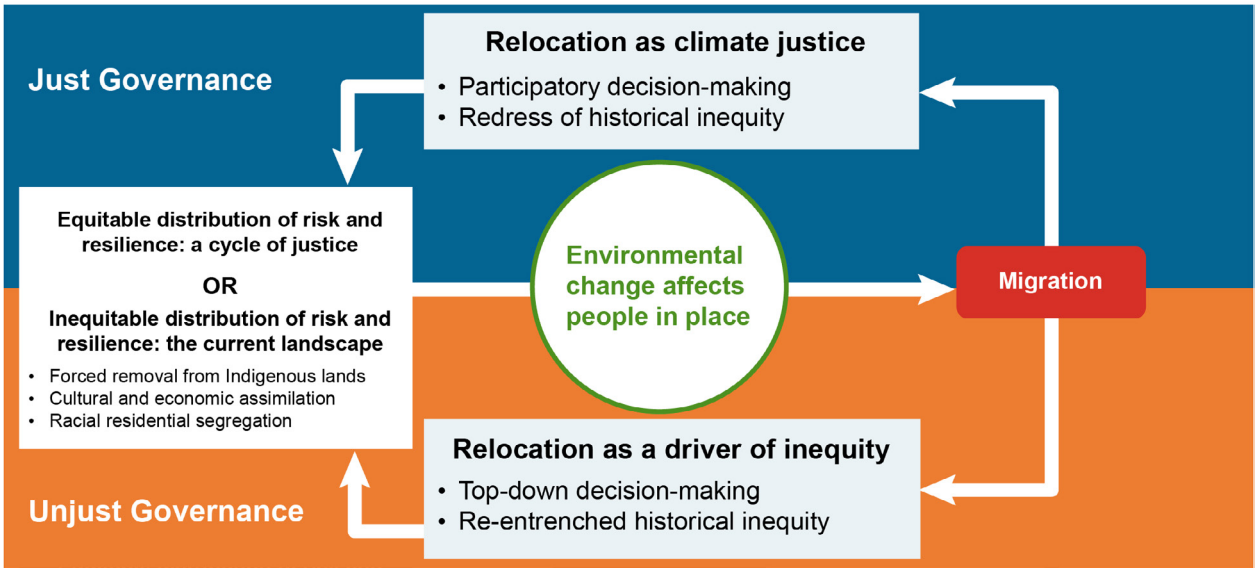
In the United States, climate change–related disasters are not yet a major driver of migration.[180,181] Most counties affected by hurricanes deviate only temporarily from their pre-disaster growth trend, although the demographic composition of affected areas may change.[182,183,184,185] Historically, 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.

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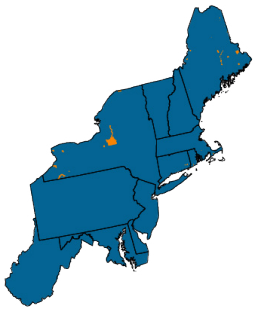
Fifth National Climate Assessment: Chapter 21

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).

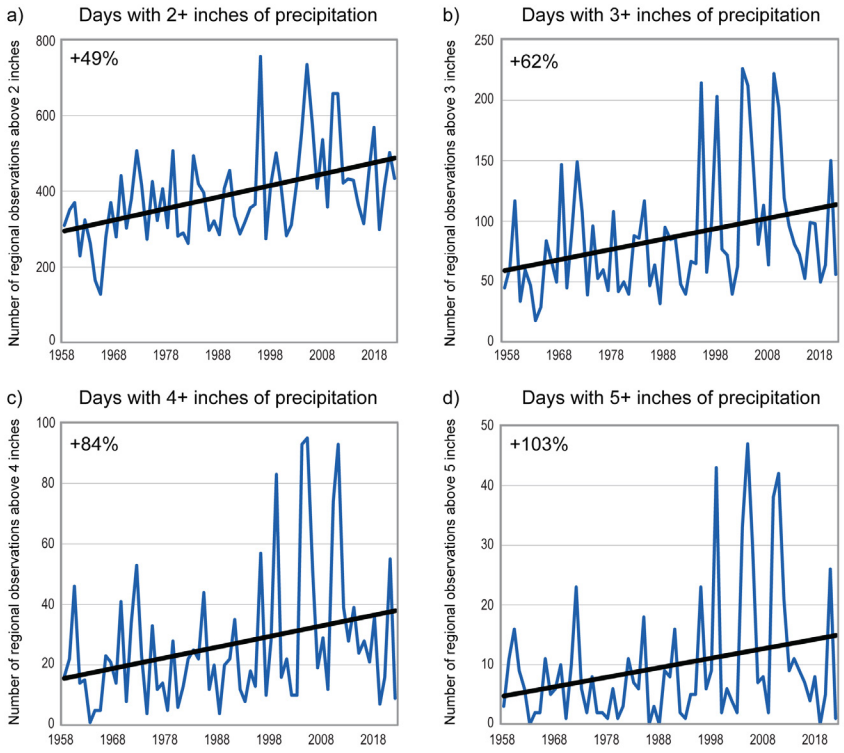
Key Message 21.1

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

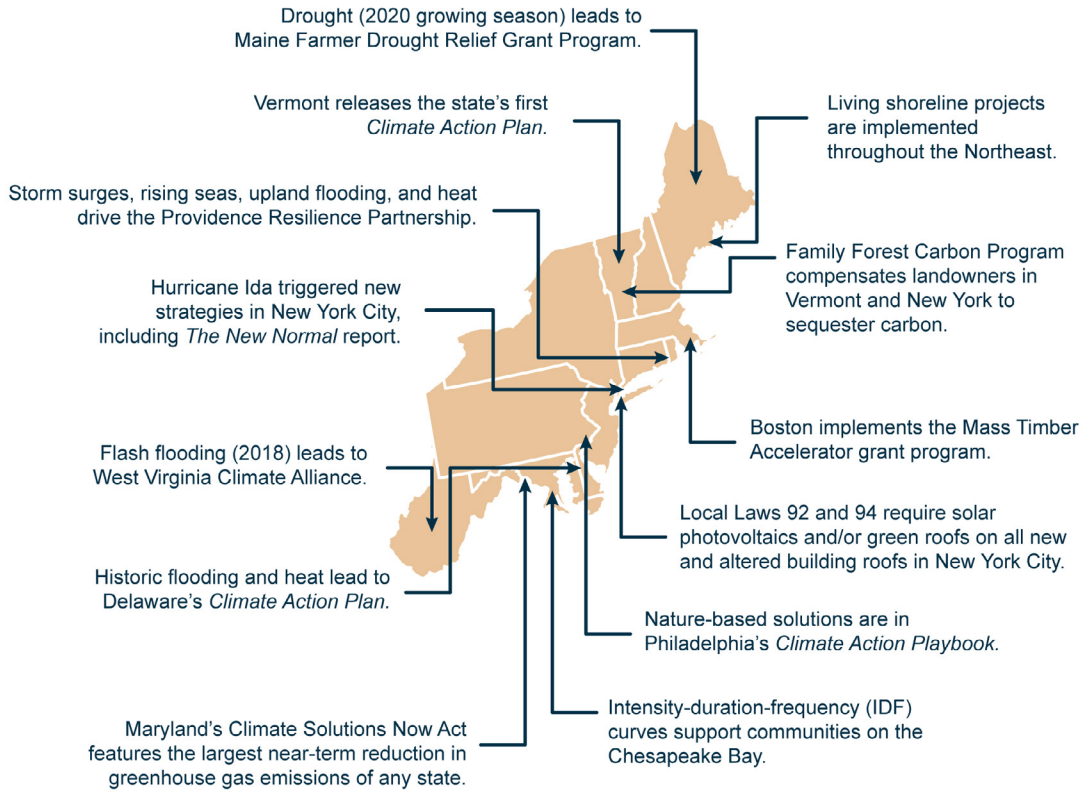


The number of days in the Northeast with extreme precipitation has increased.

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.

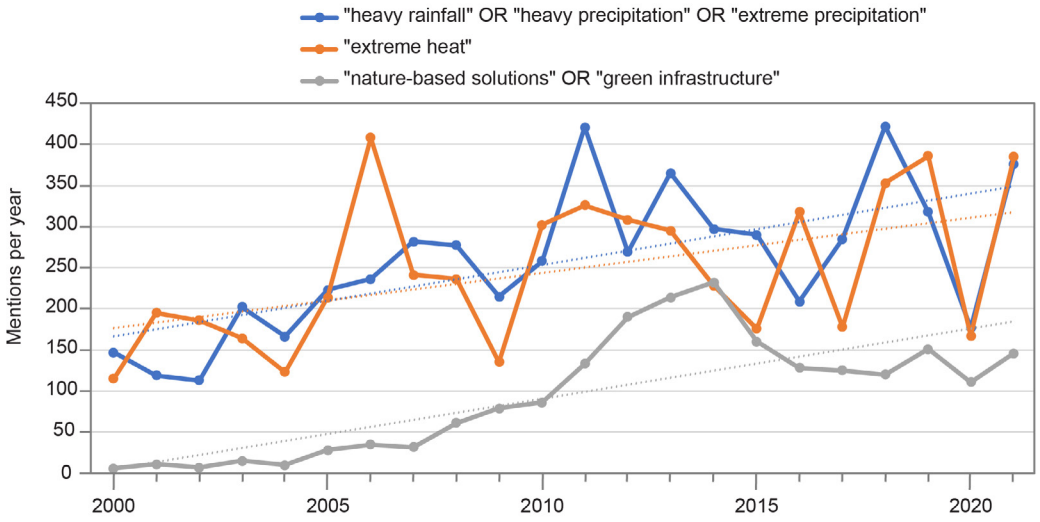
Figure 21.2. This map highlights efforts, many of which are nature-based, that address climate change impacts by building resilience or promoting mitigation measures. In some cases, these efforts are specific programs or projects, such as the Family Forest Carbon Program in Vermont and New York. In other 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

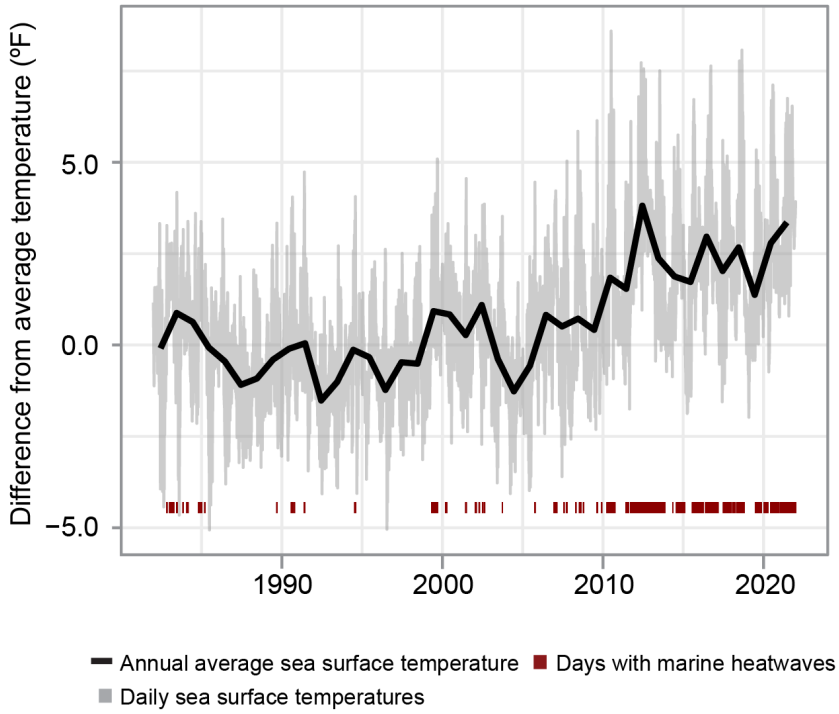
The ocean and coastal habitats in the Northeast are experiencing changes that are unprecedented in recorded history, including ocean warming, marine heatwaves, sea level rise, and ocean acidification (*high confidence*). Changing ocean conditions are causing significant shifts in the distribution, productivity, 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

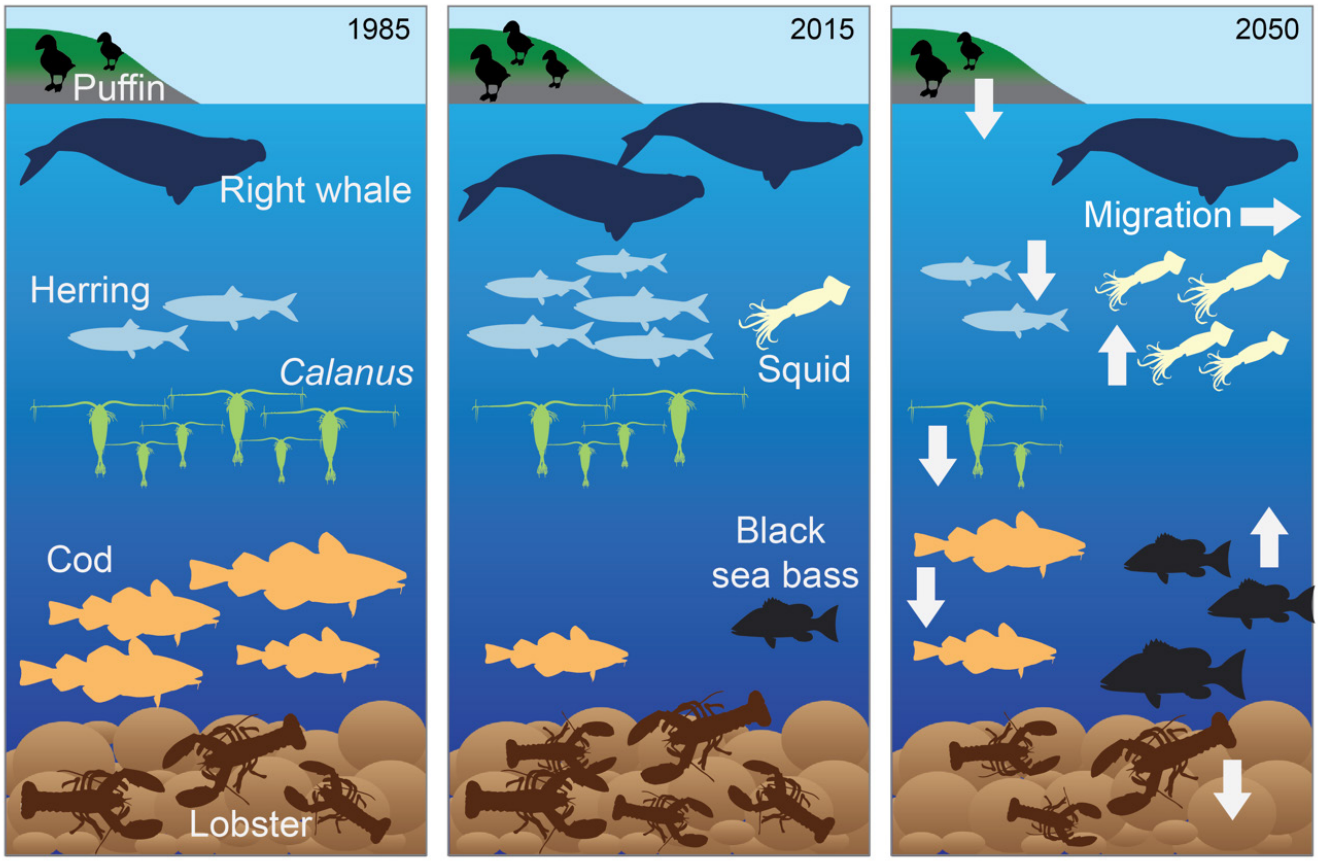


Oceans are growing warmer and marine heatwaves are more frequent, which is impacting marine ecosystems in the Northeast.

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]

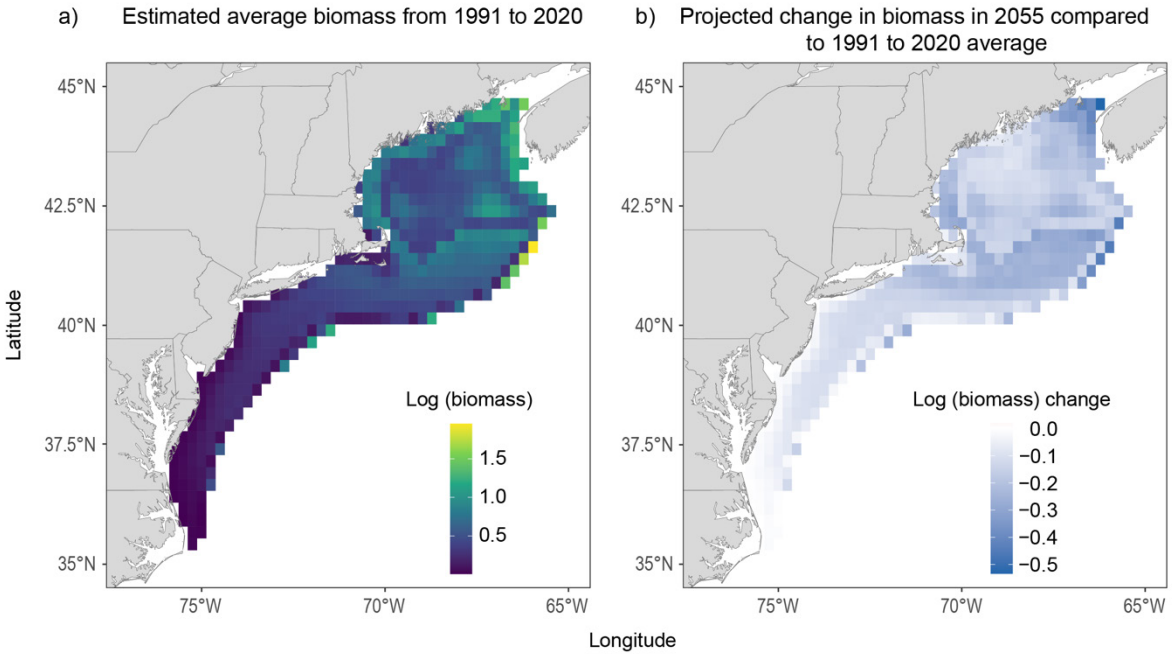
Past (1985), Present (2015), and Future (2050) of the Gulf of Maine Ecosystem



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]

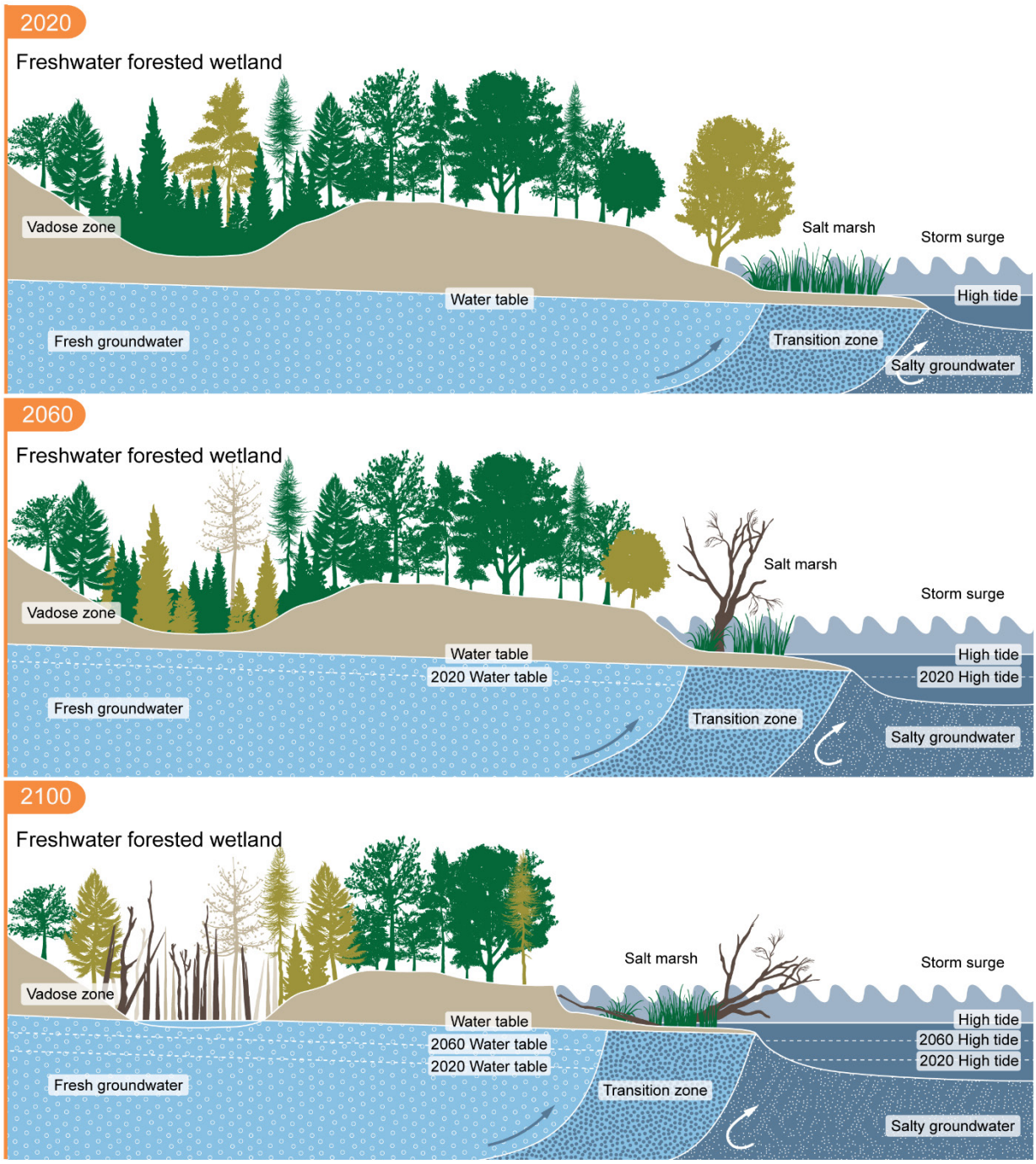
Combined with changes in salinity, ocean acidification exerts stress on shell-building organisms in the region (KM 2.3). The Mid-Atlantic Bight is acidifying faster than other Atlantic coastal regions and the open ocean.[101] Ocean acidification may impact fishery resources, including American lobster, 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*).

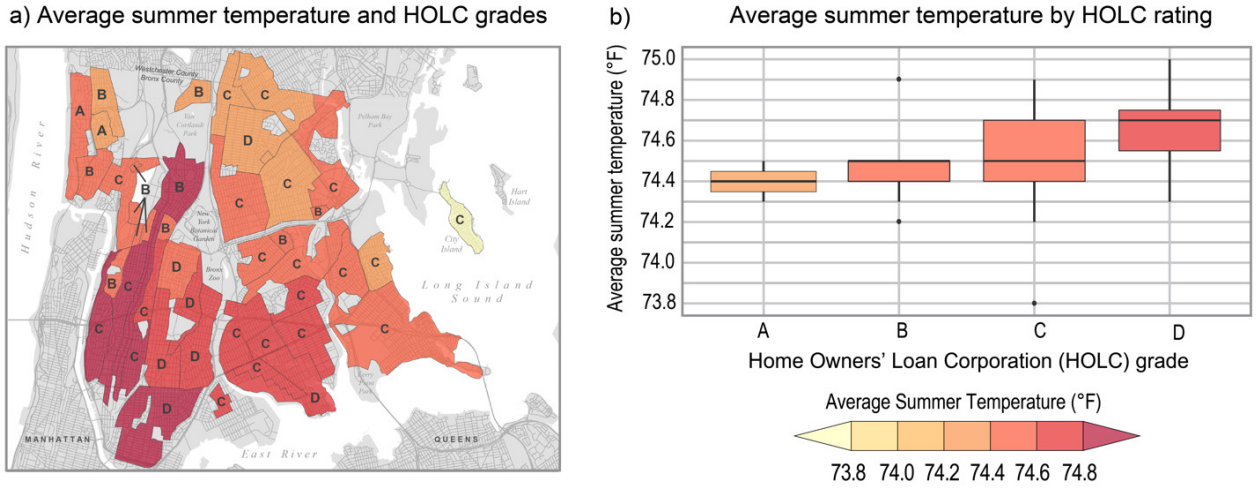
Across the Northeast, the disproportionate impact of climate change and extreme weather on racial and ethnic minorities and low- and moderate-income communities has provided focus to new advocacy and policy work to advance equity and environmental justice.

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] Maine Climate Science Update 2021[197]	Maine Won't Wait[198]	An Act to Analyze the Impact of Sea Level Rise[199] An Act to Implement Agency Recommendations Relating to Sea Level Rise and Climate Resilience[200] 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 (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] Massachusetts State Hazard Mitigation and Climate Adaptation Plan[8]	An Act Creating a Next-Generation Roadmap for Massachusetts Climate Policy[210] An Act Driving Clean Energy and Offshore Wind[188]
Rhode Island	Resilient Rhody: The Statewide Climate Resilience Action Strategy[211] Rhode Island 2022 Climate Update to the 2016 GHG Emissions Reduction Plan[212] Executive Climate Change Coordinating Council (EC4) to deliver "2025 Climate Strategy" by Dec 31, 2025	Resilient Rhody: The Statewide Climate Resilience Action Strategy[211] Rhode Island 2022 Climate Update to the 2016 GHG Emissions Reduction Plan[212] 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] 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] New York State Climate Action Council Scoping Plan[218]	Climate Leadership and Community Protection Act[192] Soil Health and Climate Resiliency Act[219] Green CHIPS[220] 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] 2020 New Jersey Scientific Report on Climate Change[225] Climate Change Impacts on Human Health and Communities[226]	2021 New Jersey Climate Change Resilience Strategy[227] 2019 New Jersey Energy Master Plan[228] New Jersey's Global Warming Response Act 80x50 Report[229]	An Act Concerning the Reduction of Greenhouse Gases[230] 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] 2021 Annual Report and Building Energy Transition Plan[237] Maryland Ocean Acidification Action Plan 2020[135]	Climate Solutions Now Act[238] Sea Level Rise Inundation and Coastal Flooding—Construction, Adaptation, and Mitigation[239]
West Virginia	N/A	N/A	N/A
Washington, DC	N/A (DC has a pre-2018 impact assessment[240])	Clean Energy DC[241] Sustainable DC 2.0 Plan[242] Resilient DC[243] Climate Ready DC[244]	Clean Energy DC[241] Sustainable DC 2.0 Plan[242] Resilient DC[243] 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]

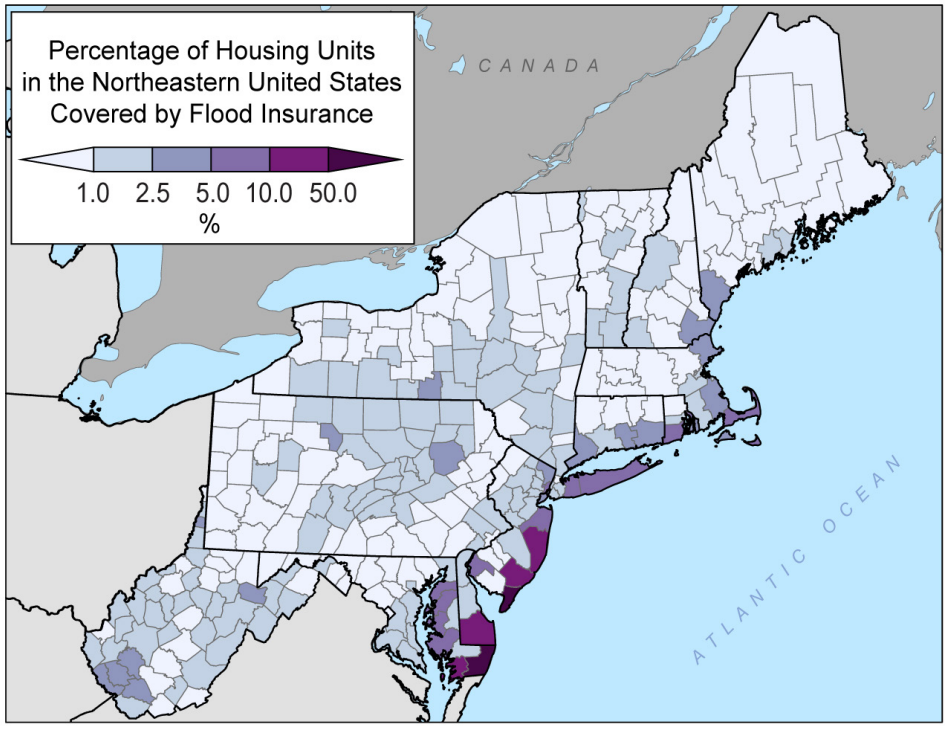
However, insurance take-up rates (the percentage of households who purchase insurance) vary greatly by natural hazard. While about 50% of fire and wind damage in the United States is covered by insurance, only 12%–14% of flood damage is insured by the federally run National Flood Insurance Program (NFIP).[272] 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]

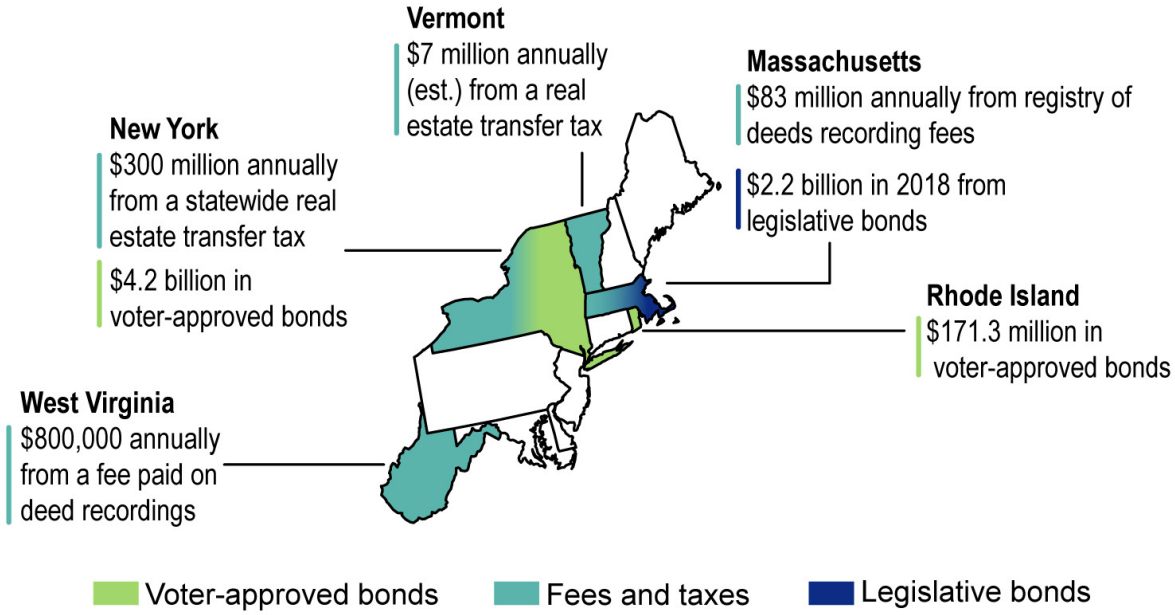
Recent innovations around the financing of climate adaptation by the private sector include community-based catastrophe insurance (CBCI), climate adaptation as a service, and climate investment intermediaries. A CBCI is a community institution (it does not have to be governmental) that helps its members 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]

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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

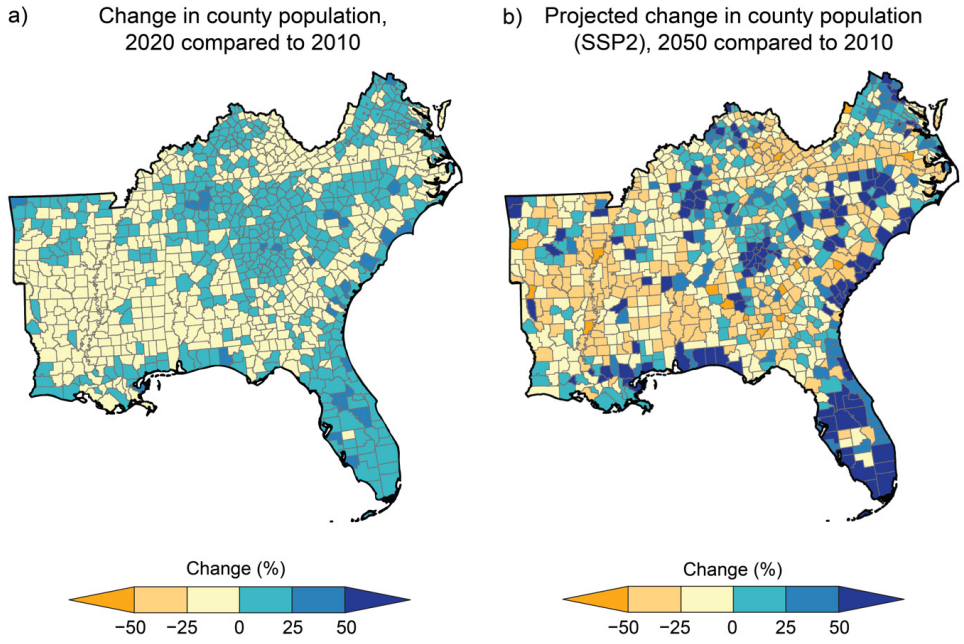
Regional Growth Increases Climate Risks

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

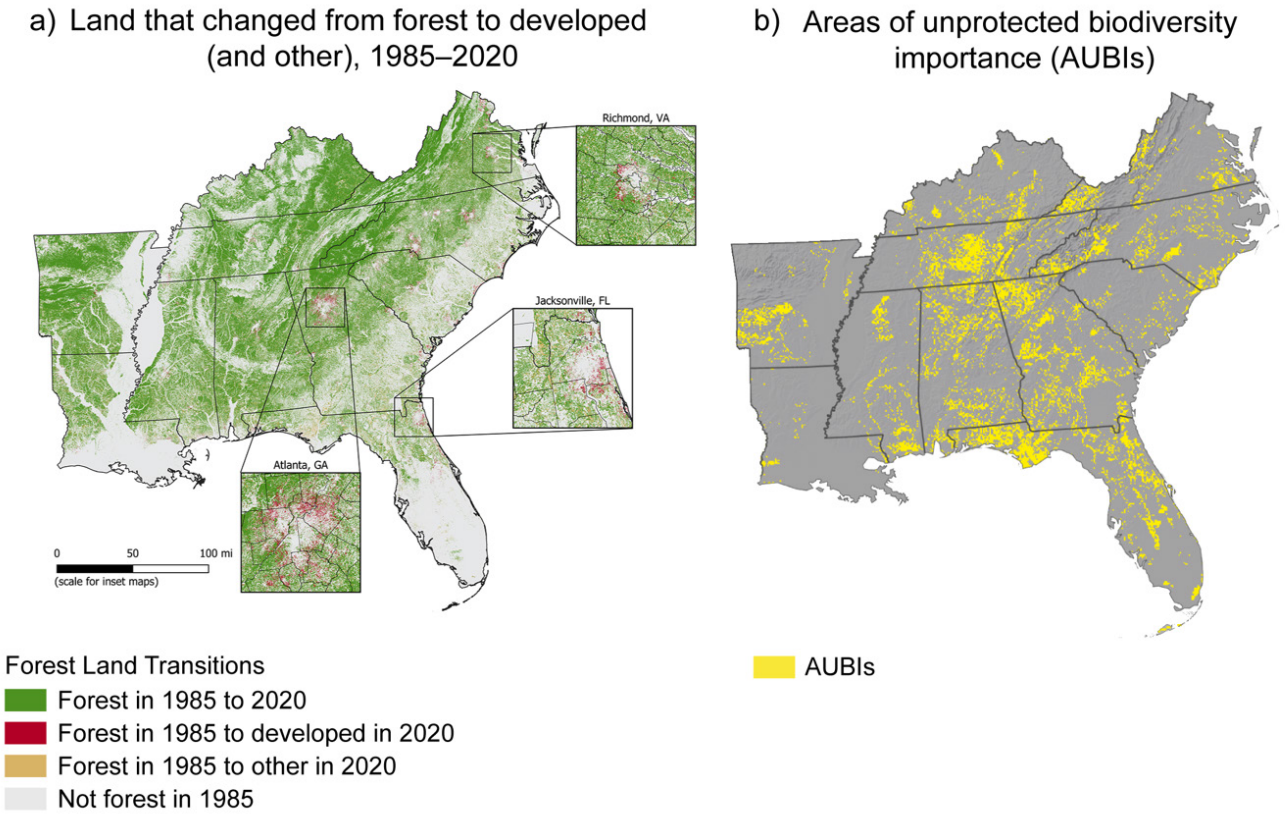


Population change in the Southeast exposes more people to climate threats along the coast and in cities while leaving rural areas with limited capacity.

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

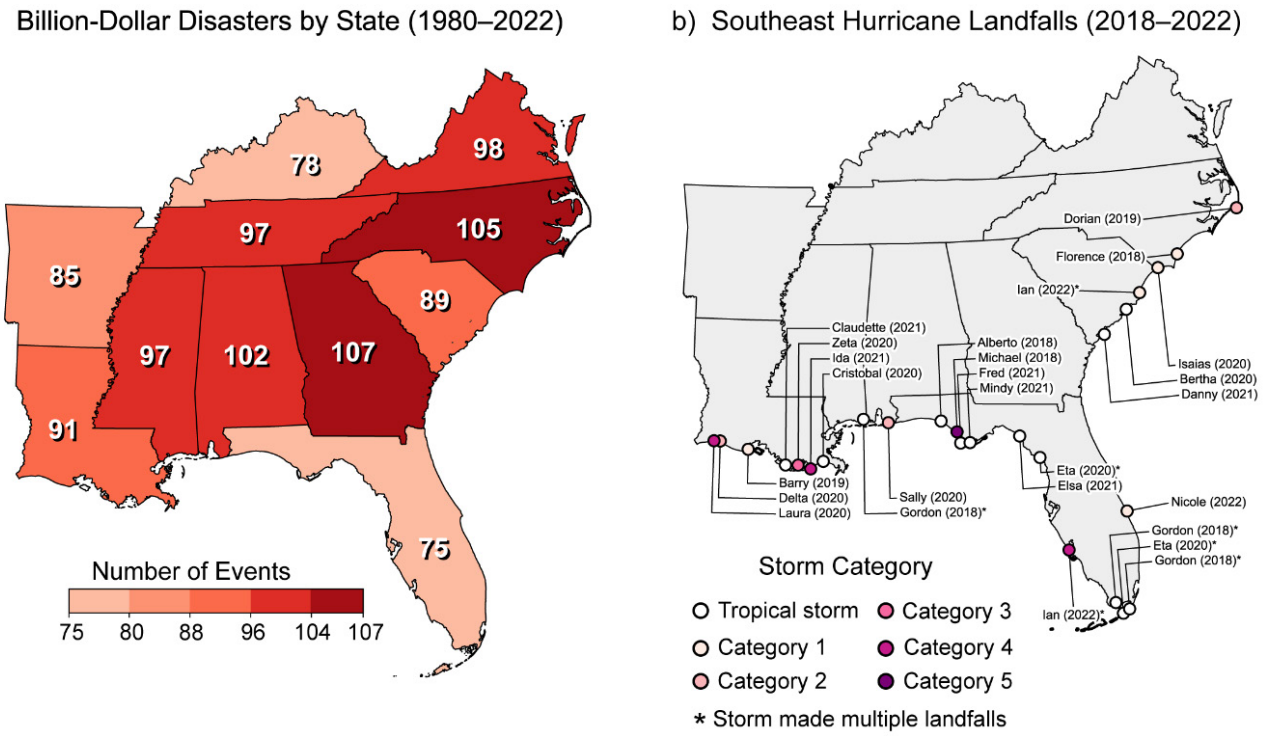


Land cover change and sprawling development threaten unprotected biodiversity hotspots in the Southeast.

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]

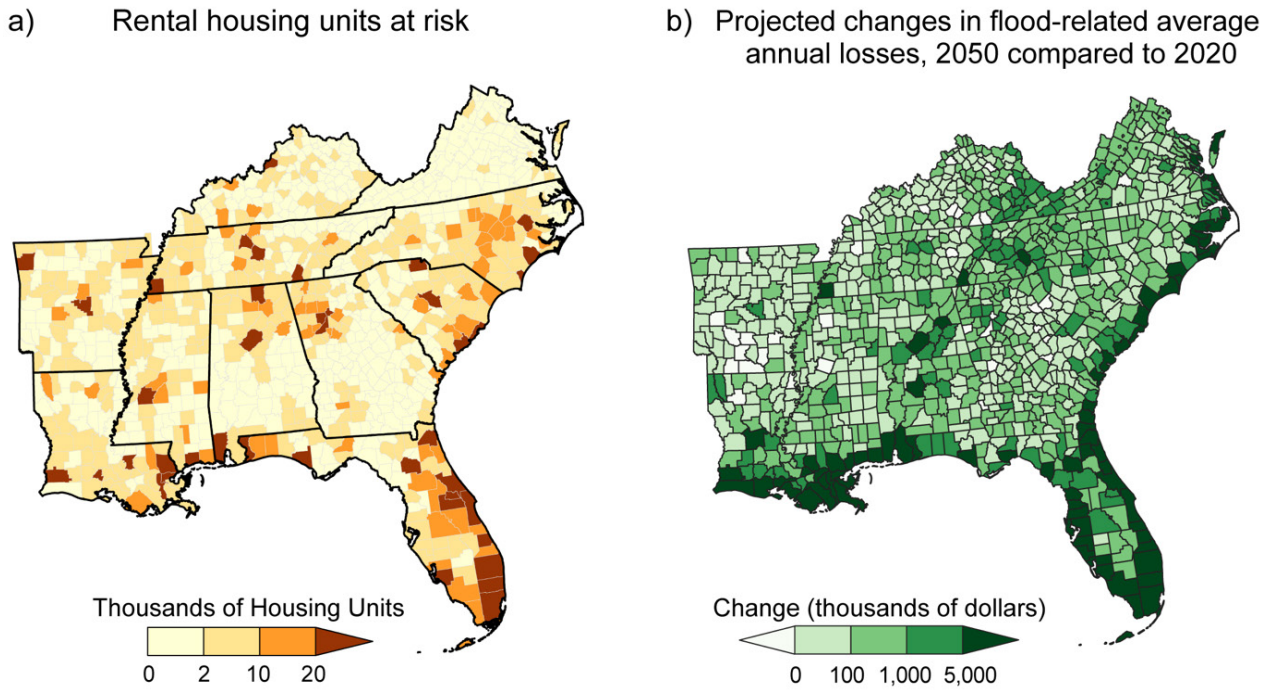
Inland and Coastal Flooding Threatens the Present and Future

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]

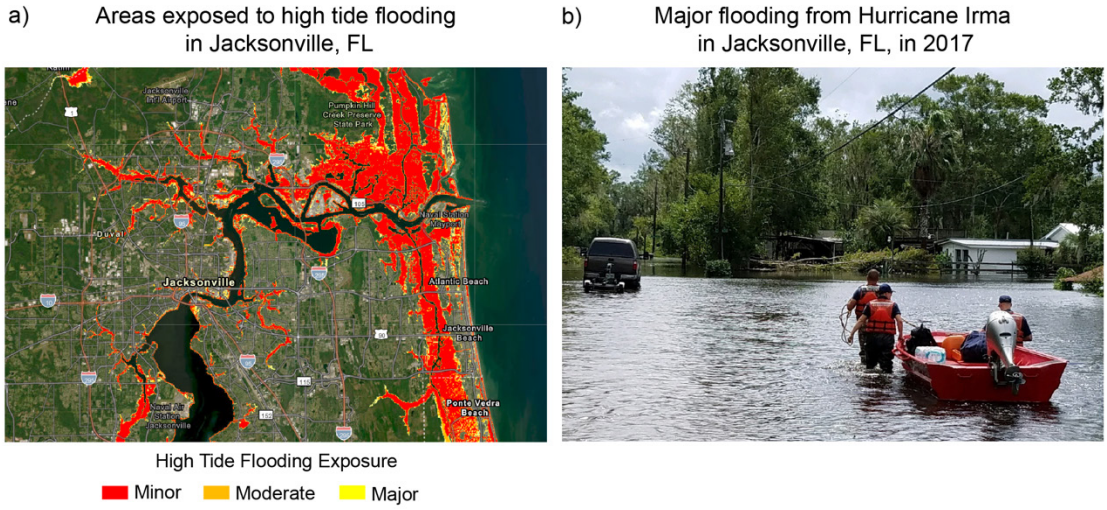
Some Southeast communities plan for these extreme events with an outdated understanding of climate-related risks.[68,120,121] Sewer infrastructure is built to accommodate a particular amount of rainfall over a specified time, and current estimates of precipitation intensity, frequency, and duration generally 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].