Key Message 30.1

Climate Change Impairs Access to Healthy Food and Water

Access to clean, fresh water and healthy food is expected to be increasingly impaired by climate change (*very high confidence*). On low-lying atolls, sea level rise has caused saltwater contamination of fresh water (*high confidence*). Regionally, food and water availability will be further negatively impacted by increasing temperatures, altered rainfall patterns, increased flooding and pollution, and degradation of nearshore fisheries (*very high confidence*). Adaptation actions such as traditional farming, fishing, and land-management practices can help build more resilient water and food systems (*very high confidence*).

Changing Climate Threatens Freshwater Resources

Dependable and safe freshwater resources and associated services in tropical islands are particularly vulnerable to rising temperatures (KM 4.1), altered rainfall patterns (Figure 30.3), runoff intensity and flooding, reduced groundwater recharge, and SLR (Figure 30.4; KM 4.2). Depletion of island aquifers compounds the potential for saltwater intrusion from SLR.[98,135,136] The availability of surface water for irrigation, drinking water, and hydropower is affected by increasing frequency and severity of flooding and by reductions in stream baseflow;[137] water contamination through increased *Staphylococcus sp.*, *Leptospira* (a waterborne pathogenic bacteria), fecal coliform bacteria, and suspended sediment (KM 15.1);[138,139,140,141] and extreme drought (KM 2.2).[103] In response to these changes, adaptation-focused restoration techniques are being applied, including revegetating with native species, reducing impervious surfaces, and redundant water distribution systems. Climate-induced land-cover change can have significant control over groundwater recharge, indicating that land-use adaptation is viable for managing impacts on water resources (KM 6.1).[142,143] Flood frequency is projected to increase across the region,[70] while drought frequency is projected to vary across the region (KMs 2.2, 4.1).[27,28,29,113]

Changes Undermine the Sustainability of Water Supplies

Pacific Islands potable water supplies depend heavily on accessing clean groundwater or rain catchments, while other needs, such as irrigation, are often met with surface water resources. Groundwater recharge is affected by annual or longer-scale climate processes, while surface water supplies are more sensitive to shorter-term climatic influences.[144,145,146,147,148] Although few studies assess regional changes in drought, evidence is clear that Hawai‘i has experienced a drying trend since the 1950s and in La Niña years.[149,150] On atolls and low-lying islands, freshwater aquifers typically occur as very thin lenses and are highly sensitive to groundwater extraction and SLR-driven saltwater intrusion.[135,136] Shifting rainfall patterns and runoff conditions are affecting the availability of surface water to meet growing demands.[103] Climate change has elevated region-wide efforts to protect and conserve freshwater resources. Communities that rely heavily on rain-fed catchments and surface water are acutely susceptible to short-term and, in particular, long-term drought and the resulting reductions in streamflow.[103]

Salinization and Pollutants Deteriorate Water Quality

Increased intensity of extreme rainfall events, coupled with SLR, is projected to exacerbate freshwater contamination risks.[151] Past and ongoing disposal of military, industrial, agricultural, and municipal waste contaminates island water supplies.[35,152] Although SLR-driven mobilization of subsurface contaminants has received little study in the Pacific Islands, evidence of diverse groundwater contaminants in the region[153] and their mobilization[154,155] raises concerns for low-lying island aquifers (KM 4.2). Salt is a critical freshwater contaminant; wave-driven overwash[135,136,156] and SLR-induced rise of the freshwater–saltwater transition zone[157,158,159,160] cause salinization and saltwater intrusion.

Changes in the frequency, severity, and duration of drought, associated fires, and flooding all interact to exacerbate sediment loading to streams.[103,161] Given the short ridge-to-reef distances in the region, sensitive nearshore coral ecosystems and fisheries are directly impacted by increased sediment and pollutant loads to streams,[162] compromising biodiversity, subsistence practices, and economies (KM 9.2).[162,163,164]

Food Systems Disrupted

Climate change will increasingly impact food production, transport, processing, packaging, storage, retail, consumption, and waste for Pacific Island communities (KMs 11.2, 13.1). The aforementioned challenges will disrupt imports reliant on fragile supply chains and reduce viability of local agriculture and fisheries, thus reducing access to nutritious foods.[31,165,166,167,168,169] Fisheries are the principal protein sources for many Pacific Islanders, with locally grown staple food crops such as bananas, taro, breadfruit, and sweet potato supplying critical calories and nutrients.[170,171,172] However, Pacific Island communities have increasingly relied on imported foods, which come with complex and sometimes hidden environmental, financial, social, cultural, and nutritional costs (KM 30.2).[173,174] COVID-19 and previous disasters exposed the fragility of global supply chains (Focus on Risks to Supply Chains) and emphasized the need to bolster local food production capacity to increase resilience.[166,167,175,176]

Declining Fisheries

The global capacity of coral reefs to supply fish has declined by half since the 1950s, a change that climate stressors have exacerbated (KM 9.2)[62,177,178,179,180] through coral bleaching, acidification, SLR (Figure 30.4), terrestrial sediment, and contaminants (Box 30.3).[78,79,181,182] Small-scale coral reef fisheries supply Pacific Island communities with a substantial portion (in some cases 50% to 90%) of their dietary protein and important micronutrients.[82,172,177,183,184,185,186] Warming waters, acidification, and deoxygenation redistribute open-ocean fish stocks, and fisheries catch within regional EEZs is projected to decline by up to 40% by 2050 relative to the early 2000s under a very high scenario (RCP8.5; KM 10.1).[109] Fishing fleets are ill-equipped to adapt to this deficit (KM 10.2).[81,187] Warming, extreme events, acidification, and SLR may also compromise efforts to expand mariculture (marine farming), through damage to aquaculture systems,[188] decreased species richness,[189] and decreased local access to nearshore and open-ocean species.[190,191,192]

Box 30.3. Changing Fisheries: Local Knowledge from Palau

Indigenous practitioners are often the first to observe and respond to changes in the environment (KM 16.3). For hundreds of years, fishers in Palau have gathered at seagrass meadows on the sixth day after a new moon during late-afternoon low tide to catch rabbit fish using cast nets (Figure 30.6). Since 2021, fishers have been unable to participate in this age-old tradition.[193] The normal low tide no longer occurs, and ocean levels remain too high for rabbit fish aggregation. It is unclear whether these changes can be attributed to SLR, human impacts (e.g., overfishing), or natural variability. If this change persists, loss of this fishery would threaten the fishers' livelihood and resilience as ocean people (KM 10.2). Integrating place-based and complementary knowledge systems into assessments can help ensure sustainable management under future climate change.[194,195]

Traditional Cast Net Fishing



Species loss threatens the traditions, livelihoods, and resilience of Pacific Islanders.

Figure 30.6. Traditional Palauan cast net fishing remains important for local food security. Photo credit: © Reid Endress

Agriculture

Crop production in the USAPI has generally kept up with population growth over the past 20 years.[165,173] Although local agriculture provides a fraction of nutritional needs in the region,[165] it remains a critical food source, complementing imported foods, serving as an emergency food source, providing culturally important items, and supplementing household income and government revenue.[196,197]

Climate change is projected to impact island food systems through a variety of different mechanisms (KMs 11.1, 23.3).[77] Warmer nighttime temperatures and saltwater intrusion, especially in FSM and RMI, are projected to increase damage from disease on staple crops such as taro, bananas, and breadfruit.[77,198] Cash crops are also *likely* to be affected, with higher temperatures and increased plant pathogens decreasing coffee yields, increased flooding depressing sugar yields, and higher winds damaging coconut palms, bananas, and breadfruit.[191] In Hawai'i, droughts have become longer and more severe and are the principal cause of crop loss.[49]

Adaptation Strategies to Improve Local Food System Resilience

Strategies are being developed and implemented across the region to revitalize healthier traditional food systems, resulting in more just access to food (KM 11.2).[117,118,165,199] Subsistence-based food system practices such as agroforestry and fishing have sustained Pacific Island peoples for millennia and have aided in recoveries from natural disasters such as typhoons, earthquakes, volcanic eruptions, and tsunamis.[119,171,200,201] Restoring Indigenous agroecology practices can support conservation, food security, and broader sociocultural objectives in the face of shifting precipitation and SLR (e.g., Bremer et al. 2018;[202] Winter et al. 2020[203]). Community food-sharing networks that empowered the most overburdened to overcome economic and social hardship during the COVID-19 pandemic offer a model for resilient food systems in the face of climate change.[175,204,205] Promising fisheries adaptations include establishing networks of marine protected areas to preserve coastal resources, safeguarding fish habitats from pollution runoff, and restoring traditional fishpond mariculture (KM 10.3; e.g., Bell et al. 2013;[73] McLeod et al. 2019;[119] Farmery et al. 2022[116]).

Box 30.4. Food Security and Traditional Knowledge

For thousands of years, Pacific Islanders have relied on traditional food systems that now face threats from climate change. Traditional agroforestry and aquaculture investments are critical to strengthen food security and reduce reliance on food imports.[4,5,206] The Melai Mai Breadfruit Project was initiated in 2016 to increase food security in typhoon-devastated outer islands of Yap, FSM.[207] Importing diverse breadfruit varieties to extend the harvest length increased food production and sustainability. Other examples include programs working to identify saltwater-tolerant taro species (Figure 30.7) in Palau and distribute them to the community.[111,208]

Key Agricultural Plants: Giant Swamp Taro



Programs aimed at supporting traditional crops help strengthen food security.

Figure 30.7. Several varieties of giant swamp taro are salt tolerant, making them valuable for adapting to saltwater intrusion. Photo credit: © Ann Singeo, Ebiil Society Inc.

Key Message 30.2

Climate Change Undermines Human Health, but Community Strength Boosts Resilience

Climate change undermines the place-based foundations of human health and well-being in the Pacific Islands (*high confidence*). Climate shocks and stressors compromise healthcare services (*medium confidence*) and worsen long-standing social and economic inequities in both mental and physical health (*high confidence*), and these negative impacts are expected to increase in the future (*very high confidence*). Adaptation efforts that build upon existing community strengths and center local and Indigenous Knowledge systems have great potential to boost resilience (*high confidence*).

Climate change can degrade societal foundations of health and well-being, including access to shelter, nutritious food, clean water, and cultural and social relationships (KM 15.1). Prominent international frameworks and Pacific Island Indigenous conceptualizations of health and well-being recognize that the health of people is closely connected to the health of nonhuman beings, to the shared environment, and to place (Figure 16.3).[209,210,211,212]

Indigenous communities of the Pacific Islands have actively responded to climate-related and other health risks, as well as external economic shocks (Box 30.3; KM 16.3).[119,205] However, colonization and economic disparities have resulted in disproportionately high rates of morbidity and mortality for Native Hawaiian and Indigenous Pacific Island peoples (KM 15.2).[213] Moreover, Pacific Island populations experienced severe economic shocks during the COVID-19 pandemic (KM 30.3),[214] which interacted with existing societal and non-climate stressors that worsen health inequities (KM 18.2).

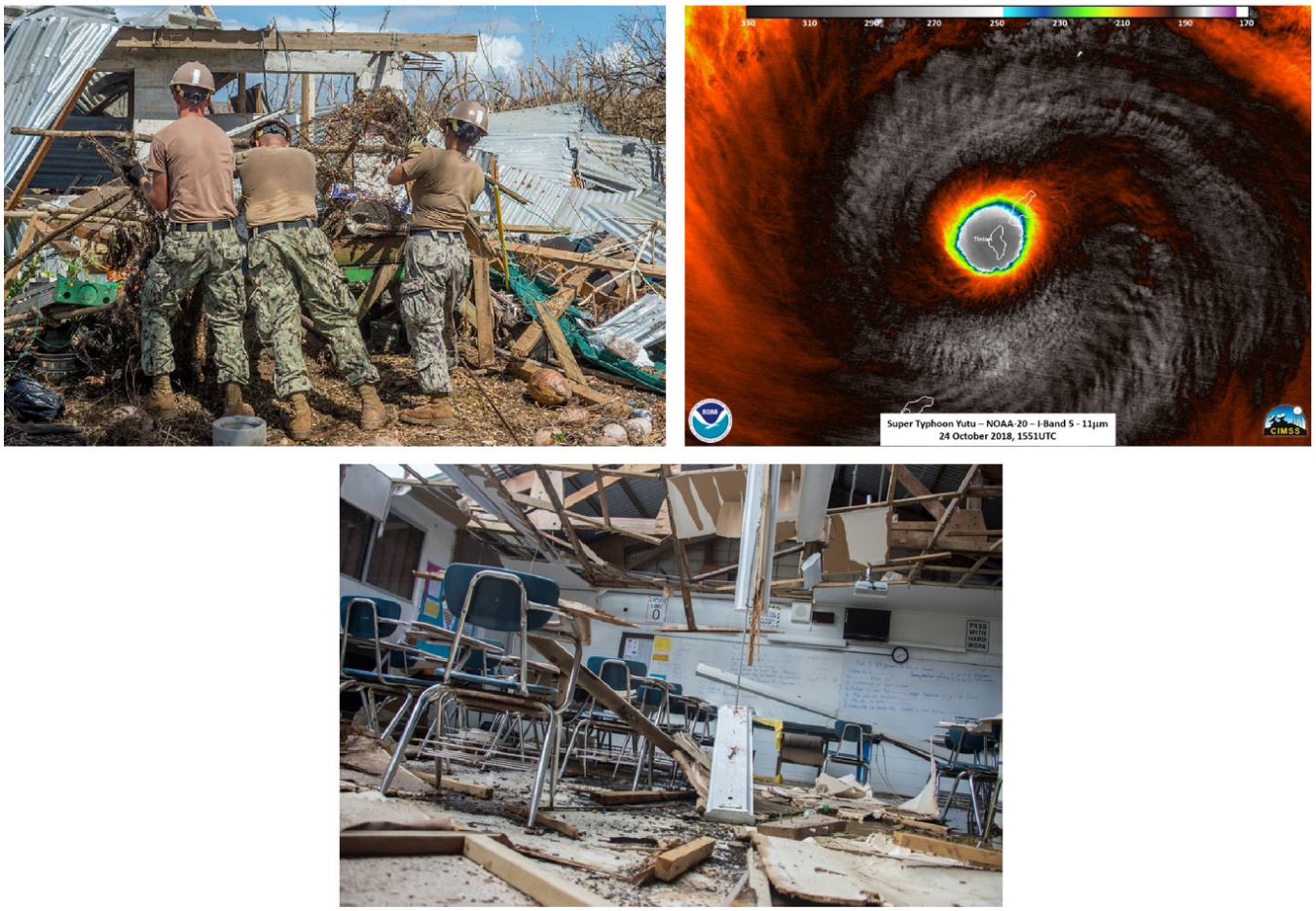
The Health Impacts of Extreme Events

Tropical cyclone intensity,[53,215,216] drought frequency,[150,217] and flood potential (KMs 30.3, 2.2)[70,98,218,219] are expected to increase and continue to aggravate social and geographic inequities (KMs 2.2, 4.2, 10.1, 16.1, 17.4).[53,98] Extreme weather impacts health in ways that persist beyond the initial disaster,[220,221] including increases in food- and waterborne pathogens, loss of access to medications and emergency services, loss of electricity needed for medical equipment and medical facilities, and disruptions to transportation networks, all of which increase illnesses and deaths (KM 15.1).[222] Healthcare facilities in the Pacific Islands are located primarily on coastlines, making them especially susceptible to tropical cyclones and SLR-driven flooding (KM 9.2),[104,223] with limited space and resources for relocation (KM 30.3).

The built environment is especially affected by extreme weather because of high costs of building materials, supply shortages, delays in code updates, and physical isolation (Figure 30.8; KM 30.3).[224] Given the limited emergency infrastructure and evacuation options, extreme weather events create high risks for the mental and physical health of island populations, with individuals with low-income, older adults, children, and persons with disabilities at disproportionately higher risk (Box 15.1).[26,225,226,227]

Drought poses health challenges, particularly for rural island populations. A 2013 drought in the northern atolls of RMI caused crop failures and unsafe and insufficient water supplies, which led to nutritional deficits and increased prevalence of infectious diseases, especially in children.[103,228] Severe wildfires, which occur primarily during droughts,[229,230,231] directly threaten health and safety and can create respiratory hazards (KM 14.2).[232]

Damage from Typhoon Yutu



Extreme events acutely affect Pacific Island communities and their built environment.

Figure 30.8. In 2018 Super Typhoon Yutu struck the Commonwealth of the Northern Mariana Islands and damaged or destroyed a significant portion of the islands' buildings and critical infrastructure, leaving a sizable population temporarily unhoused. The experience underscored how events such as cyclones, flooding, and droughts combine with societal factors to acutely affect human health and safety. Images show US Naval personnel clearing debris at a Tinian family's home destroyed by Super Typhoon Yutu (**top left**); a satellite infrared image of Super Typhoon Yutu (**top right**); and a classroom in Hopwood Middle School on Saipan after the storm (**bottom**). Image credits: (top left) Matthew R. White, US Navy; (top right) NOAA/UWM-CIMSS, William Straka III; (bottom) Grace Simoneau, FEMA.

Health-Associated Impacts from Migration

Under a very high scenario (RCP8.5), human migration will increase due to SLR-driven inundation and salinization, displacing people, even entire populations, from low-lying atolls and low-elevation areas of high islands, with enormous implications for health and well-being (KMs 15.1, 17.1, 20.3).[98,105] Migrants often have difficulty navigating foreign healthcare systems[233] and face other barriers to accessing healthcare, including ineligibility for federal programs.[234] An improved understanding of the experiences and health outcomes of people who migrate, within or away from the USAPI, could inform better policy.

Mental Health Consequences and Climate Grief

Climate change directly and indirectly affects the mental health of Pacific Islanders.[235,236,237] On some islands globally, local climate stressors (such as floods, droughts, and SLR) are linked with negative mental health outcomes such as sadness, distress, and anger (KM 15.1).[238,239,240] Across the Pacific region, studies show that rural populations, socioeconomically disadvantaged groups, and people with disabilities experience more severe mental health consequences from various climate impacts (KM 15.2).[105,239,240,241,242]

Research is limited on the mental health impacts of climate-induced migration. Instability caused by voluntary and involuntary migration is expected to be a continuing source of anxiety,[99] although evidence indicates that social cohesion and reducing disparities can counter negative impacts.[105,243] Some data show that distress from thinking about climate stressors can be comparable to that from experiencing direct impacts.[239] Additionally, because Indigenous People in the Pacific are strongly connected to place, and place is central to conceptions of cultural identity, sudden ecological devastation or gradual change to the environment can create considerable stress (KMs 10.1, 15.1, 15.2, 23.1, 29.1).[99]

Mental health services related to climate change show effectiveness when they are designed to serve Pacific Islander populations in a culturally centered way and include diverse ways of knowing.[235,243,244] Finally, the lack of studies on mental health and climate change in Hawai‘i and the USAPI indicates that additional research may provide a more nuanced understanding of local implications.

Increase in Vector-Borne Disease

Outbreaks of mosquito-borne diseases such as dengue, chikungunya, and Zika are increasing in frequency, extent, and duration across the region.[245,246] Changes in rainfall (Figure 30.3) and temperature, combined with environmental and demographic changes, are anticipated to exacerbate this trend.[34,247] Resources for vector control and managing outbreaks are limited on small tropical islands, and outbreaks sometimes overwhelm health systems.[245,247] Health officials in FSM, RMI, and Palau are developing predictive modeling to create a dengue early warning system.[248] Similar to how chikungunya and Zika recently emerged and expanded in the Pacific, other vector-borne diseases may emerge in the future.[249]

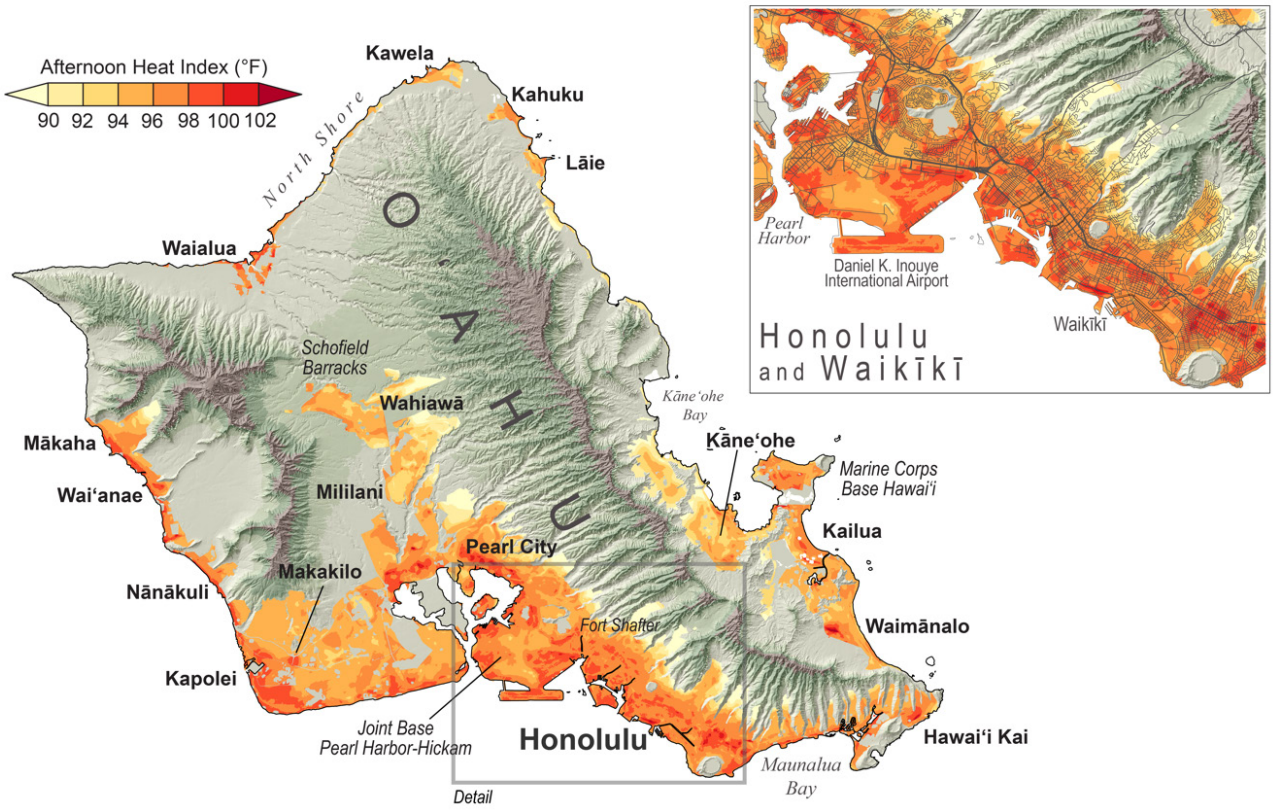
High Temperatures and Heat-Related Illness and Death

As in much of the US (Figure 2.11), the number of hot days has increased across the Pacific Islands; 2020 was the region's hottest year on record.[27,28,29,45,113] A community heat assessment in O‘ahu, Hawai‘i, in August 2019 found many neighborhoods with record-high afternoon heat indices between 100°F (38°C) and 107°F (42°C) (Figure 30.9).[250,251]

Climate change–driven hot weather causes heat-related illness and increases hospitalizations and deaths; 82% of heat-related deaths in Honolulu are already attributable to climate change (KM 15.1).[252] Those more likely to experience heat-related illness include young children, older adults, outdoor workers, economically burdened and disadvantaged people with little access to cooling or healthcare (KM 15.1), military personnel whose duties require heavy gear and vigorous activity, and non-acclimated visitors.[91] Shock events interact with heat: for example, after the 2009 tsunami in American Sāmoa, dehydration, heat stress illnesses, and barriers to receiving medical care increased.[253]

Imported low-quality foods have replaced local, nutritious, traditional diets (KM 30.1), resulting in some of world's highest prevalence of noncommunicable diseases (NCDs).[165,190,199,254,255] Heat worsens health outcomes for people with NCDs such as heart disease, cancer, stroke, and diabetes[256] and creates challenges for the management of obesity and other diseases because exercise is more difficult to do safely. Overweight and obesity in young children are at a higher prevalence in American Sāmoa, CNMI, and Guam than globally.[257]

O‘ahu Community Heat Assessment (August 31, 2019)



High temperatures are responsible for heat-related illnesses, hospitalizations, and death.

Figure 30.9. This community heat assessment map shows the afternoon heat index and “hotspots” for the island of O‘ahu, Hawai‘i. The inset is urban Honolulu. Data were collected by community volunteers and the City and County of Honolulu on August 31, 2019. On this day, the high temperature tied the hottest-ever recorded for Honolulu. Multiple neighborhoods on O‘ahu experienced afternoon heat indices above 100°F (38°C), with a maximum recorded heat index of 107.3°F (42°C). Climate change is increasing the frequency, intensity, and duration of heat extremes, putting individuals and communities at risk. Figure credit: Arizona State University, University of Hawai‘i at Mānoa, NOAA NCEI, and CISESS NC.

Social Adaptive Capacity and Community Resilience

The ability of individuals, communities, and institutions to endure stress and adapt to change determines health impacts of climate change. Recent examples demonstrating the importance of social capital (such as community networks, equitable access to education [KM 15.3], sharing, and relationships) in disaster response include community initiatives addressing flooding on the island of Kaua‘i[258] and drought in RMI.[259] Traditional Knowledge and coping strategies can enhance adaptive capacity and disaster response in some contexts.[260,261,262,263] The resilience of organizations, including health-related institutions and disaster response systems, depends on the ability of organizations to form relationships and communicate with one another, participation by traditional leaders and faith organizations, and effective planning by disaster management agencies (KMs 16.2, 20.2).[227,264,265,266,267] Prioritizing social and mental health initiatives in the health sector would aid in responding to the psychological issues that emerge with disasters and climate change.[268]

Key Message 30.3

Rising Sea Levels Threaten Infrastructure and Local Economies and Exacerbate Existing Inequities

Climate change, particularly sea level rise (SLR), will continue to negatively impact the built environment (*very likely*, *high confidence*) and will harm numerous sectors of the islands' economies (*very likely*, *high confidence*). SLR intensifies loss of territory and exclusive economic zones, particularly in low islands (*high confidence*). Climate-driven changes will exacerbate existing social challenges by disrupting livelihoods (*likely*, *medium confidence*). Adaptation to climate change and recovery from disasters is logistically challenging and disproportionately more expensive in the islands (*high confidence*). Government and community groups have developed innovative ways to reduce emissions and improve resilience by moving toward renewable energy and green infrastructure, nature-based urban planning, forward-looking building codes, and sustainable and equitable economic growth, guided by Western science and Traditional Knowledge.

Built Environment

The built environment refers to all human-made structures, including buildings, transportation infrastructure (ports, airports, roads, and bridges), military installations, and distribution systems for food, water, wastewater, communications, and power (electrical, oil, and gas). For this region, it includes traditional structures such as burial grounds, fishponds, and taro terraces (KM 30.5). These structures are critical to connecting people and providing access to goods and services, yet their location within a few feet of sea level renders them particularly vulnerable to SLR (Figure 30.4) and natural disasters (KM 9.2). For example, 98% of RMI's and 80% of Palau's built infrastructure is located within approximately 1,600 feet of their coastlines.[85]

Impacts to Infrastructure

Sea level rise will increasingly impact coastal infrastructure through increased magnitude and duration of storm wave–induced flooding (KMs 2.2, 9.1),[98,219,269] rising high tides,[270] and increased coastal erosion (Figure 30.10).[271] In Hawai'i, 3.2 feet of SLR above 2000 levels, which could occur as soon as 2100 under the Intermediate SLR scenario or 2070 under the High scenario (for information on the likelihood of these scenarios, see Appendix 3; Figure 30.4),[65] would affect 550 cultural sites, 38 miles (6%) of major coastal roads, 6,500 structures, and 25,800 acres of land, potentially displacing 20,000 residents and incurring $23.1 billion (in 2022 dollars) in economic loss.[92] Approximately 3 feet of SLR is projected to affect at least 58% of Guam's built environment[90] and most atolls in FSM and RMI.[98] Highly urbanized atolls may not be able to adapt to future SLR (KMs 9.2, 12.2),[106,107] leading to land loss and potential uninhabitability.[98,108] Elevated SSTs can increase bleaching and degradation of coral reefs, which are some islands' primary natural defenses (Figure 30.11; KM 30.4) against coastal flooding.[272] Lastly, increased flooding and erosion due to SLR and stronger future cyclones threaten US military bases in the region, potentially destabilizing regional security and the ability of the Department of Defense to respond to natural disasters (KM 17.1).[53]

Coastal Flooding Events



Sea level rise is increasingly impacting infrastructure and communities.

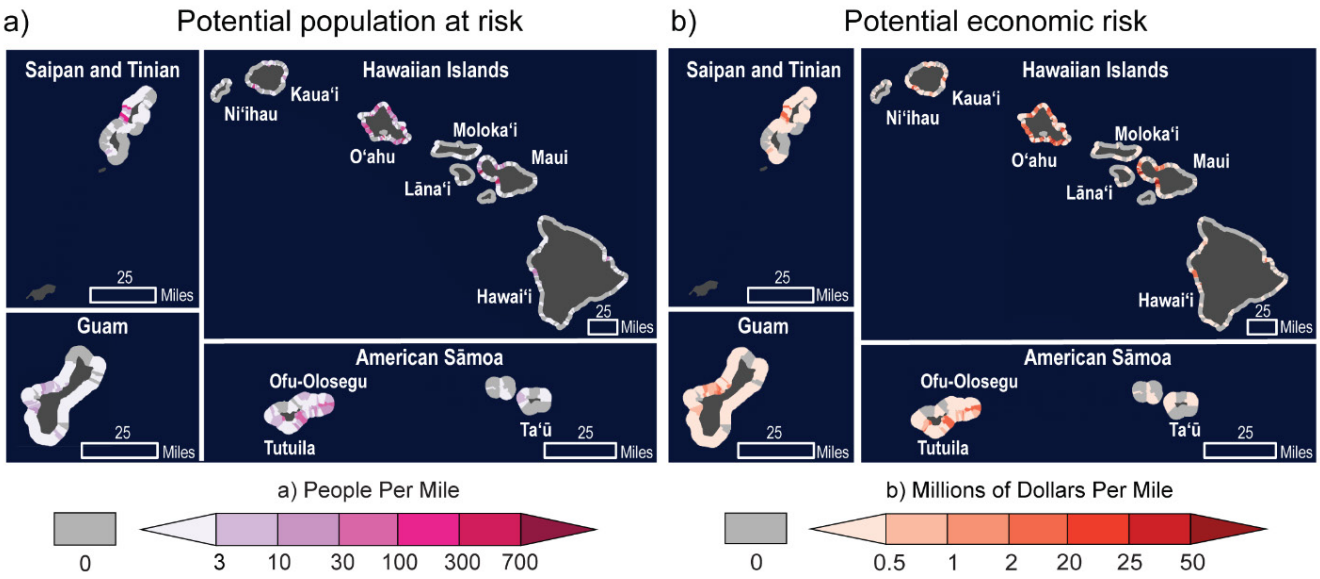
Figure 30.10. Rising sea levels are increasing the frequency and magnitude of coastal flooding events. (**top left**) Cars travel through king tide flooding on Oʻahu, Hawaiʻi, in August 2019. (**top right**) High tide inundates a low-lying coastal area in Majuro, Marshall Islands, in February 2020. (**bottom left**) A residence on Oʻahu, Hawaiʻi, has collapsed due to coastal erosion during a large wave event in February 2022. (**bottom right**) American Sāmoa experienced flooding around homes in May 2021. Photo credits: (top left) Maya Walton via © Hawaiʻi Sea Grant King Tides Project, 2019 [CC BY 4.0]; (top right) Max Sudnovsky via © Hawaiʻi Sea Grant King Tides Project, 2020 [CC BY 4.0]; (bottom left) © Shellie Habel; (bottom right) Kelley Anderson Tagarino via © Hawaiʻi Sea Grant King Tides Project, 2021 [CC BY 4.0].

Adapting the Built Environment

Protecting coastal infrastructure on small islands is costly and requires strong governance and thoughtful urban planning.[273] Hawaiʻi has enacted forward-looking state and county policies, including increased minimum setbacks for coastal development,[274,275,276] setbacks incorporating science-based erosion rates and long-planning horizons that account for future SLR,[275,277,278,279] a first-in-the-Nation mandate to disclose SLR hazards prior to real estate transactions,[280] a requirement for state agencies to assess and plan for SLR impacts,[281] and a mandate that environmental impact assessments consider SLR and other climate factors.[282] While evaluating a balance between public and private property interests (KM 30.5), Hawaiʻi is also assessing the feasibility of relocating some coastal developments,[283] prohibiting most coastal hardening,[274] and helping to preserve public beach access.[283]

Nature-based solutions such as coral reef restoration[284,285] have been proposed at the federal (DARPA Reefense Program),[286] state (e.g., State of Hawai'i 2021[287]), and territorial[288] levels. Such solutions are potentially cost effective for protecting coastal infrastructure[289] and habitats, sustaining ecosystem services such as fisheries (KM 30.1), and supporting tourism and recreation.[290]

Annual Risk Reduction Benefits Provided by Coral Reefs



Coral reef degradation could affect thousands of people and cause millions of dollars in damages.

Figure 30.11. The maps show coastal flood protection that the top-most 3.28 feet (1 m) of coral reefs provide annually in American Sāmoa; Guam; Saipan and Tinian (Commonwealth of the Northern Mariana Islands); and Hawai'i. The maps display (**a**) the number of people per mile at risk and (**b**) the potential economic losses (in millions of dollars per mile) from direct building damages and indirect economic disruption from flooding. Adapted from Storlazzi et al. 2019.[291]

Livelihoods and Economy

Demographics and Migration

Compared to Hawai'i, the USAPI have smaller populations and smaller land masses, as well as fewer financial resources, making adaptation more challenging. During 2010–2020, populations increased in Hawai'i and decreased in American Sāmoa, CNMI, Guam, and Palau.[16,17,18,19,20,21] Pacific Islanders are moving from rural to more urban areas that sometimes lack resources and infrastructure to accommodate influxes of people.[273,292] Migration is a traditional strategy for coping with resource scarcity in Micronesia—for example, a family member often migrates to an urban area for employment, sending money home to support family needs.[293] In 2020, these external remittances accounted for 5.7% of FSM's GDP, 0.08% of Palau's GDP, and 12.7% of RMI's GDP.[294,295,296] As livelihoods in climate-sensitive sectors are impacted by climate change, the amount of money migrants send to relatives will be affected. Climate change may displace populations,[297] but the extent to which climate change drives migration is not well established because migration is an inherent part of Pacific Island cultures.[298] However, some evidence points to a strong correlation between climate impacts on ecosystem services (e.g., food and water provision, protection against floods and storms) and people's propensity to migrate.[299]

Economy

The costs of adapting to, mitigating, and suffering the consequences of climate change are projected to increase over time, amounting to between 3% and 13% (under the 450ppm and SRES [Special Report on Emission Scenarios] A1FI scenarios, respectively) of Pacific Island regional GDP by 2100 (KM 19.1).[300] Relative to Hawai'i and larger countries, USAPI economies have smaller total GDPs and GDP-per-capita and higher dependence on fisheries and agriculture—climate-sensitive industries representing a large portion of GDP.[301] They also are more dependent on remittances, federal aid, and foreign aid (KM 17.1).[302,303]

Tourism is a major economic engine in the Pacific.[304] Before COVID-19, tourism accounted for over 80% of total exports for Palau and less than 20% for RMI[305] and approximately 25% of total GDP in Hawai'i. Climate change impacts tourism-based jobs and revenue. Damages to the built environment, especially coastal infrastructure, deterioration of natural assets, and expanding vector-borne disease occurrence could reduce tourism.[300]

Fishing is a critical economic sector in many Pacific Islands.[178,306] Tuna license revenues represent a significant source of government income for the FAS but are expected to decline due to projected changes in fish availability in the EEZs (KMs 10.1, 10.2),[79,80,81,83,306] with ramifications for local canneries in American Sāmoa and the FAS. Changing coastlines and potential land loss from SLR may result in changed maritime entitlements via changes in the size and shape of the respective EEZs,[306] affecting not just fisheries but also marine mineral rights. Climate-related marine and coastal habitat impacts threaten artisanal fisheries, a critical source of food and income for many households (KMs 30.1, 10.1, 10.2).[78,82,178,184]

Estimated Economic Costs of Climate Change

The estimated economic impacts of climate change will vary by sector. Coastal hazards have a disproportionately large impact on small islands' GDPs.[307] Specifically, the projected increased duration and magnitude of storm wave–induced flooding[98,219,269] and increased coastal erosion[271] can damage infrastructure underpinning the local economy. Degradation of coral reefs due to a rise in SSTs[272] could incur coastal damages costing approximately $1.2 billion (in 2022 dollars) annually to the economies of Hawai'i and the US Pacific territories.[218]

In American Sāmoa and Guam, coastal flooding and erosion are projected to disproportionately harm at-risk individuals, including minority and low-income populations and those younger than 16 or older than 65 (groups defined by the 2010 US Census data).[218] High-risk coastal properties (i.e., those located in hazard-erosion areas of updated FEMA Flood Insurance Rate Maps) will be difficult to insure.[308] Increased coastal flooding events and drought are expected to negatively impact agricultural revenues (KM 30.1). For example, between 2008 and 2016, Hawai'i lost approximately $53.5 million (in 2022 dollars) in cattle production due to the most severe drought on record, and federal crop insurance programs paid $11.2 million (in 2022 dollars) to farmers for drought losses during 1996–2018, mainly for macadamia nuts and coffee.[49]

Adapting Livelihoods and Economies

As a percentage of GDP, the costs of climate change adaptation are significantly higher for small islands than for larger countries.[300,309] Islands' geographic isolation, reliance on imported goods, and vulnerable infrastructure can increase adaptation and disaster recovery costs (see Figure 30.8).[224] Hawai'i and the USAPI have adopted the United Nations Sustainable Development Goals (Box 30.2)[130] to increase resilience by creating more equitable approaches to adaptation and mitigation. Financing costly climate adaptation is a shared international challenge for the FAS (KM 17.4).[300,301] Unlike American Sāmoa, CNMI, Guam, and Hawai'i, the sovereign FAS are eligible for foreign direct investment and receive substantial funding from the Green Climate Fund,[310] the Asian Development Bank,[311,312] the US Government via the Compact of Free Association,[310,313] and other nations (KMs 19.2, 19.3).[314] Because credit agencies are increasingly considering

vulnerability to climate change as a factor in their ratings, however, Palau's and RMI's credit ratings may decrease, with negative impacts on their abilities to borrow external funds, attract foreign investment, or access below-market-rate financing to accelerate development.[315]

Decarbonization, Sequestration, and Resilience

Although many Pacific Islands emit minimal greenhouse gases, they are striving to reduce emissions and sequester carbon while addressing ecosystem resilience needs.[119] For example, Guam and Hawai'i established 100% renewable portfolio standards for the electricity sector, to be achieved by no later than 2045.[316,317] Hawai'i established a net-negative emissions target by 2045 and created a sequestration task force[282] charged with establishing baselines and benchmarks, recommending policies including mitigation, and developing strategies for sustainable agriculture. This work led to a carbon pricing evaluation.[318] Similarly, RMI pledged emissions reductions of 45% below 2010 levels by 2030 and carbon neutrality by 2050.[319] Palau recently committed to 100% energy generation from renewable sources by 2032.[320] Opportunities exist for ecosystem-based, place-based adaptation and mitigation informed by Indigenous Knowledge systems (KMs 30.1, 30.5).[321,322,323]

With limited land areas, each island in the region is carefully evaluating options for transitioning to renewable energy. In 2016, American Sāmoa's island of Ta'ū transitioned its energy supply from 100% diesel to 100% solar with battery backup.[324] In Hawai'i, rapid growth of rooftop solar generation—combined with centralized solar, battery storage, wind power, and pumped hydropower storage—is enabling a transition away from an oil-predominant grid.[325] The potential for success is high: Kaua'i's grid achieved a 69.5% renewable portfolio standard in 2021, and the island is occasionally 100% renewably powered during midday hours; it is projected to achieve a 90% renewable portfolio by 2026.[326,327] Hawai'i's Act 100[328] required a community-based renewable energy program; power utilities and communities in the region are now developing mechanisms to enable shared ownership of renewable infrastructure.[329]

Key Message 30.4

Responses to Rising Threats May Help Safeguard Tropical Ecosystems and Biodiversity

The structure and composition of Pacific Island coastal and marine ecological communities are directly threatened by rising ocean temperatures, ocean acidification, and sea level rise (*very likely*, *high confidence*). Increasingly severe droughts and warming are increasing fire risk (*high confidence*) and will have broad negative impacts on native plants and wildlife, including an increased risk of forest bird extinctions (*very likely*, *high confidence*). Adaptation strategies improve the resilience of ecosystems, including ecosystem protection, ecological restoration, invasive species prevention and control, and investments in fire prevention (*medium confidence*).

Marine and Coastal Ecosystems

Pacific Island marine environments serve as the foundation for local food systems and cultures (Figure 30.12). Rising ocean temperatures, declining dissolved oxygen concentrations, and marine heatwaves are projected to impact the structure and composition of marine ecosystems (Figure 30.5; Ch. 8; KM 10.1).[330] Global marine food web models project biomass declines of 10% to 40% across the region throughout this century, with greater declines projected for large predators.[331] Finally, marine species within the region's EEZs are projected to shift beyond historical ranges as early as 2030—sooner than much of the globe.[83]

Coastal and oceanic environments supply direct goods and services such as fish, recreation and tourism areas, regulating services such as coastal protection and carbon storage, and means for trade and transportation—collectively valued at over $3.1 trillion per year (in 2022 dollars; KM 23.2).[332] Rising SSTs and marine heatwaves continue to be the most pressing climate change impacts facing Pacific reefs,[333,334] leading to more frequent and severe bleaching events with less recovery time.[61,62,335,336] Bleaching-induced mortality has reduced coral cover and decreased available habitat for reef-associated species.[62,334] Increased SSTs will negatively affect some animal species distributions,[337,338,339] and rising ocean and sand temperatures lead to a higher ratio of female sea turtles observed around the Pacific, threatening the viability of sea turtle populations.[340] Increased air temperatures and reduced precipitation are *likely* to have negative effects on coastal vegetation[341] and coastal pond communities,[342] adversely affecting coral reefs, seagrasses, and mangroves via altered sediment and pollutant delivery to coasts.[343] Increased ocean acidity[344] and increased nutrient runoff from the land[345] negatively impact corals, shellfish, and associated fisheries (KM 30.1). Although these systems generally have limited capacity to adapt to large climatic changes, regional strategies are being developed to reduce impacts.[337,338,346]

Box 30.5. Blue Carbon Ecosystems

USAPI mangroves and seagrasses are among the world's most productive blue carbon ecosystems (BCEs—ocean and coastal ecosystems that capture carbon; Focus on Blue Carbon),[347] storing over 30% of total island carbon despite their small area.[120] Guam, the Republic of the Marshall Islands, the Federated States of Micronesia, and Palau plan to use BCE carbon to offset emissions while also protecting coastal infrastructure.[285,348,349] BCEs also provide food, fiber, fuel, and income to Pacific Islanders.[350] Mangroves are non-native to Hawai'i and threaten shorebird habitat, coastal access, and cultural sites and services.[351] However, evidence suggests that these non-native species can provide some ecosystem benefits, for example, by significantly increasing coastal sediment accumulation[352] and carbon capture rates.[353] Mangrove loss in Micronesia is projected to start by 2080 under Intermediate SLR scenarios (Figure 30.4).[86] The conservation and restoration of BCEs and their associated reef systems provide cost-effective solutions for protecting coastal communities and increasing other benefits (KM 8.3).[289]

Sea level rise will cause more frequent and extensive flooding of coastal ecosystems, impacting plants[354,355] and animals,[356] especially on low-lying atolls such as those in the Northwestern Hawaiian Islands, PRI, RMI, and FSM. In some cases, flooding is *likely* to increase erosion rates, reducing the elevation of mangroves, vegetated dunes, and beaches. Development exacerbates these drivers by exposing soils, creating impervious surfaces, and impeding inland migration of coastal ecosystems, limiting their adaptive capacity.[357]

Characteristic Ecosystems of the Pacific Islands



Pacific Island marine environments provide the foundation for local food systems and cultures.

Figure 30.12. Pacific Islands offer a diversity of ecosystems that include mangroves (**top left**), limestone forests (**bottom left**), tropical alpine habitats (**top center**), dry forests (**bottom center**), coral reefs (**top right**), and cloud forests (**bottom right**). Photo credits: (top left) Richard Mackenzie, USDA Forest Service; (top center) © Paul Krushelnycky, University of Hawai'i; (top right) © Underwater Earth / XL Catlin Seaview Survey / Christophe Bailhache; (bottom left) Christian Giardina, USDA Forest Service; (bottom center) Hawai'i Department of Land and Natural Resources; (bottom right) Lucas Fortini, USGS.

High Island Ecosystems

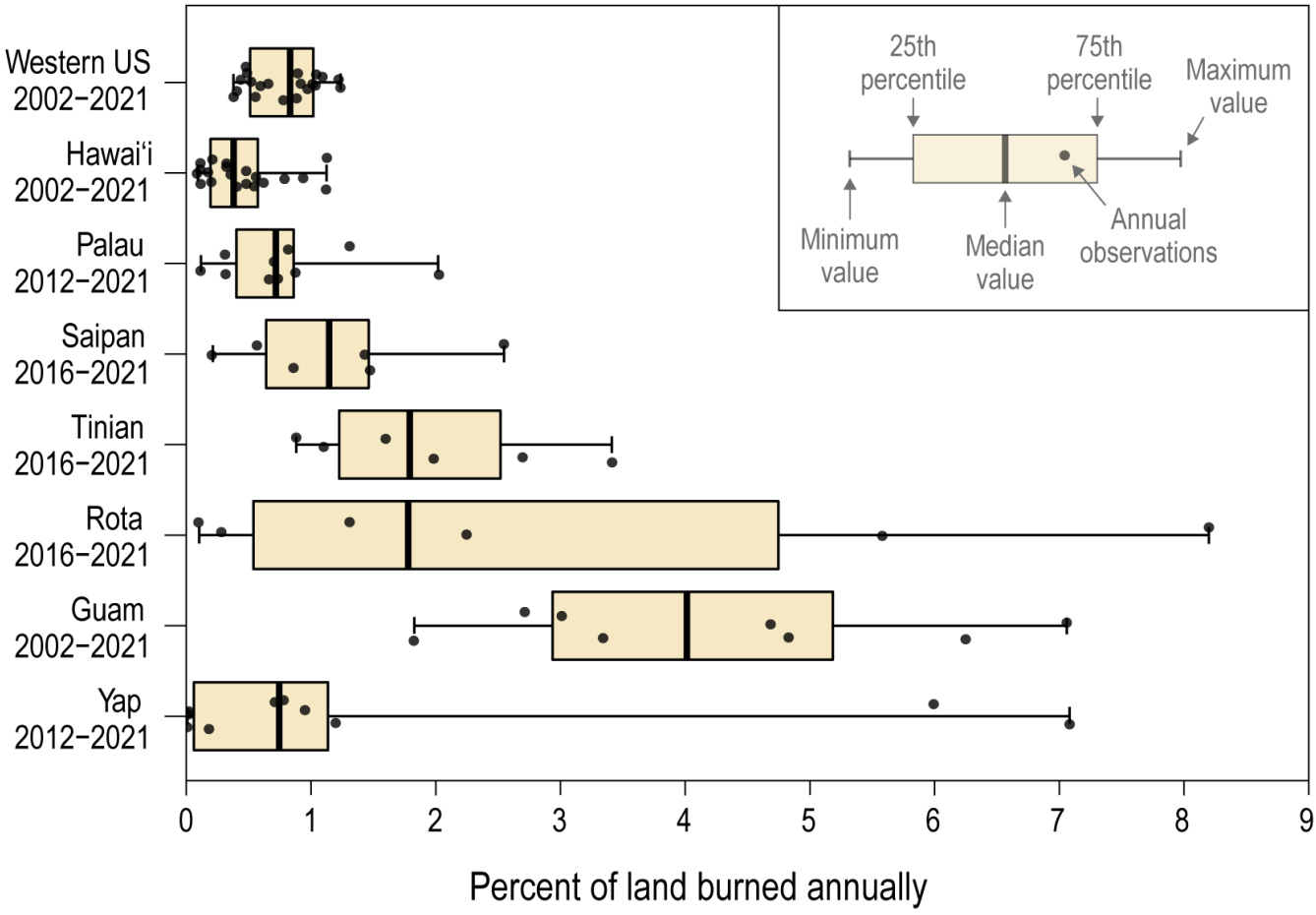
Terrestrial ecosystems of high islands (i.e., islands characterized by volcanic origin and consequently more diverse topography) have evolved in isolation from continental areas, resulting in unique and diverse fauna and flora with a high proportion of native species naturally occurring only on these islands (Figure 30.12). However, the combination of invasive plants and animals and diseases; habitat destruction; and intensifying fire regimes and ecological drought has resulted in severe range contractions and native species extinctions.[93,358,359,360,361,362,363]

In Hawai'i, past droughts and rainfall variability had landscape-level impacts on vegetation[364,365] and cascading ecological effects.[366] Long-term climatic shifts are *likely* to accelerate range contraction and extinction rates,[93,367] but responses will vary by species, including differences in drought tolerance across populations.[368,369,370,371]

Rainfall changes (Figure 30.3) will affect island aquatic ecosystems. In Hawai'i, declines in dry-season streamflow will result in more intermittent streams[137] and loss of habitat connectivity and conservation value.[372] Decreased streamflow will also negatively impact stream organisms by reducing fitness and increasing disease and habitat for invasive fish and mosquitoes.[373,374,375]

Across the region, climatic shifts are expected to impact native ecosystems via interactions with fire (e.g., Trauernicht 2019;[376] Nugent et al. 2020[377]). Wildland fires already burn a higher proportion of total land area in the Pacific Islands than in the continental US (Figure 30.13)[229,378] and are strongly linked to El Niño events.[49,103] While limited future climate projections indicate increasing fire probabilities,[376] the future of fire in the region is highly sensitive to management and policy decisions, since ignitions are largely caused by humans (e.g., Dendy et al. 2022;[229] Trauernicht et al. 2015[378]). Education and outreach will continue to play a critical role in wildfire mitigation (e.g., HWMO 2021[125]).

Wildfire Area Burned in the Pacific Islands Compared to the Western US



Wildfires burn large percentages of land in Pacific Islands compared to the western US.

Figure 30.13. The annual percentage of total land area burned for seven Pacific Islands is equivalent to or greater than the percent area burned for western US states. Years examined are noted for each location. Figure credit: USDA Forest Service, USGS, NOAA NCEI, and CISESS NC.

Interactions between invasive species and climate change in isolated Pacific Islands are complex (KM 8.2),[379,380,381,382,383] with climate change most often exacerbating invasion.[384,385,386,387] Invasive species may aggravate local water stress, for instance, by using more water resources than native plants[148,380,388,389] or by causing less rainfall to reach the forest floor, as in the case of strawberry guava invasion.[148,390] Similarly, fire-prone invasive vegetation is likely to further increase future climate-driven fire risk.[376] With the steep increase in the number of naturalized species on Pacific Islands,[391] these climate and invasion interactions will become increasingly important for managers to address.[392] Critical region-wide investments are being made to prevent the introduction of potentially invasive species and diseases,[393] given that climate change can alter pathways for species introductions.[394,395,396]

Responding to Rising Threats

Regional efforts increasingly focus on restoration management that enhances climate resilience.[397,398,399,400,401] Besides boosting adaptive capacity,[402] ecosystem restoration efforts may provide multiple benefits to islands, including hydrological (KM 8.3)[140,148,161,401,403,404] and sociocultural benefits,[404,405] as well as carbon sequestration[406] and sediment retention.[407] Hawai'i and the USAPI have established both marine and terrestrial protected areas (Box 30.2),[119,134,408,409] which elsewhere have successfully supported ecosystem resilience

under climate change (e.g., Gaüzère et al. 2016;[410] Lawler and Hepinstall-Cymerman 2010;[411] Roberts et al 2017;[412] Virkkala et al. 2014[413]).

The urgency of conservation actions (Figure 30.14) is exemplified by the Hawaiian forest bird crisis. Forest bird populations are declining due to avian malaria spread driven by warming.[414,415] Managers are exploring options for safeguarding species near extinction,[416,417,418,419] including habitat restoration, avian malaria vector control,[420] and translocation.[421,422,423,424]

In addressing these myriad challenges, conservation efforts increasingly involve broader partnerships with educators (e.g., Bolden et al. 2018[123]) and Indigenous Knowledge holders, who play a vital role in conservation planning and implementation (KM 30.5; Ch. 16).[405,425,426,427,428]

The Climate Urgency of Pacific Island Conservation



Conservation efforts across the region help to restore ecosystem health and protect native species.

Figure 30.14. These images depict on-the-ground climate-related conservation actions across Pacific Island ecosystems: wildfire management in Hawai'i Volcanoes National Park (**top left**); planting native species in Palau to restore watershed health (**bottom left**); installing protective fencing around native habitat in Hawai'i (**bottom center**); conservation of native snails using captive populations to prevent extinction of vulnerable populations (**top right**); seabird translocations in the Northwestern Hawaiian Islands to safeguard against sea level rise (**center right**); and climate-resilient coral reef restoration experiments in Hawai'i (**bottom right**). Photo credits: (top left) D. Benitiez, NPS; (top right) © Chris A. Johns; (center right) © Lindsay Young, Pacific Rim Conservation; (bottom left) © Ann Singeo, Ebiil Society Inc.; (bottom center) NPS; (bottom right) Hawai'i Department of Land and Natural Resources.

Key Message 30.5

Indigenous Knowledge Systems Strengthen Island Resilience

Indigenous Peoples and their knowledge systems are central to the resilience of island communities amidst the changing climate (*high confidence*). Reciprocal and spiritual relationships among the lands, territories, waters, resources, and peoples are being strengthened and sustained as communities adapt and manage their resources collectively (*high confidence*). Indigenous Peoples are identifying and quantifying the potential loss and migration of critical resources and expanding the cultivation of traditional food crops on high islands (*high confidence*).

Reciprocal Relationships Between People and Place

Communities throughout Hawai'i and the USAPI demonstrate Indigenous cultural and community resilience grounded in Traditional Knowledge as they continue to adapt to global changes, just as their ancestors have for millennia (KM 18.3; Figure 16.3).[87] These adaptations and the collective resilience of Indigenous communities are strengthened and sustained through reciprocal exchanges between the peoples and the lands, territories, waters, and resources to which they are genealogically connected (Figure 30.15). Resilient communities are vital to the overall health and well-being of island peoples. To effectively advance the science of sustainability and manage resources amidst the changing climate, spiritual rituals and engagements are central to biocultural well-being—the collective well-being of landscapes, seascapes, and Indigenous communities (Box 30.6).[429] Through these rituals and engagements, island communities individually and collectively are able to connect to the place and all of its life-forms, cultivating reciprocal relations that enhance future resource abundance based on responsibility rather than ownership.[430]

Restoring and Caring for Hawaiian Limu (Seaweed)



The resilience of Pacific Island communities is strengthened by their connection to place and all of its life-forms.

Figure 30.15. *Limu* refers to ocean plants, including seaweed. The governor of Hawai'i designated 2022 as the Year of the Limu as a part of a statewide community effort to raise awareness about the importance of limu to Hawai'i's cultural identity and the health of the nearshore marine environment. The KUA Limu Hui (a seaweed practitioners group) shares traditional knowledge and practices related to limu gathering, use, and restoration. *Limu kala* (*Sargassum echinocarpum*; **left**) is incorporated into various food dishes, is used as bait for reef fish, and is an important component in Hawaiian forgiveness ceremonies. Limu such as *palahalaha* (*Ulva fasciata*; **right**) also play a critical role in intertidal ecosystems as they provide food and shelter for invertebrates and herbivores. Photo credits: © Haunani Kane.

Box 30.6. Local Cultural Resilience to Climate Change

Communities across the region are working to build local cultural resilience to climate change. In Hawai'i, community-based subsistence fishing[431] and forest[432] areas were established as place-based approaches to strengthen communities' ability to formally manage their natural resources through traditional and customary skills, practices, and social networks. Communities are cultivating reciprocal relationships as a shared responsibility[433] and including sacred relationships and ritual approaches to land and sea stewardship.[429] In Hawai'i, a common practice within the community is to ask for permission to physically and spiritually enter a sacred space, as this allows community members to introduce their genealogies to the lands and people, as well as express gratitude and respect for the land—the elder sibling—to sustain future generations.

Cultural and Historical Sites

Archaeological, cultural, and historical sites are representations of the living culture and ancestral knowledge of Indigenous and island peoples, and they serve as potential resources and models as communities seek to remediate increasing climate risks and impacts (Figure 30.16).[87,118,119,434] Indigenous communities are identifying and protecting cultural and historical sites, assessing climate impacts on natural resources, and creating restoration plans (KM 16.3).[435,436]

Archaeological sites and oral history document the culturally grounded and traditional resilience of island peoples to historical coastal change that resulted from extreme events and higher sea levels. Approximately 2,000–4,000 years ago across the equatorial Pacific, sea level was at least 3.3–6.6 feet higher than present, which directly influenced the timing of atoll formation and the initial migrations and settlement of island people.[437] Initial settlers of Majuro atoll, RMI, arrived within 100 years of island formation, when sea level was 3.3 feet higher than present, and they cultivated trees and shrubs into crop systems rather than waiting for natural vegetation succession.[438] On Yap, FSM, coastal stone-built structures are expressions of innovation, cultural identity, and pride that allowed islanders to occupy coastal areas under elevated sea level, and modern structures such as the coastal men's houses (*faluw*) and taro gardens document cultural resistance to rising waters.[87] On Guam, traditional CHamoru houses were elevated on limestone pillars (*latte*) along the coast, protecting them from coastal inundation.[439] Across higher islands like Sāmoa, settlement along narrow coastal plains occurred after nearly 1,000 years of sea level fall and subsequent natural development of habitable coastal environments.[437] The oral histories, stories, myths, storyboards (Palau), and songs/chants of Indigenous Peoples record their observations of the changing environments and lifestyles. The proverb *He pūko'a kani 'āina* describes the natural evolution of a coral reef into an island and is also interpreted by Native Hawaiians to describe the resilience of a person who begins in a small way and gains steadily until she becomes firmly established.[440]

Climate Change Impacts on Cultural Sites



Cultural sites, representing the living culture and ancestral knowledge of Indigenous Peoples, are at increasing risk.

Figure 30.16. Sea level rise (SLR), strong winds, and large storm waves impact a fishpond in Kaloko-Honokōhau, Hawai'i (**left**). Kukau El Bad, a cultural site in Ngarchelong State, Palau, is inundated by salt water and continues to be threatened by SLR, storm surge, and erosion (**right**). Photo credits: (left) © Kimberly Crawford; (right) © Ann Singeo, Ebiil Society Inc.

Across the region, one approach to mediating climate impacts is to reinvigorate and restore food production across landscapes (KMs 11.1, 30.1; Box 30.4).[441] This is being accomplished through several pathways. At a policy level, work is being done to amend law in Hawai'i to add a "Traditional Lands" zone under the state's Land Use Commission that would streamline permit and building requirements[194] for eco-village-type living with mixed-use housing and other sustainable infrastructure such as commercial kitchen and food-processing facilities, as well as the use of traditional agriculture lands such as *lo'i kalo* (irrigated taro, agriculture), *loko i'a* (fishponds), and large expanses used to traditionally farm staple crops such as *'uala* (sweet potato).[442] Communities and cultural practitioners are working with scientists to identify areas where food production could be expanded under future climate scenarios (KM 12.4). For example, taro cultivation was modeled under future SLR scenarios[434] and sweet potato[442] and breadfruit under increasing temperature and rainfall scenarios,[118] showing the potential resilience of these traditional agricultural practices.

Indigenous Knowledge Systems and Values of Ecosystem Services

Indigenous island communities are also working to ensure that Traditional Knowledge is central to resilience strategies (KM 16.3). A growing body of Indigenous-led research describes how biocultural methods can successfully be incorporated into efforts focused on community-based subsistence,[431,432] relationships to place,[433] cultural–ecosystem service assessments,[443] and the protection of historical and cultural resources.[444] Biocultural approaches start with and build upon local cultural perspectives by encompassing values, knowledge, and needs and by recognizing reciprocal restoration between ecosystems and human well-being (KM 20.3).[195,443] The act of restoring ecosystem services contributes to cultural revitalization[433] by reaffirming connection to place, enhancing community relationships and social networks and the physical and mental well-being of Indigenous Peoples,[405] increasing local food production,[202] and diversifying the local economy[427]—all while distributing the abundance through reciprocal exchange.[431] In return, the renewal of culture promotes the restoration of ecological integrity through the creation and expansion of habitat for native species[434] and further supports recovery and resilience of ecosystems following future environmental disturbances (KM 8.3).[445] Equitable outcomes from climate research and planning are predicated on properly citing Indigenous elders and knowledge keepers,[446] enhancing Indigenous control of Indigenous data via data sovereignty, protecting intellectual property rights, and establishing free, prior, and informed consent (KMs 16.2, 20.2, 31.2).[447,448]

Traceable Accounts

Process Description

To build the author team, the federal coordinating lead author and the regional chapter lead author utilized the Fourth National Climate Assessment (NCA4) Key Messages and their assessment of new emerging issues to select key sectors of importance to the region. The lead authors compiled a comprehensive list of potential authors with expertise in those sectors. The regional chapter lead author then selected a total of 14 authors to join the team, representing a wide range of geographical and technical expertise (including physical and social scientists as well as cultural practitioners) and a diversity of career stages, affiliations (federal, academic, and private), and previous assessment experience.

The author team met weekly (virtually) to discuss chapter content and plan engagement activities. After brainstorming and agreeing on the five key topic areas for the chapter, authors identified which sections they would contribute to and met regularly in subgroups to discuss content. The team held a virtual public engagement workshop on January 24, 2022, to solicit public feedback on the chapter outline. In addition, the author team held five virtual technical meetings (one for each topic) where technical experts were invited to brainstorm and collect information to ensure the chapter covered the latest scientific results and most important topics in the region. The author team utilized interactive engagement tools to facilitate meetings, including collaborative writing exercises. Participants who contributed significantly to shaping chapter content were invited as technical contributors. Inputs from the workshop and technical meetings were synthesized by the author team and incorporated into the chapter draft.

Throughout this chapter, future projections of the physical environment come from general circulation models and earth system models from the fifth and sixth Coupled Model Intercomparison Projects (CMIP5[449] and CMIP6[450]).

Key Message 30.1

Climate Change Impairs Access to Healthy Food and Water

Description of Evidence Base

Global assessments support findings that coastal land loss attributable to sea level rise (SLR), increased precipitation, wave impacts, and increased aridity drive food and water insecurity on small islands.[89] Regional literature shows decreasing water quality and food production in both observed trends and modeled projections (KM 11.1).[77,135,147] However, these climate change manifestations are highly variable across different islands and within islands. Limited studies (e.g., Denton et al. 2014;[152] Felton 2021;[151] Ghazal et al. 2019;[144] Jarsjö et al. 2020;[154] Kibria et al. 2021;[155] Leta et al. 2017,[145] 2018;[146] Mair et al. 2019;[147] Strauch et al. 2014,[140] 2015,[451] 2018[141]) have quantified these effects on water resources and water quality throughout the large and diverse region. Although available studies and their results may be applicable to other, understudied islands, given the high diversity among islands, additional site-specific assessments in the Pacific Islands region would improve understanding of the impacts of climate change on water.

The importance of fisheries and agriculture for nutrition and livelihoods, and the nexus between food, trade, and malnutrition, come from a well-established evidence base,[31,32,165,175,191,199,255,452,453] although localized assessments dissecting socioeconomic–ecological dynamics remain limited.[166,199] Clear evidence shows that local agricultural and fisheries production is not keeping up with population, with outputs falling due to climate change.[31,452,454]

It is clear that fish, and particularly reef fish, are essential for regional nutrition and food security.[82,177,183] Evidence indicates that climate change is driving and will continue to drive changes to coral reefs and fisheries yields (along with pollution and overharvest).[78,81,113]

A broad literature base clearly establishes strong connections between drought and water security, sanitation, food productivity, and increased risk of wildfires.[191,217] Although few studies assess regional changes in drought,[49,50] Hawai'i has clearly experienced a drying trend,[48] particularly since the 1950s in La Niña years.[149,150]

It is generally agreed that reinvigorating local agricultural and marine food systems will be necessary, but not sufficient, for food security[116,175,190] and that investment in climate-resilient food supply chains is needed.[166,167,176]

Major Uncertainties and Research Gaps

Global and downscaled projections of rainfall exhibit large uncertainty in direction and magnitude of future change (e.g., Elison Timm et al. 2015;[51] Xue et al. 2020;[455] Zhang et al. 2016[57]). Island-specific downscaled projections of hydrometeorological extremes (drought, flooding, heavy precipitation) are not currently available for Hawai'i or the US-Affiliated Pacific Islands (USAPI). Understanding of future groundwater availability is limited by the lack of island-specific groundwater models for islands outside of the main Hawaiian Islands, some atolls in the Federated States of Micronesia, and Guam (e.g., Bailey et al. 2008;[456] Gingerich 2013;[457] Izuka et al. 2021[458]). Very little research exists regarding enhanced mobilization of subsurface contaminants from rising sea levels, despite the existence of many coastal contamination sites. Watershed management could be improved through better understanding of the current impacts of invasive plants (e.g., strawberry guava, *Psidium cattleianum*) on evapotranspiration and water cycling, and of how future climate change will modify such impacts.

Localized food supply chain vulnerability assessments are lacking (e.g., Dyer 2018[32]). Salt tolerance in many key agricultural plants is still not well understood (e.g., Palanivel and Shah 2021[198]), nor are the interactions between climate change and invasive agricultural pests. Reliable fish consumption information is not disaggregated by socioeconomic demographics nor by fish type, precluding analysis of nutrition (and risk from contaminants) by group. Barriers to and opportunities for reinvigorating local food systems are localized and require further analysis.

Description of Confidence and Likelihood

There is *very high confidence* that climate change will impair future access to clean and fresh water and healthy food. Broad global and regional literature support the finding that future water access will be compromised by reduced water availability, compromised water quality (KMs 2.2, 4.1),[26,103,138,139,140] and saltwater contamination, which has already been exacerbated by SLR, especially on atolls (*high confidence*).[98,135,136] The literature agrees that climate change will disrupt global food imports and supply chains through declines in nearshore and open-ocean fish stocks in the Pacific,[31,81,109,165,166,167,168,169,177,178,179] increased crop disease,[77,191] and drought.[49,103]

There is *very high confidence* that food and water availability will be negatively impacted by increasing temperatures, altered rainfall, flooding, pollution, and fisheries degradation. This confidence assessment is demonstrated by numerous peer-reviewed studies, robust global climate projections, and observations of changes to crop yields, fisheries, and freshwater ecosystems (e.g., Frazier et al. 2019;[103] Ghazal et al. 2019;[144] Leta et al. 2017,[145] 2018;[146] Mair et al. 2019;[147] Strauch et al. 2014,[140] 2015,[451] 2018[141]). Based on a broad evidence base including peer-reviewed literature and Indigenous Knowledge, there is *very high confidence* that adaptation actions such as traditional farming, fishing, and land management practices can help build more resilient water and food systems.[73,116,119,175,194,195,202,203,204,205]

Key Message 30.2

Climate Change Undermines Human Health, but Community Strength Boosts Resilience

Description of Evidence Base

Multiple assessments find an increasing trend in people affected or killed by climate-related disasters and extreme weather events worldwide.[220,221] While health infrastructure exposure to climate risk is well documented globally, few vulnerability assessments for islands, territories, and states in the Pacific (e.g., Greene and Skeele 2014[223]) have examined health infrastructure vulnerability. Just one study of medical facility vulnerability was found; it included an analysis of medical facility locations in 14 Pacific Island countries, including in FSM, the Republic of the Marshall Islands, and Palau.[104]

There is significant evidence in the international Pacific Islands region that the current and future projected impacts of climate change are negatively affecting peoples' mental health, although studies are lacking specifically in Hawai'i and the USAPI. Evidence also indicates that impacts are more severe for Indigenous Peoples because their central identity is tied to an ancestral place. Studies linking climate impacts directly to mental health outcomes point to strong differences in how mental health impacts are experienced among different populations.[105,239,240,241,242] There is general agreement on the benefits of tailoring mental health services for Pacific Islanders to the specific needs of the population, including different services for migrants who have voluntarily or non-voluntarily migrated.[237,243]

There is strong evidence of the high prevalence and impact on human health of vector-borne disease in the Pacific Islands. Recent data from 2014 to 2020 document 104 dengue, chikungunya, and Zika outbreaks across Pacific Island countries and areas.[246] Literature agrees that the viruses had unexpected virulence and epidemic potential[245,247] and that future climate-driven spread and emergence of vector-borne diseases the Pacific region is expected.[247,249]

Multiple lines of evidence demonstrate the impacts of high and extreme temperatures on human health.[220,459] Substantial and growing evidence supports the disproportionate and acute effects of heat on vulnerable populations.[220] However, analysis of the burden of heat-related illness and death among specific populations in Hawai'i and the Pacific Islands is lacking.

Social and community adaptive capacity has a long history and broad disciplinary foundations, with many studies specific to Pacific Island countries and territories highlighting the importance of social capital, cultural norms, Traditional and Indigenous Knowledge, and women's voices in successful adaptation and disaster response (e.g., Bryant-Tokolau 2018;[260] Cinner and Barnes 2019;[460] Cohen et al. 2016;[461] McNamara et al. 2020;[321] Nunn et al. 2020;[462] Warrick et al. 2017[463]).

The literature on necessary adaptations for Pacific Island public health systems is relatively underdeveloped compared to the global literature on the topic. For example, a study of Organization for Economic Co-operation and Development countries' national-level public health adaptation found a diverse array of adaptations related to cross-sectoral collaboration, vertical coordination, and national health adaptation planning.[264] Two studies focus on needed adaptations in the Pacific Islands,[227,265] while the World Health Organization[267] produced national climate change and health vulnerability assessments to guide health system adaptation plans.

Major Uncertainties and Research Gaps

Trends and changes in climate extremes in the USAPI represent a current research gap. Studies that account for compound or cascading extremes can best inform planning. Extreme event attribution studies

for Pacific Islands and Hawai'i would improve confidence and understanding of the role of climate change in driving societal impacts from extreme weather and climate events. The region lacks site-specific vulnerability assessments for critical health infrastructure. Dynamic inundation models that include wave-driven flooding and future scenario planning tools for coral reef–protected shorelines can improve understanding of health infrastructure vulnerability.

Few studies specifically investigate climate change impacts on mental health in Hawai'i and the USAPI, which, given the evidence that effective interventions must be culturally appropriate and tailored, indicates a strong need for additional research. Few studies in the region specifically address the mental health impacts of climate-induced migration on displaced populations. New research can point to ways to build personal resilience to climate change among frontline workers and climate adaptation practitioners, a topic preliminary research has examined.[464]

Changes in climate are expected to exacerbate the increasing risk of vector-borne disease transmission throughout the region, and various species of invasive mosquitoes are already linked to outbreaks of Zika, chikungunya, and dengue. The ways in which climate change will affect disease emergence are complex and yet to be fully explored. Place-based surveillance to assess the association between climate factors and infections, as well as climate early warning systems for vector-borne disease, would help better understand and prevent epidemics.

Regional stakeholders have called for community-based approaches to research assessing climate change readiness. Such research may include assessments of community strengths and local knowledge, community-led pilot initiatives, and identification of priorities for climate resilience planning.[27]

Description of Confidence and Likelihood

There is *high confidence* that warming temperatures, impacts from tropical cyclones, food and freshwater insecurity, and flooding are already negatively impacting human health in the Pacific Islands region. This is based on agreement among multiple lines of evidence, including peer-reviewed publications and reports and national and regional government reports, that show increases in heat-related illness and vector-borne diseases, damage to critical infrastructure, and psychological stress. Documented impacts to critical electric, medical, and transit infrastructure provide evidence that healthcare services have been compromised, although formal assessments of regional healthcare infrastructure are lacking, resulting in an assignment of *medium confidence*. Data linking local climate impacts such as drought and flooding with negative direct and indirect health outcomes in different communities in the international Pacific Islands demonstrate that there is *high confidence* that these impacts have worsened existing health inequities in both physical and mental health across the region. Based on current scientific consensus, there is *very high confidence* that the drivers of the negative impacts of climate change, such as high temperatures and SLR, are expected to worsen in the future. Meta-studies show that examples of health and disaster adaptations and recovery that center Indigenous ways of knowing and social cohesion have had success in the region, and there is *high confidence* that expanding these activities will increase resilience.

Key Message 30.3

Rising Sea Levels Threaten Infrastructure and Local Economies and Exacerbate Existing Inequities

Description of Evidence Base

The finding that climate change, especially SLR, will continue to negatively impact buildings, infrastructure, and the built environment is based on future projections of SLR (App. 3) encompassed in a suite of scenarios that include physical and socioeconomic factors from Sweet et al. (2022).[65] Available literature agrees that wave-driven flooding and high sea level events and associated inundation will continue to increase in frequency and severity.[98,218,219,465] There is scientific consensus that tropical cyclone (TC) intensity is increasing globally with warming.[70,216] One study of TC changes shows a likelihood of fewer but possibly stronger storms (increasing maximum intensities) in the northwestern Pacific.[53]

Mycoo et al. (2022)[89] have extensively documented the impacts of SLR, heavy rain events, TCs, and storm surges on the coastal built environment and rural communities on small islands. The primary sources of economic data for Freely Associated States are the Asian Development Bank, the World Bank (2022b);[22] United Nations, and the CIA World Factbook economic impact (costs) studies. Population figures and trends for American Sāmoa, the Commonwealth of the Northern Mariana Islands, Guam, and Hawai'i are from the US Census.[19,20,21]

Major Uncertainties and Research Gaps

Wave run-up models incorporating Sweet et al. (2022)[65] SLR scenarios are not yet available. Needed for the development of wave run-up models are high resolution elevation and water depth data (topobathymetric information), which are currently lacking for many Pacific Islands.

The amount and timing of future SLR experienced across the region is a key area of remaining uncertainty. There is uncertainty in the physical processes—particularly marine ice sheet instability and marine ice cliff instability—that could lead to rapid ice mass loss over a period of several decades (KM 3.3).

There is uncertainty in the effectiveness of migration as a climate change adaptation strategy, as the outcomes are dependent on individual situations and there is limited evidence in the literature.[69,89,466,467,468,469,470,471] Anthropological and population geography literature (e.g., Connell and Brown 2005[293]) for Micronesia establishes that past and present migration was an adaptation strategy associated with resource scarcity and that, historically, migrants traveled for economic and educational reasons.[472] There is limited current empirical evidence of migration that includes historical records of disaster-driven displacement; projections of displacement are also not available.

There is a gap in the literature examining the linkages between climate change, transport, and tourism, as well as the impacts of ecological change and heat on tourism demand. Future economic losses and impacts to livelihoods due to climate change–driven invasive species distribution shifts are understudied. For example, recent coconut rhinoceros beetle (CRB) invasions in Guam and Hawai'i and impacts on coconut palms have led to economic losses and declines in aesthetic value and have threatened food security.[473] Increased invasion of CRB following strong tropical cyclones is apparent,[474,475] but the specific interactions between climate factors and invasions are not yet well studied. The invasive brown tree snake on Guam has caused billions of dollars in damage to infrastructure[476] and causes up to 200 electrical blackouts per year,[477] adding stress to Guam's electrical grid, which is already facing compound climate stressors; the economic costs of species invasions in a changing climate are likely underestimated.

More guidance is needed on how equity, inclusion, and justice can be embedded in decision-making across the diverse governance arrangements in the region.[478]

Research on nature-based solutions has improved considerably,[322,479,480] although there is limited research evaluating the benefits, economic efficiency, and long-term effectiveness of these solutions.[89,481,482] Recent literature has examined the effectiveness of protection services that mangroves provide, which has important implications for long-range adaptation planning on islands (e.g., Saintilan et al. 2020;[355] Sasmito et al. 2016;[483] Zeng et al. 2021[484]).

Description of Confidence and Likelihood

It is *very likely* and there is *high confidence* that SLR will continue to damage the coastal built environment in the Pacific Islands region. This is documented by multiple lines of evidence, including peer-reviewed literature, planning documents, models, and government reports analyzing flooding, erosion, and wave impacts on coastal infrastructure across the region.

It is *very likely* and there is *high confidence* that climate impacts, including SLR, drought, and storms, will impact key economic sectors, such as tourism and fisheries. These likelihood and confidence assignments are based on peer-reviewed literature, strategic planning documents, development bank reports, and government reports detailing the projected impacts on and understanding of the behavioral, logistical, and biological features of these economic sectors.

There is *high confidence* of the potential for loss of territory and maritime entitlements, particularly in low islands, based on models, reports from governments, international financial institutions, and international meetings.

It is *likely* and there is *medium confidence* that climate-driven changes will exacerbate existing social challenges, thereby disrupting livelihoods. Evidence related to livelihoods disruptions under future scenarios remains sparse and will vary across contexts, thus the assignment of *medium confidence*. *High confidence* in the higher costs of adaptation and disaster recovery in islands is based on various factors that characterize islands, including geographic isolation (e.g., ASCE 2020[224]), reliance on imported materials and labor, vulnerable infrastructure, and sensitive ecosystems.

Key Message 30.4

Responses to Rising Threats May Help Safeguard Tropical Ecosystems and Biodiversity

Description of Evidence Base

Based on consensus across the cited literature and the latest available climate projections, there is *high confidence* across all future scenarios that deteriorating climate conditions will continue to threaten regional ecosystems and biodiversity throughout the this century (e.g., Buffington et al. 2021;[86] Eakin et al. 2019;[61] Fortini et al. 2015;[93] Gove et al. 2022;[62] Jacobi and Warshauer 2017;[354] Kwiatkowski et al. 2020;[60] Liao et al. 2015;[94] Lotze et al. 2019;[331] Reynolds et al. 2015;[356] Palacios-Abrantes et al. 2022[83]).

Projections of how physical changes will affect ecosystems come from a range of approaches: ecosystem and food web modeling, statistical modeling, and extrapolations from change already observed. Despite the data inequities present across the region (Box 30.1), there are multiple observations documenting past and ongoing changes in marine and terrestrial ecosystems and their physical environments (e.g., Dendy et al. 2022;[229] Judge et al. 2021;[414] Raymundo et al. 2019[334]).

Major Uncertainties and Research Gaps

The adaptive capacity of organisms and ecosystems in the face of climate change remains uncertain. For example, there is uncertainty about the plankton community's response to climate change, which will influence the effect of climate change on higher-trophic-level organisms such as those targeted by subsistence, commercial, and recreational fisheries. Ecosystem response to simultaneous stressors and novel climate conditions is a complex subject area with high uncertainty. The effects of climate change on fish stocks outside the EEZs are underexplored.

While regional climate projections and historical climate analyses for Hawai'i have been developed, similar sets of studies for USAPI are much more limited, lowering our confidence in projected terrestrial impacts of climate in other US-affiliated jurisdictions (e.g., future wildfire probabilities).[376] This gap in available climate data and projections is paralleled in the Caribbean region (KM 23.2), indicating a broad uncertainty for the future of our Nation's island areas.

The impacts of extreme events on Pacific Island terrestrial ecosystems are still poorly studied given the limited data to characterize past and current events and project future shifts in intensity and frequency of such events. These uncertainties in extreme event impacts on island ecosystems are similar to those identified in the Caribbean chapter (see Traceable Account, KM 23.2), highlighting a common challenge faced by underserved island areas.

The societal response to regional climate impacts can have a large impact on surrounding ecosystems and is also a major area of uncertainty.

Description of Confidence and Likelihood

There is *high confidence* and it is *very likely* that the structure and composition of Pacific Island coastal and marine ecological communities are directly threatened by ocean changes. This assessment is based on similarities across climate scenarios through the mid-21st century, as well as on the degree to which climate conditions have already impacted regional ecosystems and biodiversity, and given species-specific climate and habitat tolerances.

Fire is already a substantial challenge to Pacific Islands (Figure 30.13),[229,378] with risks expected to rise under additional warming and drying (*high confidence*).[376] A wide body of literature links increasing droughts and temperatures to increased fire risk (Chs. 7, 8).

Regarding native plants, climatic shifts have already been shown to influence plant communities, from broad landscape shifts to individual species population trends (*very likely*, *high confidence*).[364,365,366,370] Future projections indicate continued and drastic effects.[93,367] Regarding forest birds and other wildlife, the link between forest bird declines in Hawai'i and warming is clear,[414,415] with underlying mechanisms well understood.[485,486] These declining trends are consistently projected to continue under additional warming (*very likely*, *high confidence*).[93,94]

There is *medium confidence* in the ability of certain adaptation strategies to improve the resilience of Pacific Island ecosystems. Ecological restoration efforts and invasive species prevention, eradication, and control enhance regional climate resilience and provide multiple benefits to islands (e.g., KM 8.3; Barbosa and Asner 2017;[398] Bremer et al. 2018;[202] Ferrario et al. 2014;[289] Wada et al. 2017[401]), including helping to reduce water stress and fire risk (e.g., KM 8.2; Dudley et al. 2020;[388] Fortini et al. 2021;[380] Strauch et al. 2017;[148] Trauernicht 2019[376]). However, due to the uncertainties in regional projections and climate and invasive species interactions, there is *medium confidence* in restoration and invasive species control efforts. The establishment and management of protected areas are also widely considered effective components of ecological adaptation strategies,[119] but large climatic shifts may reduce their effectiveness over time,[399] leading to *medium confidence* in their long-term effectiveness. Fire management strategies have been shown to be quite

effective across the Pacific Islands region.[125] However, the effectiveness of these strategies under extreme fire conditions is expected to be reduced (e.g., atypically high wind and dry conditions), thus *medium confidence*.

Key Message 30.5

Indigenous Knowledge Systems Strengthen Island Resilience

Description of Evidence Base

There is no doubt that fostering reciprocal relationships between people, place, and cultural and historical sites across Hawai'i and the USAPI is central to the ongoing adaptation of island communities to the changing climate (e.g., Diver et al. 2019;[430] Nunn et al. 2017[87]). However, these types of relationships are usually documented in an oral rather than written format. For the most part, there is agreement that the culture of Indigenous Peoples influences their interpretation of the value of place and ecosystems and, subsequently, their resilience to climate change. The studies cited in this section use the Intergovernmental Panel on Climate Change (IPCC) Fifth Assessment Report CMIP5 results for temperature, rainfall, and SLR to assess impacts on traditional foods and cultural resources.[118,434,442]

Major Uncertainties and Research Gaps

Research that assesses the impacts of climate change (SLR, temperature, etc.) on cultural resources and historical sites is limited and largely focused on Hawai'i. Many of the studies that assess climate-related impacts to cultural resources were published prior to the release of the updated IPCC Sixth Assessment Report and NOAA's updated SLR projections. There is limited information on how climate change–driven shifts in the distributions of invasive plants and animals may disrupt cultural services and familial relationships (e.g., Brewington et al. 2023[359]).

Description of Confidence and Likelihood

Literature focused on community and place-based approaches to natural resource management supports that there is *high confidence* that Indigenous Peoples of the Pacific Islands, their knowledge systems, and their rituals are central to local climate resilience. Literature also supports that there is *high confidence* that reciprocal and spiritual relationships among people and place are being strengthened through adaptation and collective management of resources.

There is *high confidence* that the application of future climate scenarios has enabled the collective efforts of Indigenous researchers, stakeholders, and scientists to begin to identify and quantify the potential loss and migration of critical resources and expand the cultivation of traditional food crops on high islands. However, such assessments are limited in scope across Hawai'i and the USAPI, and as a result the impacts of climate change on cultural resources are still identified as a major gap in knowledge.

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Fifth National Climate Assessment: Chapter 31

Adaptation



Chapter 31. Adaptation

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Introduction

Changes in the climate have been observed and experienced across every region of the United States (Ch. 3). Chronic changes such as increasing temperatures, sea level rise, and changing precipitation patterns are affecting the frequency and intensity of diverse extreme weather events. These changes directly impact many millions of people and ecosystems (Ch. 2)[1] and are projected to increase in the future. Adaptation is essential for human and ecological survival in this rapidly changing, complex, and interconnected world.

Adaptation refers to actions taken to reduce risks from today's changed climate conditions and to prepare for further impacts in the future. It includes diverse activities designed to reduce climate-related risks and increase capacity to prepare for climate impacts (Table 31.1). Actions taken to adapt to climate change often provide major opportunities to create a healthier and more resilient future for generations to come. Through these actions, billions of dollars can be saved by investing now and avoiding future losses, new jobs can be created, innovative solutions can be realized, and productivity and efficiencies can be increased across all sectors. Done well, adaptation can protect human lives, improve quality of life, enhance social equity, reduce healthcare costs, and safeguard and restore the natural ecosystems on which society depends for its very survival.

The various risks driven by climate change are extensive, diverse, and intensifying, and they interact with complex social, geographic, economic, and political contexts to exacerbate underlying stresses in overburdened and frontline communities. These communities already experience disproportionate impacts of climate change, and these impacts will only increase over time if equitable adaptation actions are not taken now (KM 31.2). The loss of biodiversity and ecosystem services, the displacement of people due to rising sea levels and more frequent extreme weather events, the loss of natural resources, the increased demand on the aging energy grid and critical infrastructure, and many other challenges will only get worse if society does not transform the way it tackles climate change in the US today.

The urgency for climate adaptation is clear and very well documented.[1,2,3,4,5] The benefits of climate adaptation can be immense and felt by everyone if advanced and scaled sufficiently in relation to the pace of climate change (KM 31.1), if equity is centered from the start (KM 31.2), and if both transformative and incremental adaptation actions are taken now (KM 31.3). Transformative adaptation aims to reduce risks through fundamental shifts in systems, values, and practices. Equitable adaptation intentionally incorporates recognitional, procedural, contextual, and distributional principles of equity in design, planning, and execution. Equitable adaptation addresses the disproportionate effects of climate change for overburdened and frontline communities. It dismantles barriers, considers underlying stresses, creates opportunities, and enables learning through iterative evaluation and sustained engagement.[6]

Effective adaptation governance needs to empower all voices to navigate (e.g., discuss, weigh, and prioritize) competing goals in a collaborative manner (KM 31.4), and adaptation-related services need to go beyond the traditional offerings of science, data, and information to be more accessible and to meet the needs of overburdened and frontline communities (KM 31.5). Adaptation finance and investments will be needed to scale, support, and implement adaptation, and systems will need to be developed to adequately track and evaluate the effectiveness of these investments (KM 31.6). In brief, widespread and dedicated adaptation efforts will be essential for securing a sustainable and prosperous future for all.

Table 31.1. Example Climate-Related Adaptation Actions

This table provides examples of incremental and transformative actions being implemented at various scales across US regions and sectors and by various actors to adapt to a range of different climate hazards. See cross-references to other chapters for more detail on certain adaptation actions. The "action" categories in this table have been adapted from Biagini et al. 2014, Hicke et al. 2022, and GCC 2022.[1,7,8]

Action	Description
Capacity Building	Community building (KM 23.5); interdisciplinary public education, literacy, and outreach at all age levels; trainings (KM 21.4) and workshops; knowledge and skill development; technical assistance; dissemination of decision-useful information; equitable partnerships (KM 24.5); sharing best and leading practices; local groups and coalitions to assist communities (KM 25.5)
Early Warning and Observing Systems	Developing, testing, and deploying monitoring and observing systems; early warning systems (e.g., for heat, famine, drought, wildfire); strategic foresight; upgrading weather or hydrometeorological services
Financing	Insurance (KM 21.5); microfinance; funding; investments; grants; contingency funds; environmental impact bonds (KM 21.4); land trusts (KM 21.5); equitable availability and accessibility of capital before and after disasters (KM 31.6); community-based public–private partnership (KM 24.4)
Physical Infrastructure	Coastal accommodation; ecosystem-based adaptation; minimizing ecosystem stressors; restoration or creation of natural areas (KMs 23.5, 31.4); revegetation; afforestation woodland management; increased landscape cover; natural coastal embankments; floodable parks and parking structures; flood mitigation (Box 22.1; KM 24.4); urban flood management (KM 31.4); stormwater management (KM 21.4); retention and detention ponds; "living" roofs; rain gardens; green space (KM 21.3); building or retrofitting infrastructure to withstand future climate change (KM 31.5); water capture and storage; water supply and distribution; infrastructure for health services; improvements to water and sanitation infrastructure; adaptive buildings; reservoirs for water storage; irrigation systems (KM 31.3); canal infrastructure; seawalls; solar infrastructure for electrification; restoration of native species diversity; increase in structural diversity (e.g., variation in age structure; KM 24.2); air conditioners (KM 21.1); cooling centers (KM 31.2); sustainable development (KM 23.5)
Information	Decision support tools (KM 21.1); data analytics; public reporting and disclosures; visualization tools; data acquisition efforts; digital databases; remote communication technologies; climate hazard, vulnerability, and probabilistic mapping tools (KM 21.1); collaboration and coproduction of data and information (KM 24.2); toolkits (KMs 21.1, 31.5)
Management and Planning	Scenario-based planning (KM 25.5); spatial planning; incorporating climate change and adaptation into planning (e.g., hazard mitigation plans), design standards, management, and decisions (KM 21.1); collaborative adaptation planning at multiple scales (e.g., federal, regional, state, territorial, Tribal, local, organizational [public and private]); assessing underlying conditions and needs (KM 21.4), risks (KM 23.5), adaptive capacity, and options; adaptive management; cooperative governance (KM 31.4); cultural adaptation; regional collaboratives (KM 31.4)
Policy	Law and governance (KMs 21.3, 23.5); local climate policy (KMs 21.3, 23.5, 27.1); revised design parameters, adaptive building codes, and integration of future climate projections into codes and standards (KMs 12.3, 31.5); creation of new policies or revisions of policies or regulations to allow flexibility to adapt; mainstreaming adaptation into development policies; improvement of water resource governance
Practice and Behavior	Institutional change; changes to diets and food waste; diversification of livelihoods and income sources; adaptive farm, fishery, or livestock practices (Box 29.5); improved crop varieties; food storage, distribution, and security; disaster risk reduction; permanent migration, planned retreat, or relocation (KMs 21.3, 24.4); seasonal or temporary mobility; social safety nets and cohesion; adaptive social protection; water use and demand; soil or land management techniques; post-harvest storage; rainwater collection; expanding integrated pest management; strategic coastal retreat (KM 9.3); land protection; changes in transportation habits; improved public health (KM 23.5)
Technology	Developing new or expanding existing technologies to enable and advance adaptation; water use or water access improvement technologies; solar energy capacity; wind power; energy storage; biogas; water purification; solar salt production; microgrids; artificial intelligence and machine learning

Key Message 31.1

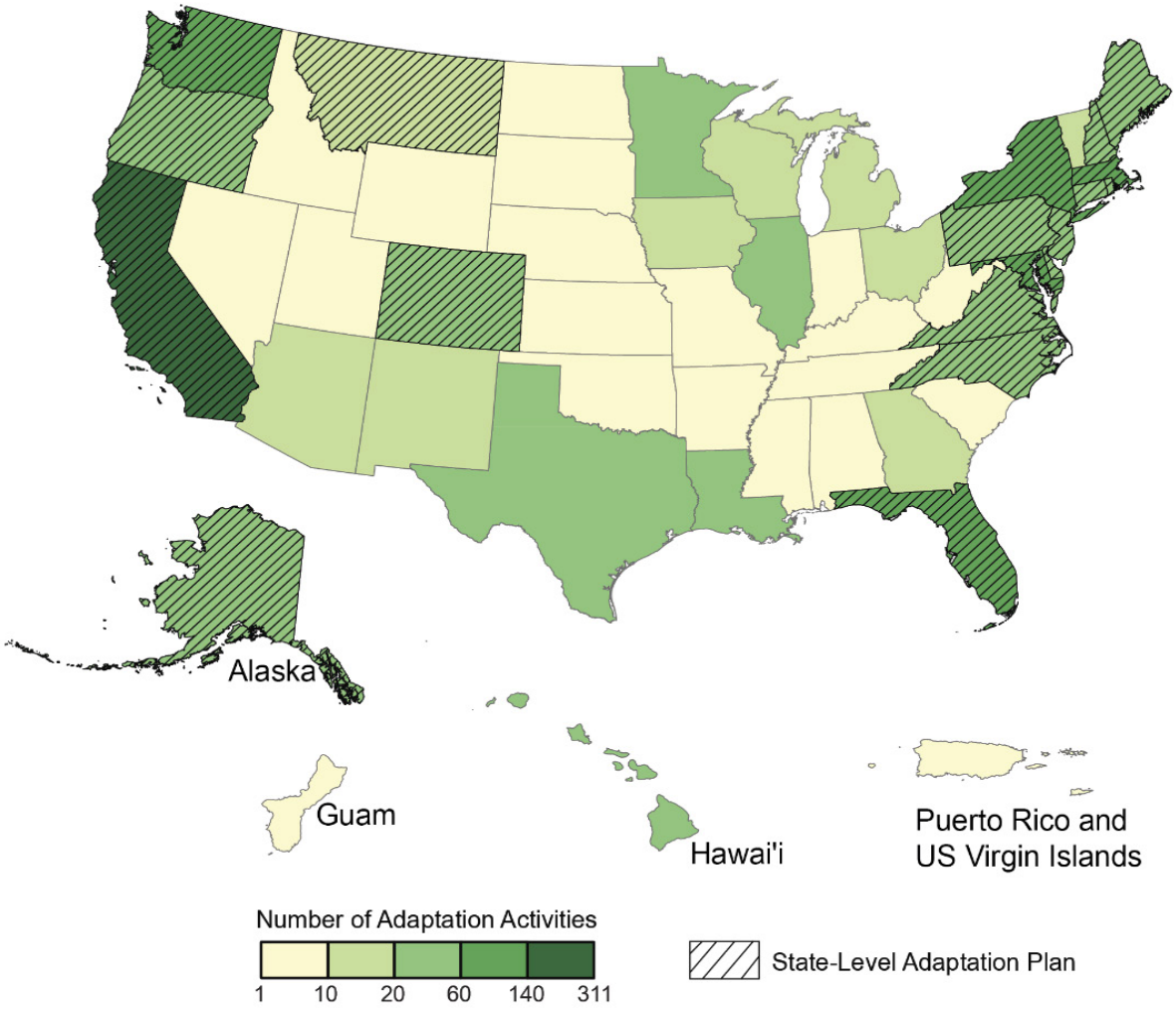
Adaptation Is Occurring but Is Insufficient in Relation to the Pace of Climate Change

Diverse adaptation activities are occurring across the US (*very high confidence*). Adaptation activities are increasingly moving from awareness and assessment toward planning and implementation (*medium confidence*), with limited advancement toward monitoring and evaluation (*high confidence*). Numerous social, economic, physical, and psychological barriers are preventing more widespread adoption and implementation of adaptation (*high confidence*). Current adaptation efforts and investments are insufficient to reduce today's climate-related risks (*high confidence*) and are unlikely to keep pace with future changes in the climate (*medium confidence*).

Actors, stakeholders, and rights-holders (hereafter actors)—from individuals and organizations to companies, communities, and government entities across all levels, regions, and sectors—are already investing in adaptation measures (Figure 31.1) to reduce the harms caused by climate change and leverage new opportunities to enhance their ability (or capacity) to adapt.[9,10,11,12,13,14] The extent, type, and stage (Box 31.1) of these activities vary regionally and across sectors (Figure 31.1; Chs. 4–16, 21–30). Adaptation has increasingly progressed from the awareness and assessment stages toward planning and implementation (Box 31.1). However, few adaptation activities advance monitoring or evaluation.

To date, adaptation across the US has been incremental in nature, and given the expected future pace of climate change, more action is needed at greater rates and larger scales, across more sectors, and in context-specific ways.[1,15,16,17,18] Historically, actions to adapt often have not centered equity (KM 31.2) and were not designed using a systems-oriented, regional, or collaborative approach for transformation (KM 31.3). Adaptation lacks the attention, investment, financing, and monitoring needed to prepare for both acute and chronic climate impacts (KM 31.6).

Number of Publicly Documented Adaptation Activities (2018–2022)



The level of documented public- and private-sector adaptation activity varies widely across US states and territories.

Figure 31.1. This figure illustrates the number of public- and private-sector adaptation activities—see examples offered in Table 31.1—publicly documented and/or updated since 2018. There are several states that have publicly documented numerous adaptation activities, while others have very few or have not documented the activities. Figure credit: WSP, University of Delaware, and University of California, Irvine. See figure metadata for additional contributors.

Box 31.1. Evidence of Adaptation Occurring Across the Five Adaptation Stages

Adaptation actions are generally categorized into five stages, from raising awareness to implementation and evaluation.[4,19] Evidence of action exists along the five adaptation stages at varying scales and levels.

Stage 1: Awareness and Engagement

American adults understand that climate change is happening (72%).[20] However, they have low risk awareness (e.g., they underappreciate how severely climate change might affect themselves and society) and lack a clear understanding of adaptation and its importance (KM 31.2).

Stage 2: Assessment

Approximately 40% of US states have assessed their climate change risks.[8] Of US-based companies disclosing through CDP (formerly the Carbon Disclosure Project), 88% have assessed their climate-related financial risks in alignment with the Task Force on Climate-related Financial Disclosures (KM 31.6)[21] and, if material, disclosed such risks in their financial statements. Assessments of adaptive capacity (the potential of a system to adjust to climate change) and climate resilience have progressed but lag assessments of climate risks, raising concerns that some actors, including local governments, may be ill-equipped to prepare for climate change. There is an increase in the number of publicly available datasets and tools to inform assessments, as well as use of Traditional Knowledge and climate storytelling.

Stage 3: Policy and Planning

Many governments and organizations have individual sustainability, resilience, or adaptation plans (Figure 31.1). Eighteen states have climate adaptation plans, and another six states have plans underway. Thirty-two states lack a public adaptation plan, a select few US-based companies have disclosed adaptation-related actions they are taking, and very few jurisdictions have adaptation plans co-designed between the private- and public-sectors. Across jurisdictions, plans are developed for different reasons (e.g., climate impacts, investor requests, regulatory requirements) and rarely in a coordinated, collaborative, or regional manner.[22,23] As required in Executive Orders 14008 and 14057, more than 20 federal agencies have prepared and updated climate adaptation plans.[24] Funding and implementation of adaptation plans remains moderate or low (KM 31.6).[1,25] Climate adaptation–related congressional legislation is becoming more prevalent, but it is often embedded within other topics (e.g., infrastructure, disaster relief, water). Federally funded opportunities remain untapped and inaccessible to overburdened and frontline communities.[26]

Stage 4: Implementation

Implementation of adaptation actions has made some progress. However, most actions have been incremental in nature; have focused on acute extreme weather events rather than systemic, chronic climate change; and/or involve small infrastructure changes to business-as-usual activity, such as changing irrigation systems or expanding stormwater pipes to withstand increased flooding.[1,15] Current levels and types of adaptation being implemented are insufficient to deal with future climate change.[1,15,27,28]

Stage 5: Monitoring and Evaluation

Adaptation researchers and practitioners are starting to track the number of actions, assess the adaptation effectiveness of those that have occurred, and evaluate the long-term sufficiency of adaptation projects. However, frameworks, monitoring, indicators, and evaluations that assess adaptation practices, co-benefits, equality, and implementation at appropriate levels of granularity are still under development.[1,29,30,31,32,33,34,35] Research is focused on evaluating adaptation-enabling governance structures and barriers to adaptation.[36,37]

Evidence of Adaptation Barriers

Although adaptation is occurring across the US, barriers remain. These barriers can mostly be overcome with financial, cultural, technological, legislative, or institutional changes.[38,39]

There is growing divergence in the ways government, private industry, and civil society are planning for climate adaptation, with each focusing on a subset of climate vulnerability—disaster resilience, risk and liability, and equity and justice, respectively[40]—and individual climate hazards (e.g., sea level rise, flooding, heat), instead of compounding and complex events (Focus on Compound Events). This incoherence increases the potential for investments that may unintentionally exacerbate climate-related risks or overlook the need to target adaptations for frontline communities that experience a plethora of compounding issues (both chronic and acute), creating greater societal vulnerability to climate impacts (KM 31.3).[41] It is also important to distinguish between *planning* for adaptation and *actually* adapting; there is still more of the former than the latter. The ability to adapt is uneven and inequitable: communities or businesses with means, wealth, or access to resources are more able to adapt, while those with fewer means or opportunities are less able to adapt. The gap between planning and action could also be due to the ease of tracking adaptation plans compared to tracking evidence of systems, people, or environments that are adapting, which can take years to show progress.[1] With the lack of consistent tracking and evaluation of adaptive capacity and how effectively society and ecosystems are adapting to climate change, it is challenging to measure progress, continually improve, and understand the overall impact of adaptation actions and investments.[42]

Adaptation is routinely limited by a range of political, structural, psychological, and normative barriers.[1] Few regulatory requirements focus directly on adaptation.[26] Existing environmental and disaster policies, frameworks, and governance systems are ill-suited to handle the long-term, widespread, transformative changes needed to adapt to climate change; tend to be reactive rather than proactive; and assume fixed rather than dynamic environments.[43,44,45]

Methodologies and tools to assess climate risks, adaptive capacity, and adaptation options are lacking in transparency or are nascent (KM 31.5). While there are many datasets and tools to inform adaptation, their usefulness for decision-making remains uncertain.[46] Resources remain constrained and dispersed when it comes to assessing climate change and adaptation.[43,44,47,48] There is a lack of clear pathways for sharing datasets and tools among multiple actors and jurisdictions (KM 31.4) and a lack of streamlined and transparent processes for integrating local and Traditional Knowledge. The inherent time lag in the scientific peer-review process of science and assessments does not allow for progress to be made swiftly.

Competing values and goals held by diverse public entities and organizations and differentiated responsibilities across levels of government or types of organizations create challenges in developing shared goals (KM 31.4).[44,45,48] The lack of coordination across government agencies at all scales and with diverse actors creates a fragmented and ineffective adaptation governance system.[47,48,49,50,51] The continued reliance on fossil fuel economies discourages transition and economic diversification,[52,53,54] limiting collaborative planning with these high-emitting industries.

Justice and equity are rarely centered in adaptation activities by all sectors and actors (public and private; KM 31.2).[55] In many settings, there is not a widely accessible forum for local participation, particularly of Indigenous communities living in remote and vulnerable locations. Social hierarchies and structures can prevent overburdened groups from sharing their opinions, preventing achieving equitable adaptation. Frontline communities are hit first and worst by climate change, and oftentimes adapting to climate change may not be their immediate concern. Intentionally centering equity in adaptation solutions in partnership with frontline communities has the potential to improve some systemic issues such as inequality, discrimination, and limited access to essential resources and opportunities (KM 31.2).[56]

Finally, there remains a minimal degree of investment and funding for adaptation. As for the funding that is available, communities with the highest climate vulnerability do not have adequate and equitable access to these funds (KM 31.6).[43] Organizations often do not understand potential returns on investment in adaptation, so there is less appetite for expensive measures (KM 31.6).[57]

Key Message 31.2

Effective Adaptation Requires Centering Equity

People and communities are affected by climate change in different ways (*very high confidence*). How people and institutions adapt depends on social factors, including individual and community preferences, capacity, and access to resources (*very high confidence*). Adaptation processes, decisions (about whether, where, and how adaptation occurs), and actions that do not explicitly address the uneven distribution of climate harms, and the social processes and injustices underlying these disparities, can exacerbate social inequities and increase exposure to climate harms (*high confidence*).

Climate adaptation that responds to people's values, concerns, and priorities requires not only identifying disparities in how people are affected by climate change but also understanding the underlying causes and conditions of climate vulnerability. Vulnerability (predisposition to adverse impacts) is shaped by interactions across physical, social, and ecological processes (Chs. 3, 20).[58] The places most vulnerable to climate change share traits of high *exposure* to climate change and climate hazards (e.g., long-term water scarcity and extreme drought), high *susceptibility* to adverse impacts, and constraints on *capacity* to adapt.[1] The specific mechanisms that produce vulnerability vary from place to place and over time; are shaped by historical racial, ethnic, gender, and socioeconomic inequalities (Chs. 16, 20);[59] and are sensitive to climatic and demographic change in the future.[60]

Inequalities in social, economic, and political power and resources[61] mean that populations marginalized by society and underserved by government or private-sector systems often face disproportionately worse effects of hazards. For example, higher proportions of Native American, Hispanic, Asian and Pacific Islander, and African American populations live in places prone to extreme wildfire, heat, floods, and permafrost thaw.[62,63,64,65,66,67] Such differential exposure often results from historical injustices such as housing discrimination, forced displacement, social exclusion, lack of investment in hazard mitigation, and lack of provision of other social services by government or the private sector (e.g., insurance, mortgage lending).

Uneven patterns of climate hazard exposure are well documented. Recent work is helping to untangle context-specific processes through which the geographic distribution of climate hazards and social inequality interact to shape local experiences of vulnerability (Ch. 20). Examples include illuminating how disaster damage exacerbates long-term wealth inequality,[68] how disaster assistance distribution policies and differential access constrain recovery outcomes,[69,70] and the influence of racial and economic privilege in flood buyout programs.[71,72,73] Greater understanding of the complex human drivers of climate vulnerability can illustrate how and why transformative adaptations may be required (see KM 31.3) to address interlocking social processes and to remedy vulnerability at its roots (Ch. 20).[40] This improved understanding reinforces why effective adaptation extends beyond cost efficiency and technocratic concerns to intentionally incorporate equity and environmental justice principles.[18,74] Effective adaptation that centers equity is needed to address disparities in the causes and effects of climate risks, dismantle barriers, and create opportunities for all people to thrive.

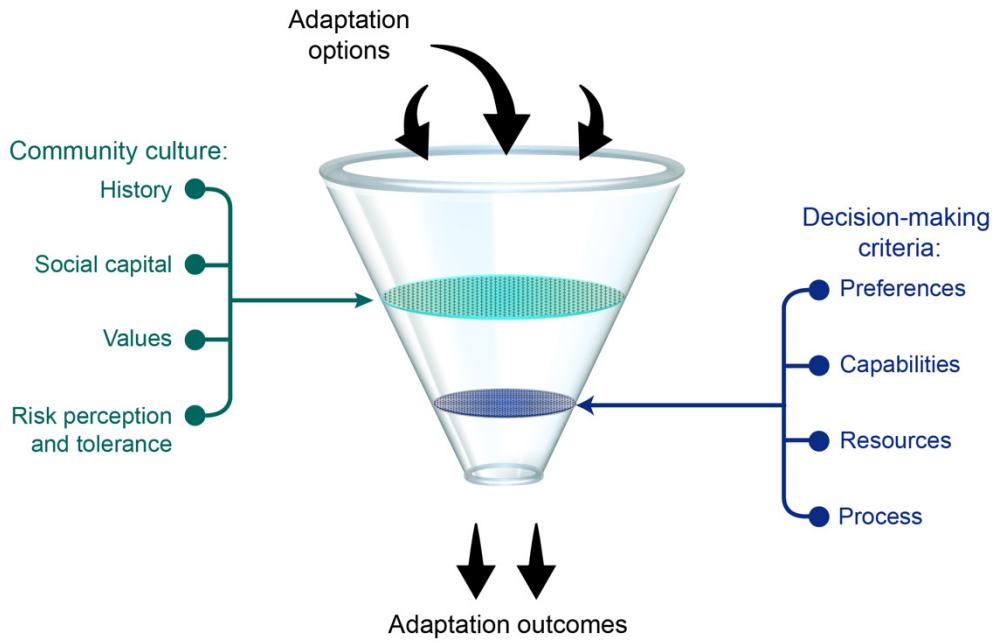
Whether, when, and how people adapt to climate change depends on complex geographic, political, economic, social, and cultural contexts (Chs. 18, 20; Figure 31.2). The ability of individuals and institutions to engage in adaptation is affected by their access to resources, which is unevenly distributed and mediated by factors such as income, race, ethnicity, and gender.[72,75,76,77,78] Factors such as citizenship status and land ownership can create administrative hurdles.[79,80] Federal or state resources for adaptation are often available to individuals, communities, and Tribes only if they navigate bureaucratic systems or succeed in competitions. Equity concerns arise when the system privileges those who already have resources—time, English-language skills, personnel, power, and/or funds to acquire adaptation resources.[68,81,82] Rural or less populous towns, for example, may have fewer professionals to dedicate time to grant applications, fewer resources to meet federal cost-share requirements, or difficulty in proving that adaptation would be cost effective (Ch. 11; KMs 11.3, 31.6). Private-sector adaptation resources are similarly more available to some people than others, as when insurance companies cease to offer wildfire insurance in some risk-prone areas.[83]

Social factors—including place attachment, identity, social capital, and perceptions of what is fair and effective—influence the adaptation actions people are willing and able to pursue.[84,85,86,87] Risk perceptions and risk tolerances are influenced by social factors such as experience, culture, and demographics, and increased risk awareness alone does not predict increased adaptation.[88,89] For example, a survey of Puerto Rican farmers found that half did not engage in adaptation even though they perceived themselves to be at risk and to be capable of taking action.[89] A survey of homeowners in North Carolina found that knowledge of climate change and its risks had no effect on the adaptation actions taken.[88]

Geographic, political, economic, social, and cultural contexts also influence how people adapt (Figure 31.2). Different types of adaptation actions reduce risk to different degrees and in different ways, cost different amounts, have different downsides, and benefit and harm different groups.[90,91,92] Individual and community values, circumstances, and priorities shape which benefits are considered most important, which trade-offs people are willing to endure, and what opportunities they are willing to forego. For example, building seawalls can disconnect communities from the water, which may affect their place attachment, recreational and economic amenities, sense of identity, local ecosystems, and long-term risk profile, while providing short-term gains in safety and property values.[93,94] Culture, heritage, and traditional ties to the land influence adaptation preferences[95,96] and can be important sources of motivation and guidance, especially for locally led adaptation efforts.[97] People may disagree about the goals of adaptation and their preferences for trade-offs, values, or risk tolerance levels, and how these disagreements are handled within a community or institution further shapes adaptation practices.

Participatory processes create space for people to discuss goals, values, social factors, and resources and are a necessary element of participatory justice, which holds that those affected by decisions should be involved in the decision-making process. Such processes benefit from practices that facilitate participation, such as convenient meeting times, language translation, and provision of transportation, food, and childcare. To more deeply embed equity, participatory processes designed to stunt power imbalances—such as those featuring transparency, information access, and opportunities for substantive influence—are most likely to represent the full range of people affected by a decision.

Adaptation Actions Defined by Multiple Factors



Adaptation outcomes are the result of individual and group values and decision-making processes and constraints.

Figure 31.2. The path from potential adaptation options to adaptation outcomes is filtered through culture and decision-making criteria, processes, and resources. Individual traits, circumstances, and preferences mean that adaptation outcomes are not identical for all members of a community. These social factors may create, perpetuate, or exacerbate existing social inequities in a systemic fashion, such that even passive actions can produce inequitable outcomes. Intentionally integrating equity into adaptation, which requires accounting for differences in access, capacity, and resources, can lead to more inclusive and sustainable outcomes. Figure credit: ICF, University of Delaware, and University of Iowa.

Failure to intentionally center equity—as in the distribution of resources, participatory processes, and recognition of local contexts—may unintentionally increase the vulnerability of people and places.[98] This is a type of maladaptation, in which efforts to address a climate vulnerability unintentionally increases vulnerability.[99,100] Maladaptation can occur, for example, if engineered infrastructure (e.g., levees) or disaster response programs create a false sense of security that incentivizes continued development in hazardous areas, which in turn produces higher losses in the event of system failure—a situation known as the safe development paradox.[101,102,103] Adaptation tailored to a specific context can become maladaptive if subjected to a different hazard type or context, as when crowded spaces in community shelters or cooling centers contribute to the spread of a pandemic.[104,105] Interventions advanced in the name of engineering adaptation may undermine ecological adaptation, and adaptation for some people (e.g., wealthy communities, homeowners) may lead to maladaptive outcomes for others (e.g., low- to moderate-income communities, renters). Given the potential for maladaptation to substantially redistribute or amplify risk, the topic would benefit from significant attention from practitioners and policymakers.[106,107,108]

Intentionally centering equity in the design, planning, and implementation stages of adaptation would require a paradigm shift. This shift would include asking a number of questions: For whom, with whom, and by whom would proposed adaptation actions be undertaken? Who would benefit and who would be burdened by these actions? Are steps being taken to lessen the burdens borne by underserved populations (Ch. 20; Figure 20.1)?[109,110] This type of proactive engagement from disadvantaged and frontline communities

would be especially important in transformative adaptations that may cause substantial social upheaval (KM 31.3). Accounting for intersecting identities and structural inequalities as organizing principles of adaptation planning could help produce adaptation actions that simultaneously mitigate the effects of climate change and address compounding social inequities.[111,112] Other strategies for equity-centric adaptation include prioritizing adaptation actions and assessing adaptation effectiveness based on satisfying the needs and preferences of the most vulnerable.[113] Adaptation equity and environmental justice involve multiple concepts, including recognition of how past injustices have contributed to current patterns of exposure and capacity, consideration of cultural values and norms, fair decision-making processes and distribution of resources, and efforts to redress past and current injustices.[95,108,114,115,116] Adaptation efforts that center equity and justice are best positioned to avoid perpetuating social injustices.[40,113,117]

The Justice40 Initiative[118] is an example of public policy that centers the redress of social inequity in adaptation. Justice40 defines investment focus areas of climate change, energy, health, transit, affordable housing, pollution reduction, water infrastructure, and workforce development. It calls for 40% of benefits from federal investments in these areas to occur in communities disadvantaged by historical marginalization, pollution hazards, and long-standing underinvestment. To identify disadvantaged communities, the White House Council on Environmental Quality developed an online geospatial application called the Climate and Economic Justice Screening Tool (CEJST). CEJST is primarily designed to be used by federal agencies[119] and could significantly shape the distribution of adaptation resources by the Department of Energy, Department of Housing and Urban Affairs (HUD), Federal Emergency Management Agency (FEMA), and other agencies. CEJST can also inform adaptation investment decisions by business and philanthropic organizations and raise public awareness of the social factors that shape climate vulnerability and adaptation.

Key Message 31.3

Transformative Adaptation Will Be Needed to Adequately Address Climate-Related Risks

Climate adaptation actions undertaken in the United States to date have generally been small in scale and incremental in approach, involving minor changes to business as usual (*very high confidence*). Transformative adaptation, which involves more fundamental shifts in systems, values, and practices, will be necessary in many cases to adequately address the risks of current and future climate change (*high confidence*). New monitoring and evaluation methods will also be needed to assess the effectiveness and sufficiency of adaptation and to address equity (*high confidence*).

Most adaptation efforts across a wide range of sectors across the United States have involved incremental adaptation: minor shifts in usual practices that affect small geographic areas and that have been limited in their ability to affect multiple sectors or hazards by technical, social, and economic barriers.[1,15,27,120] Although the performance of adaptation actions is difficult to assess, the available evidence suggests that many US adaptation practices are not sufficient to deal with either current or future climate change.[27,121] Future adaptation may require not only more adaptation efforts (more actions, scaled up, across a wider range of actors, sectors, and systems) but also more transformative adaptation: actions that involve persistent, novel, in-depth changes that shift the fundamental traits of institutions, behaviors, values, or technologies across multiple scales and sectors.[90,122,123] Transformative adaptation can involve changes to the built environment,

or it may involve fundamental changes in economic and governance paradigms to redress historical injustices and center equity and justice.[40]

Adaptation actions in the US more often involve using air-conditioning during heatwaves, increasing irrigation or temporarily reducing water consumption to address frequent droughts, using sandbags to resist coastal erosion, redefining fisheries boundaries in response to shifting habitats, or elevating homes above flood waters—rather than more transformative actions such as redesigning cities and buildings to address heat, shifting water-intensive industry to match new rainfall patterns, or directing new housing development to less flood-prone areas.[1,15,27,120,124] A range of cognitive biases sometimes make people favor incremental change, such as status quo bias (an inclination to preserve the current state even if changes would bring greater benefits).[73,125] However, preserving the status quo can perpetuate existing systems of inequality (KM 31.2).[116,126] Incremental adaptation has also been favored in part due to the framing of adaptation as a type of disaster risk reduction rather than long-term planning (e.g., response to hurricanes rather than permanent inundation due to sea level rise).[15,127,128,129] For instance, a national survey of metropolitan transit organizations found that most agencies rely on traditional emergency management approaches to address extreme weather during or after the event, rather than advance planning for such events and making changes to preemptively avoid harms.[130] Disaster risk reduction provides an important set of tools and frameworks, but responding to and preparing for permanent changes in climatic conditions requires a different set of approaches than reactively responding to extreme events or sudden hazards. In the long term, an overemphasis on incremental adaptation can lead to maladaptation, where efforts to address climate risk unintentionally increase risk.[99,100] A classic example is that using more air-conditioning to deal with rising temperatures and extreme heat events may increase fossil fuel consumption (if the electricity is generated from fossil fuels), contributing to more climate change and even higher temperatures.

Other incremental adaptation actions may displace risk,[131,132] such as when one home is elevated on a filled mound that pushes rain and floodwaters onto neighboring homes, or have unintended consequences, such as reducing motivation to engage in adaptation (KM 12.4). An emphasis on financially conservative "no regret" decision-making, which limits current costs and prioritizes adaptation options that would be justified under all plausible future climate scenarios, may lead to less expensive but less effective actions.[15,90] Local governments, individuals, communities, or businesses may have insufficient capital to cover the up-front costs of transformation even if those actions would produce long-term gains (KMs 31.5, 31.6). For example, in the short term, reducing agricultural water use through improved irrigation (an incremental change) is cheaper and easier than fundamentally reimagining how and where crops are produced, stored, and transported across the US (transformative change). However, improved irrigation may be insufficient to adapt to long-term effects of climate change and may be less cost-effective in the medium and long term than more transformative options.[27,121]

Climate change will cause both chronic shifts in baseline conditions—such as rising temperatures, sea levels, and water insecurity—and acute risks through extreme events and increased variability (Chs. 2, 3), and these effects will interact with and compound multiple complex (Ch. 18) non-climate stressors such as public health concerns (e.g., pandemics, epidemics; Ch. 15), economic events (e.g., recession, depression), and social injustices (e.g., systemic racism; Ch. 18). Complex social, economic, ecological, and technological systems can be challenging to adapt because elements within the systems reinforce and constrain one another.[1,133,134,135] Transformative adaptation—spanning both social and physical systems—may be needed to address the increasingly intense and nonlinear effects of climate change and their complex interactions with multiple non-climate stressors (Ch. 18).[28,40,136,137] Adaptation actions that consider co-benefits where possible (including contributing to climate mitigation but also biodiversity, pollution reduction, social justice, and others) are expected to provide the greatest social gains and long-term sustainability.

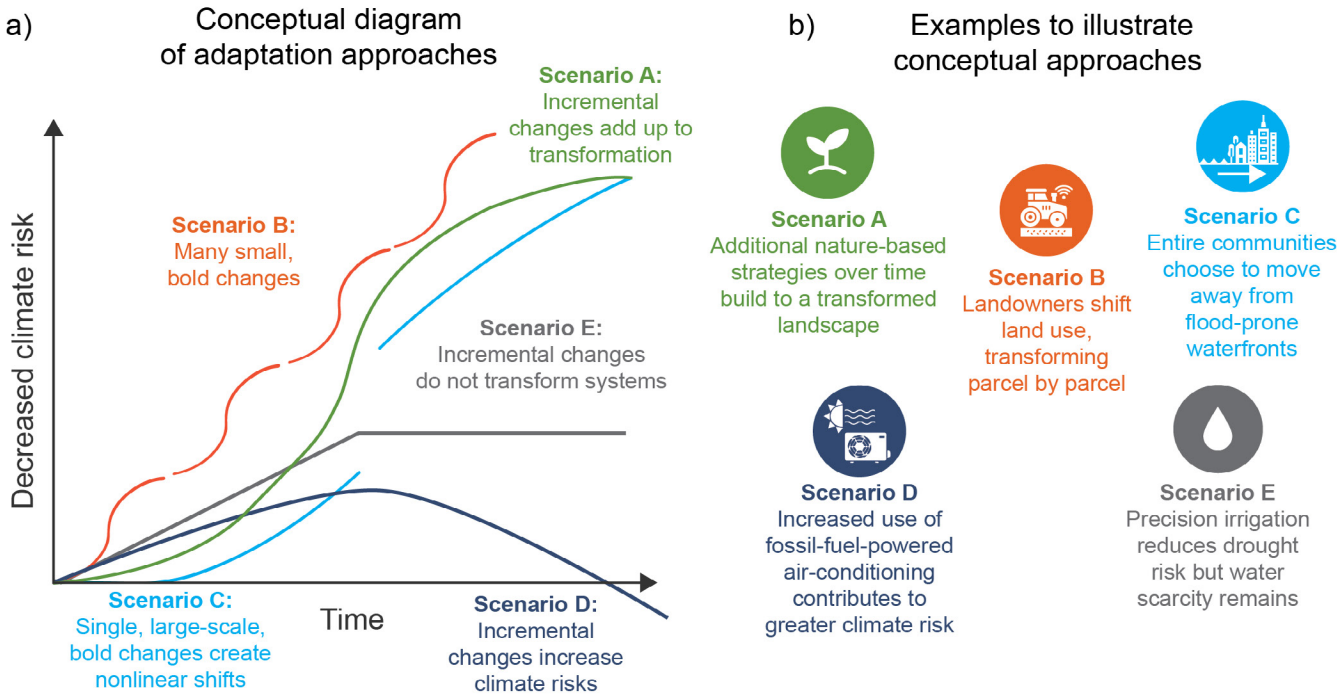
Adaptation may increasingly require a systems approach to focus on how multiple systems (e.g., social, political, cultural, ecological, physical infrastructure, energy, water, food) interact with and shape one another and to identify adaptation actions that cut across or leverage multiple systems.[6,138] Compared with transformative adaptation, most incremental adaptation requires less coordination across interested parties, making it appealing to actors working within a single sector of a larger system and where coordination is difficult to achieve. A systems approach, for example, would consider vulnerabilities across different modes within a system (e.g., highways and public transit) or across systems such as transportation, water, the electric grid, telecommunications, supply chains, stormwater management, and land-use or development patterns. A systems approach to adaptation might argue for adaptation efforts to occur in different government offices (e.g., in transportation planning and housing as well as in emergency management and environmental agencies), for coordination of public and private efforts, or for greater cooperation across silos to support transformative adaptations (KM 31.4). Adaptation actions that take a systems approach to assessing vulnerabilities and adaptation opportunities are expected to be more transformative insofar as they affect multiple systems at multiple scales.[90]

Transformative adaptation may also involve changes to systems and paradigms in ways that redress historical injustices and center equity.[40] Transformative adaptation has the potential to perpetuate or exacerbate social injustices, but inequities are not inevitable.[137,139,140] Addressing them requires express consideration of equity and justice along with direct engagement with disadvantaged and underserved communities (KM 31.2), and lessons can be learned from the "just transitions" literature and movements (Ch. 20; KM 20.6).[108,141,142,143] For example, transforming car-centric transportation systems to emphasize public transportation and walkability could increase accessibility for underserved communities and people with limited mobility if the transformation intentionally includes user input to address accessibility and equity from the start. Transformations may also advance equity by reforming systems and institutions that perpetuate inequities. For example, the reliance of local governments on property tax revenue as a major source of funding has contributed to disaster risk reduction and adaptation governance systems that sometimes prioritize protection of property values rather than people or ecosystems.[144,145] Transformations to these and similar underlying systems may be needed to address climate adaptation equitably.[40] Congressional efforts to reform to the National Flood Insurance Program, for example, have struggled to balance, on the one hand, the need to increase premiums and enrollment to accurately reflect risk and, on the other, the need to keep premiums affordable. Solutions to this problem may require broader transformations in the way insurance and risk information are provided.[146,147,148] Transformative actions are also expected to be necessary to address numerous systemic inequities such as colonialism, systemic racism, wealth inequality and distribution, and economies based on extractive industries.

Adaptation actions are not divided distinctly between incremental or transformative actions (Figure 31.3). In some cases, incremental adaptation actions add up to transformative change if they are widespread enough; however, the place-based nature of adaptation can make this particularly difficult to achieve. In others, incremental adaptation can lead to a limited degree of change that may be insufficient in the face of future climate conditions. Similarly, transformative adaptation can take different forms (Figure 31.3). The exact blend of incremental and transformative actions that will be needed across the United States is not clear, but given the current predominance of incremental action, it is expected that future adaptation will need to include more transformation. The more and faster the climate continues to change (e.g., if global greenhouse gas emissions are not aggressively cut in the near term; Ch. 32), the more severe and spatially uneven climate change impacts will be and the more transformative adaptation will be needed at greater rates, scales, and extents. Transformation and even creative incremental adaptation may be able to overcome soft limits—challenges such as affordability that may be surmounted with additional research or investment—but if global emissions continue unabated, systems and communities will eventually encounter hard limits, points beyond which adaptation cannot avoid intolerable risks and impacts.[149,150]

The pros and cons of different types of adaptation are difficult to compare because adaptation, in general, is difficult to evaluate since it involves measuring harms that do not occur (e.g., avoided losses). Assessments of the effectiveness of adaptation actions have generally been limited to project-specific performance against a limited set of extreme events or climate conditions.[32,151,152,153,154] Adaptation researchers and practitioners have begun to track the number of actions that have occurred across the US and to evaluate adaptation projects in a limited manner (KM 31.1; Figure 31.1). However, efforts to assess trade-offs, effectiveness, sufficiency, and long-term consequences of incremental and transformative adaptation actions are still largely theoretical and will need more work to implement and consistently track over time. Metrics will need to be granular enough to observe disparities among communities to reduce potential inequities.[32,33]

Incremental and Transformative Adaptation Approaches



Incremental and transformative adaptation may take many forms, but incremental adaptation involves small changes while transformative adaptation involves profound shifts.

Figure 31.3. (**a**) Adaptation actions can involve small changes to business as usual (incremental) or bold measures that break from past practices and create new systems (transformative). In some cases, incremental changes may add up to a transformation of the overall system (Scenario A). In other cases, they may not (Scenario E), or they may even cause maladaptation (Scenario D). Transformative adaptation can also take different forms, including a series of small-scale transformations (Scenario B) or larger one-time shifts (Scenario C). Neither incremental nor transformative adaptation is always preferable, and both approaches may exacerbate injustices if equity is not centered (KM 31.2). The examples in panel (**b**) illustrate these conceptual approaches to incremental and transformative change; each could be equitable if it follows the principles of equitable adaptation. Current adaptation practices in the US are predominantly incremental and do not clearly add up to system-wide transformation. Adaptation in the future, therefore, is expected to require a greater degree of transformative adaptation in the overall portfolio. Figure credits: (a) adapted with permission from Fisher and Williams 2020;[155] (b) University of Delaware and National Institute of Standards and Technology.

Key Message 31.4

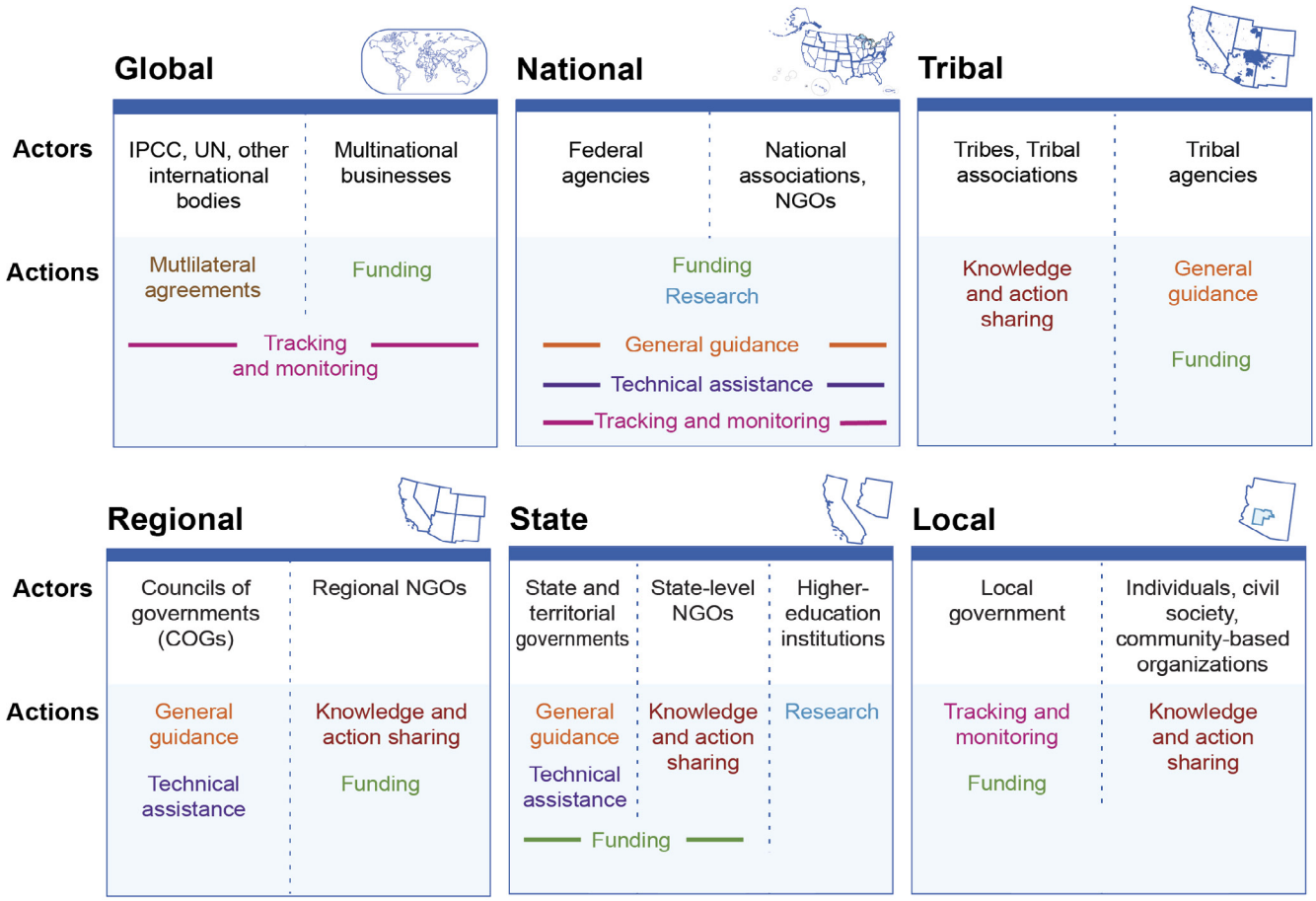
Effective Adaptation Governance Empowers Multiple Voices to Navigate Competing Goals

Adaptation involves actors from government, private-sector, nongovernmental (e.g., nonprofit and for-profit institutions), and civil society organizations, which often have different priorities and approaches (*high confidence*). Adaptation decision-makers must balance competing goals while also addressing uncertainties regarding future climate change and the ways that political, social, and technological systems will be transformed (*high confidence*). To minimize the potential for adaptation actions to benefit some at the expense of others, adaptation processes must emphasize collaboration, center equity and justice, and incorporate a wide range of values and knowledge sources (*medium confidence*).

Governance refers to the structures and processes used by governments and other decision-makers to develop and implement policies, programs, and institutions.[156] Compared to many policy fields, formal governance of adaptation is relatively underdeveloped, with weakly defined ambitions, responsibilities, routines, and evaluation methods and no overarching federal policy framework for adaptation.[157,158] Nonetheless, numerous organizations are engaging in adaptation governance in a more bottom-up fashion.[15,40] For example, urban flood management may be directed by local actors coordinating activities without a higher-level directive.

Many different types of organizations make decisions about adaptation, including federal, state, territorial, Tribal, and local governments; businesses; nonprofits; households; and individuals—all with variably overlapping jurisdictions (Figure 31.4). While some adaptation decisions are made unilaterally, such decisions often involve multiple organizations; adaptation networks have become more complex in the last decade, involving more actors from more diverse organizational backgrounds.[159] The actors involved often have distinct (and at times conflicting) views of the problem, risk tolerance levels, priorities, preferred solutions, and ideal futures.[160,161,162,163,164]

Organizations and Actors in Adaptation Governance



Climate adaptation involves numerous actions by different actors at multiple jurisdictional scales.

Figure 31.4. Climate adaptation governance occurs at multiple scales, with numerous government, private, and civil-society organizations supporting adaptation through funding, guidance, and other activities. While all actors can directly implement adaptation activities, activities implemented in a coordinated fashion and with technical assistance, funding, and monitoring provided by actors across sectors and scales have the potential to be more effective and transformative. Figure credit: University of California, Irvine, and National Institute of Standards and Technology.

When organizations have an explicit focus on adaptation, they tend to organize their governance activities in diverse ways. For instance, some cities, states, and utilities have created centralized offices focused on overall resilience and/or sustainability, while others have distributed climate adaptation tasks across critical functions, each focusing to varying degrees on hazards, social resilience, and/or environmental protection.[165] At the federal level, legal frameworks for climate adaptation cover a broad range of agencies, and these agencies may differ from those mandated to conduct research on the efficacy of adaptation governance (e.g., Executive Order 14008, Section 203[118]).

Given this complexity, adaptation governance is often fragmented and uncoordinated, with the diverse actors operating independently and ignoring potential side effects or spillovers.[48,49,50,51] This problem exists even in settings where actors recognize the need for more coordinated governance.[166] Finally, while there is increasing recognition of cross-jurisdictional impacts, fragmented governance systems are not structured to handle impacts that cross geographic borders.

Leading practices in adaptation governance are based on credible science and involve ongoing open processes to support multiple voices across government, civil society, and expert advisors (Ch. 2).[156,167,168]

Linking adaptation policy and governance involves timely and salient communication across actors, involving media, lobbyists, and boundary organizations that help translate scientific information and co-develop technical support relevant to local communities.[169,170,171]

Effective and equitable adaptation governance also benefits from intentional engagement and coordination among all involved actor groups over a sustained period.[1,51,165,172,173] For example, following multiple wildfires and postfire floods, Santa Clara Pueblo collaborated with multiple federal agencies, the state of New Mexico, and several other Tribes to restore their watershed and build resilience against future floods.[174] Such collaboration is particularly effective when a single government agency leads coordination of an interorganizational group to oversee adaptation activities.[175,176,177] Alternatively, coordinating hubs can help bridge activities of disparate actors;[178] having well-defined roles and responsibilities can avoid duplicated efforts.[165] However, federal agencies can face administrative barriers when engaging with community and nongovernmental actors, such as the Paperwork Reduction Act's requirement of extensive documentation when collecting information from the public.

Well-functioning, multilevel governance helps in adaptation strategy development.[179,180] For example, California, Florida, and other states have used informal regional collaborations (e.g., Southeast Florida Regional Climate Compact, Alliance of Regional Collaboratives for Climate Adaptation) to share resources and develop adaptation strategies that serve regional needs. The Coastal Zone Management Act,[181] which requires federal, state, territorial, Tribal, and local coordination in a single review of newly developed laws beyond borders to protect and develop coasts, is a potential model for encouraging greater cross-scale actions. Vertical linkages between governance levels can help bridge the gap between community-based and national-level adaptation efforts[179] and enhance horizontal linkages across public and private actors and institutions. Horizontal network linkages enable diffusion of information and resources across similar organizations; for example, horizontal connections between community groups facilitate selective adoption of context-specific adaptations and the scaling out of successful adaptation actions.[182]

In instances when adaptation governance brings together groups that traditionally have not worked together, guidance from conflict resolution and collaborative governance can help.[183,184] Ensuring that decision-making processes regarding adaptation planning and implementation are inclusive is necessary to enable a just and equitable distribution of burdens and benefits (KM 31.2). Additionally, adaptation decision-making structures are most effective when they allow for innovation, learning, feedback, and continual improvement.[165,173]

At the federal level, much adaptation has been governed through disaster policies (e.g., through FEMA hazard mitigation planning and grants and HUD disaster recovery grants).[185,186] These policies may not be adequate or appropriate for long-term and systemic adaptation because they are often framed in ways that may not address local adaptation needs and focus mostly on critical infrastructure and disaster response rather than institutional change.[187] Either those systems will need to be transformed or new systems will need to be developed for the US to adequately adapt to future climate hazards.

Another key issue in adaptation governance tends to be unfunded mandates or responsibilities assigned to regions or communities without dedicated increases in funding and capacity.[1,188,189] Government-led adaptation planning would benefit from a greater focus on understanding community-driven adaptation before making significant resource-allocation decisions, given the inherently local nature of adaptation.[190] Development of enabling conditions and frameworks to support adaptation is best guided by recognizing local values, competence, interest, awareness, and analytical capacity.[171,191]

Most governance institutions were created when climate change was not recognized and the climate system was relatively stationary.[123,192] New and revamped governance arrangements face tensions with structures of pre-existing institutions that are strongly embedded and may be protected by long-standing power

dynamics.[123,193] Creating adaptive systems will require fundamental changes across multiple systems and sectors, such as infrastructure, agriculture, public health, and natural resource management (KM 31.3; Chs. 6, 11, 12, 15, 18). Additionally, transformative adaptation benefits from aspirational vision and leadership, as transformative adaptation can upend existing norms and practices.[194]

Systemic change can be facilitated through changes in laws, codes, and standards; data collection (e.g., disaggregated demographic data); and regulations that shape decision-making for intentional and equitable adaptation. For example, laws requiring cost–benefit analyses prioritize infrastructure investments in neighborhoods with high-value properties unless explicit practices to target specific beneficiaries are included and the disaggregated data to identify desired beneficiaries exist.[195,196] Likewise, laws that prescribe the types of science used in decision-making may exclude local or Indigenous Knowledge, limiting both participation in decision-making and incorporation of multiple actors' views and priorities (KM 16.2).

The body of research to inform effective and equitable adaptation governance is growing, but knowledge gaps and a need for translating research findings into on-the-ground implementation action remain. Adaptation researchers can inadvertently create gaps, make translation more difficult, or duplicate efforts if they do not fully reference previous works or if the field becomes too fragmented across disciplinary or topical silos.[197] Local governments can prioritize adaptation activities and avoid maladaptation and unintended side effects by effectively identifying and assessing synergies and trade-offs that are context specific.[198,199] Building local capacity can also support more equitable adaptation governance.[197] Research on adaptation governance may increasingly address a rise in climate litigation, with thousands of US cases identified in climate litigation databases.[200] A key driver for litigation is compensation for the costs of adaptation. The dynamic sociopolitical and scientific context in which climate litigation takes place makes it challenging to assess its impact.[201] Finally, identifying institutional and systemic shifts that may support more coordinated and transformative governance would require more research.

Key Message 31.5

Adaptation Requires More Than Scientific Information and Understanding

Effective adaptation to a changing climate requires both decision-relevant climate information and evidence-based decision-making approaches (*high confidence*). Adaptation requires that researchers intentionally collaborate with communities to identify goals, assess vulnerability, improve capacity, and address contextual factors, such as values, culture, risk perception, and historic injustices (*medium confidence*). Climate services can be improved by ensuring access for historically disinvested communities and by attention to procedural and recognitional equity when scientists work with communities and decision-makers (*medium confidence*).

Climate data and information remain a limiting factor for adaptation. However, many people and organizations, especially those in historically disinvested communities, require more than scientific data and information to adapt.

Cities and states use climate data, information, and decision-support tools in adaptation decisions (Table 31.2) to, among other things, identify, assess, plan, and reduce risks. For example, the city of New York recently legislated Climate Resiliency Design Guidelines,[202] which, among other things, determine the height of flood protection measures using climate projections from the New York City Panel on Climate Change. Tools like the US Climate Resilience Toolkit,[203] Climate Mapping for Resilience and Adaptation,[204] the Sea Level Projection Tool,[205] and even the web-based format of the National Climate Assessment (NCA)[206] provide broad access to climate information across the US. Several states have developed climate data portals to

provide communities with location- and sector-specific climate hazard data (e.g., Cal-Adapt in California,[207] the New York Climate Change Science Clearinghouse,[208] and the New Mexico Climate Risk Map[209]). These tools are particularly useful for organizations with the technical and technological expertise to interpret and customize the data (e.g., insurance companies, larger cities and states, and other entities). However, many adaptation decisions are made without customized adaptation decision support,[162,210] which may be due to the overwhelming number and complexity of tools that exist.

A growing number of efforts provide science- and evidence-based support that extends beyond climate data and information. These efforts are referred to by many names, including climate services,[47,211,212,213,214] technical assistance,[215,216] decision support,[217] sustained assessment,[218] and boundary spanning.[219,220] These terms are not synonymous in that they have distinct approaches related specifically to adaptation that go beyond technical support. These various efforts might

- consider context and need in early stages of development to increase scientific adequacy and to respect processes of knowledge creation involving people with diverse values and lived experiences;[211, 221,222,223,224,225]
- honor Traditional Knowledge systems[226] and Indigenous self-determination (KM 16.2);
- address contextual factors such as risk perception, decision-making authority, and organizational agility;[227,228,229]
- customize data and information to fit the time frame and spatial scale of interest;[222,229,230]
- manage uncertainty about the extent and timing of climate change and its effects, as well as about potential social–economic–environmental futures;[161,231,232,233,234]
- plan for and anticipate multiple possible futures to respond to changing conditions and unforeseen consequences;[235,236,237,238]
- strengthen public participation and democracy by engaging multiple actors in negotiating goals, evaluating trade-offs, and making adaptation decisions (KM 31.3);[10,84,227,239,240,241,242,243,244] and
- develop evidence-based strategies for changing behaviors and systems and evaluating outcomes.[151,245,246,247,248]

There are several Federal programs that provide broader forms of climate decision support. For example, NOAA's Climate Adaptation Partnerships Program, USDA's Climate Hubs, USGS's National and Regional Climate Adaptation Science Centers, National Park Service's Climate Change Response Program, EPA's Environmental Justice Thriving Communities Technical Assistance Centers, and Department of Energy's national labs[47,249] all provide climate services for a range of sectors and regions. Similarly, the Tribal Climate Adaptation Menu (Dibaginjigaadeg Anishinaabe Ezhitwaad),[250] developed by numerous stakeholders in Minnesota, provides a framework to integrate Indigenous and Traditional Knowledge into the climate adaptation planning process. Despite these existing efforts, there are still limitations on awareness of and access to services, especially for historically disinvested communities.

Access to broader forms of technical support varies, with underserved communities facing critical gaps (KMs 16.2, 29.4). Not all regions are covered. Some sectors are further along in climate adaptation planning than others. While there has been some research on gaps by region and sector,[249] no comprehensive nationwide evaluation exists that assesses the availability of climate services, and most existing evaluations are largely based on geographic and sectoral coverage, not differential exposure and factors related to social vulnerability. Moreover, many emerging forms of support are not explicitly focused on climate services. Instead, they are providing climate-related technical assistance, which is unfamiliar to some environmental justice communities and Tribal Nations.[215,216,251] Additionally, environmental justice communities and Tribal Nations face barriers to obtain federal funding for technical assistance because there is a high level of

technical skill required to apply and/or strict eligibility criteria.[252] When, how, where, why, and for whom climate services and climate-related technical assistance are distributed can be tied to transformative and equitable adaptation (Table 31.2).

Table 31.2 Climate Services Can Be Designed to Support Transformative and Equitable Adaptation

Climate services can be aligned to the level of community engagement and the impact of adaptation efforts. Climate services are not about supporting decisions in a vacuum. They can be designed to avoid engagement fatigue and advance transformative adaptation. Climate services can assess vulnerability and adaptive capacity to support actions to reduce unjust, maladaptive choices. Engaging communities in the development of climate services related to adaptation can empower environmental justice communities and Tribal Nations. Data and information tools can help reduce engagement fatigue if the goals, outcomes, and values have been established. If community engagement is needed to codevelop goals and values necessary to evaluate the consequences of transformative adaptation options, institutional partnerships can build and sustain the inclusive participation of diverse community voices.

Level of Community Engagement in Climate Services	Incremental Approach to Adaptation	Transformative Approach to Adaptation
Low	**Are services enabling maladaptation?** Consider services that assess vulnerability and adaptive capacity to account for injustices.	**Are services supporting equity?** Consider services that remove barriers to participation in climate adaptation, including knowledge generation.
High	**Are services operationalized?** Consider services that provide decision tools to reduce engagement fatigue.	**Are services sustained and mainstreamed?** Consider institutional arrangements that maintain trust, credibility, and saliency and embed services into decision processes.

Adaptation decisions range from smaller-scale, incremental decisions with clearer and limited participants to far-reaching, transformative changes with multiple decision points and decision-makers. Climate services can support adaptation and equity by encouraging discussion between historically disinvested communities and decision-makers regarding relevant climate risks and trade-offs between adaptation options.[56,253,254,255] In some cases, the trust and relationships built through an inclusive decision-support process lead to collective learning and adaptation over time, sometimes referred to as coproduction.

Coproduction encompasses a range of collaboration modes—from consultative to collegial—that structure science and decision support to advance societal goals.[151,227,247,248,256,257,258] Coproduction involves iterative, multiway processes that can strengthen procedural equity through power sharing and collaborative knowledge creation. For example, Looking Forward, Looking Back: Building Resilience Today, a partnership between the Alaska Climate Adaptation Science Center and the Aleutian Pribilof Islands Association, involved five community teams with leaders from each spanning multiple governing bodies, including the Tribal Council, the city governments, and the village corporations.[259] Training and workshops in each community were designed to support the development of climate adaptation plans.

Coproduction needs to be structured in ways consistent with the need and potential adaptation impact (Table 31.2). Coproduction is time- and resource-intensive, which can be another burden on disinvested communities,[260] especially given that language differences, remote locations, and other logistical challenges (e.g., lack of childcare) present barriers to participation and engagement. Additionally, there is a risk of unintentionally creating competing and unaligned goals across community members, technical experts, and government officials.[227] There are also often mismatches between the urgency for climate action, the long-term development of scientific evidence, and governmental decision processes.

To improve adaptation practice, adaptation-needs assessments—not solely focused on science gaps but also on adaptation barriers—can identify how practitioners and communities are or are not supported by

the scientific community in their adaptation efforts and in what contexts different forms of support are preferred over others.[261,262,263]

In particular, decision-makers can benefit from access to or the development of methods, metrics, and indicators (App. 4.7) that support trade-off analysis when making adaptation decisions.[264] Additionally, to evaluate adaptation choices, decision-makers can

- use these tools to track progress on adaptation efforts and outcomes;[33,153]
- assess short-, medium-, and long-term adaptation effectiveness;[151,152,265] and
- evaluate the advantages and disadvantages, including cost-effectiveness, of incremental and transformative adaptation.[152,154]

Although vulnerability indicators have been developed and thoughtfully used in planning efforts,[266,267,268] and resilience indicators have gained traction recently to assess community impacts or resilience factors,[269,270,271] adaptation indicator development has lagged, because assessments of effectiveness and comparisons against baselines have been limited to evaluation of specific projects.[32] Indicators need to consider context, audience, and use to be effective, including the multiple ways that adaptation affects communities and ecosystems. For example, building a seawall may reduce the likelihood of floodwaters reaching the homes behind the wall (risk outcome), but the wall may also increase erosion of neighboring properties (risk outcome to people outside the wall), narrow the beach and affect coastal species (environmental outcomes), and cut off access to the shore, changing the way people in the community interact with the coast (social outcomes).[93,272]

Key Message 31.6

Adaptation Investments and Financing Are Difficult to Track and May Be Inadequate

Investments in adaptation are being made at the federal, state, territorial, Tribal, and local levels, as well as within the private sector, but they are not always evenly distributed, coordinated, tracked, or reported (*high confidence*) and may be inadequate (*medium confidence*). Future adaptation investment needs are expected to be significant, although projected amounts vary due to uncertainty in future emissions trajectories, associated impacts, and the timing of implementation (*high confidence*). Proactive adaptation can reduce some of the most severe costs of future climate change, particularly under very high emissions scenarios in the late 21st century (*medium confidence*), although adaptation is still needed in the present for communities and infrastructure that may not be well adapted to face current climate conditions (*high confidence*).

Estimates of the damages and associated costs of climate change without adaptation can reach into the hundreds of billions of dollars by the end of the century (Table 19.1).[273,274] Although there are national-level estimates of the economic cost (total damage) of climate change (Ch. 19),[273] there are no comprehensive national-level estimates of adaptation costs for the US. Across adaptation economics assessments, there is little consistency regarding which future emissions scenarios are considered in projecting impacts, the sectors evaluated, the types of damages considered (e.g., direct and/or indirect), the time horizon for cost estimates, and the costs of implementation.[1,275] Despite these differences, studies in the US consistently project adaptation costs on the order of hundreds of millions to billions of dollars.[273,274,276,277,278,279]

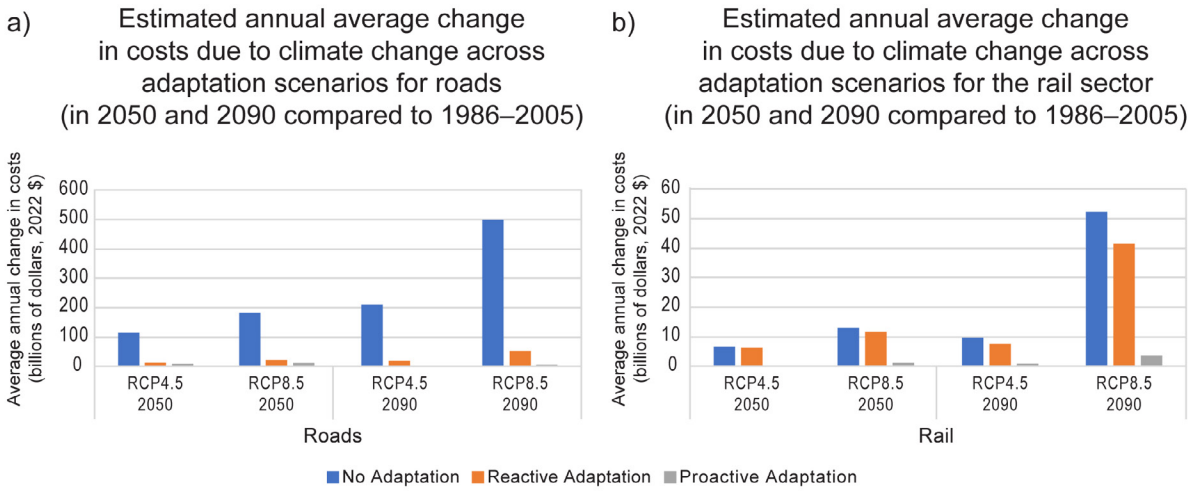
Determining how much and where to invest in adaptation involves decision-making under uncertainty, evaluation of trade-offs, and assessment of the risks associated with delaying action. Generally, this involves quantifying the projected economic impacts of climate change (KM 19.1), the projected costs of adaptation actions, and the expected benefits and/or avoided harms from those actions, all of which can be deeply uncertain. Other essential considerations include efforts to determine ideal levels of adaptation given resource constraints and how to efficiently and equitably allocate costs and benefits among stakeholders. Considerations that are implicit or explicit in adaptation-related economic analyses include questions of who pays for or benefits from adaptation, how to account for the nonmonetary or difficult-to-quantify costs of climate change (e.g., the emotional and physical toll of experiencing extreme weather events, displacement of community after an event, loss of traditional ways of living, and loss of sites of cultural significance; KM 19.1), and what stakeholder interests are reflected in the valuation (both cross-sectionally, in terms of different stakeholder groups, and temporally, as in the choice of discount rate). Some organizations have generated benefit–cost ratios to reduce the impacts of climate hazards through adaptation planning. For example, the National Institute of Building Sciences suggests a 4:1 benefit–cost ratio for hazard mitigation work, with federal grants spent on resilience achieving a 6:1 benefit–cost ratio.[280] However, even when adaptation implementation is favored, other factors such as finances, risk perceptions, inadequate incentives, community capacity, competing priorities, or social and political influences may lead individuals and communities to underinvest.[279,281]

Improvements have been made in the ability to quantify and monetize the physical impacts of climate change (KM 19.1), which are used to estimate both the costs and value of various adaptation actions,[273] although uncertainty and limitations in these estimates remain.[150,282,283] Estimating the aggregated and disaggregated (e.g., sectoral or regional) costs of adaptation, risks of inaction, and value of adaptation actions involves several methodological challenges:[284] developing damage functions that represent impacts of climate change and account for adaptation;[282] understanding the limits of adaptation options and capacity (e.g., effective options may not be presently known or adaptation limits may have been reached); analyzing the behavior of different cost estimation methodologies across climate scenarios and time horizons; incorporating the context specificity of adaptation choices and outcomes into analysis, especially at larger scales (KMs 31.2, 31.4);[285] and evaluating the effectiveness and sufficiency of the actions taken to adapt to climate change.

Both the Fifth and Sixth Assessment Reports of the Intergovernmental Panel on Climate Change state that the benefits of adaptation are expected to be larger than the costs.[284,286] However, both reports note important limitations in estimating aggregate climate damages, costs of adaptation options, and avoided damages from adaptation implementation that create uncertainty and can make it difficult to compare across studies (Cross-Working Group Box Economic in O'Neill et al 2022[150]). Proactive adaptation (e.g., actions, which can be transformative or incremental, taken with the goal of preventing repair costs associated with future climate change) has been shown to reduce climate change damage–related costs for some sectors compared to reactive adaptation (e.g., repairs to damaged infrastructure that do not generally include consideration of future climate change but do consider current climate conditions; Figure 31.5)[128,274,277,281] or no adaptation. In the context of electricity distribution infrastructure, for example, proactive adaptation might entail updating wooden pole designs to account for expected temperature and precipitation conditions over the full future life span of the asset.[128] Reactive adaptation would entail replacing the poles with designs that are only reflective of current climate; no adaptation would entail using designs that do not account for any climate change that already may have occurred.[128]

Despite the estimated value of proactive adaptation, real-world impediments to proactive adaptation, such as ill-timed revision of infrastructure codes and inadequate incentives, can inhibit feasibility of implementation,[128,274] and findings may not be applicable in all sectors.[273] In many studies, proactive adaptation becomes increasingly valuable with greater levels of warming (e.g., under higher emissions scenarios), with benefits accruing over time, particularly in the later decades of the 21st century.[274,277] Where there is considerable current risk to infrastructure and assets from climate conditions (e.g., flood-related risk), it can be cost effective to implement adaptation now even if future benefits from proactive adaptation are small when discounted to the present.[279]

Estimated Annual Change in Costs Due to Climate Change



Future costs associated with climate change will depend on adaptation efforts and scenarios.

Figure 31.5. In some sectors, proactive adaptation can help reduce projected damages from climate change. Estimates are shown for a 5-model ensemble for two sectors (roads [**a**] and rail [**b**]), two time periods (2050 and 2090), and two scenarios—an intermediate scenario (RCP4.5) and a very high scenario (RCP8.5). The three adaptation scenarios reflect the nature in which adaptation has been implemented. Estimates include only costs incurred above historical climate conditions (e.g., climate conditions associated with historical climatology) and assume that adaptation can be readily implemented. Findings should be interpreted only for the sectors shown. Adapted from Neumann et al. 2021[274] [CC BY 4.0].

The scale of the adaptation challenge requires multiple streams of investment (personal, private, and public) and multiple financing options for individuals and communities that may struggle to finance it on their own (KM 21.5). Investments in adaptation[287] are being made at the federal, state, territorial, Tribal, and local levels, as well as within the private sector, but they are not always evenly distributed, coordinated,[288] tracked, or reported.

Adaptation finance relates to monetary investments that reduce the vulnerability or increase the resilience of human and ecological systems to negative climate change impacts.[289] Funding for adaptation, which to date has traditionally originated within the public sector, lags financing for mitigation-related projects (e.g., renewable energy development, energy efficiencies).[275,290,291,292] In addition, adaptation funding is tracked and reported more transparently at the international level than in the US, both in terms of total volume of investment and flows between countries.[284,291] In 2019 and 2020, the annual average of global adaptation finance investments was approximately $55 billion, compared to $659 billion for mitigation projects (in 2022 dollars).[291] Funding is largely funneled through public lending institutions such as multilateral and national

development finance institutions but can also originate from other sources, including commercial finance institutions, governments, and corporations. Tracking of domestic public-sector and overall private-sector adaptation-related investment and financing is a known gap.[284] However, given their cross-cutting nature and co-benefits, investments in adaptation are not always clearly demarcated or obviously identified, making it difficult to explicitly track them and ultimately evaluate their effectiveness. Funding for infrastructure hardening, home weatherization, or cooling centers, all of which can be considered adaptation-related investments (and more incremental), may come from diverse organizations, be dispersed across programs, or not be clearly tagged as adaptation-related expenditures.

Federal and state budget and expenditure tracking does not always distinguish between mitigation- and adaptation-related activities (Box 12.1).[25] Assessing the landscape and uptake of available financing instruments can illuminate where adaptation finance presently originates and is concentrated. Several toolkits, such as the Equitable Adaptation Legal and Policy Toolkit[287] and Ready-to-Fund Resilience Toolkit,[293] provide an overview of different funding (e.g., government grants) and financing (e.g., debt or equity financing) options that are available and help communities design and finance adaptation projects. Services from network organizations such as the American Society of Adaptation Professionals facilitate exchange of leading practices and collaborative spaces for trusted partnerships to form and co-investments to occur for climate adaptation. Understanding how to utilize funding sources would also require understanding levels of vulnerability, hazard exposure, and adaptation and resilience requirements in a future climate context.

At the federal level, government entities such as the Department of Treasury and FEMA provide grants and manage national tax credit and similar financing programs. Other Federal Government entities such as the Department of Transportation, NOAA, and the Department of Energy fund projects to advance adaptation at various levels of government and sectors (KMs 5.3, 9.3, 13.1).

Private-sector investments in adaptation can include funding or financing options (e.g., grants from private and philanthropic organizations, impact investing from private and development finance institutions, incentives for adaptation measures from insurance companies [KM 21.5], and/or loans from green banks), as well as direct investments from private companies to implement adaptation measures to reduce physical climate risk. There has been increased activity in the private sector exploring adaptation to physical and transition risks. This activity has been driven partially by investors requesting increased transparency in climate-related and environmental, social, and governance impacts (e.g., the Task Force on Climate-related Financial Disclosures) and ranges from climate risk disclosure to organizational resilience and from capital stress testing to adaptive asset management. Private-sector organizations have also made independent and regulatory-required adaptation-related investments after natural disaster events (e.g., asset hardening after a severe storm). With limited information on corporate and other private-sector adaptation, it is hard to know the scale and sufficiency of actions implemented to date, but overall, adaptation planning and investments appear to lag significantly behind low-carbon transition planning.

Data on corporate and other private-sector investments in adaptation are very limited, in part due to confidentiality restrictions, uncertain causality, and lack of agreed-upon impact metrics.[275,294] Lack of data makes it difficult to determine where private-sector investment is occurring and any gaps in sectoral, geographic, or community access to privately funded opportunities. Investments in adaptation by the private sector may face more hurdles due to greater challenges with quantifying return on investment compared to mitigation-related projects, uncertainty in policy and regulatory environments, mismatched investment time horizons, and challenges in mapping climate impacts to business-related activities.[57] Increasing transparency in climate-related disclosures that describe the actions corporations and other private-sector entities are taking to minimize the physical and transition risks to their organization, their value chain,

and the communities where they reside and operate may advance the ability to track action and progress toward adaptation where climate risks are extensive. Concerns remain, however, about the comprehensiveness, alignment, and quality of information included in disclosures, as well as the ability to compare across responses.[295] Responses also overwhelmingly skew toward large corporations in specific sectors, in part due to the significant resources required to prepare disclosure responses.[295]

In practice, there are multiple examples of communities leveraging the diversity of investment instruments, risk finance mechanisms, and broader finance-relevant solutions to support adaptation. Examples include federal and state public funding (e.g., Louisiana's Strategic Adaptations for Future Environments program[296]), municipal public–private funding (e.g., DC Water's Environmental Impact Bond[297]), development institution investment (e.g., Coastal Enterprises Inc., a community development financial institution based in Maine[298]), and public–private risk transfer (e.g., a parametric insurance program for the Miami-Dade School District, developed by reinsurer Swiss Re). Financial instruments can serve multiple purposes—to finance activities that reduce direct exposure and vulnerability to physical climate change impacts and to transfer and/or reduce risk where physical climate impacts are difficult to eliminate through more direct measures (e.g., through insurance and other instruments). In late 2022, the 117th Congress passed the Community Disaster Resilience Zones (CDRZ) Act[299], requiring FEMA to continue to maintain a natural hazard assessment program, designate community disaster resilience zones based on census tract hazard-risk ratings, and provide an increased federal cost share to those communities. The CDRZ Act is an amendment to the 1988 Stafford Act,[300] requiring the identification and improvement of the climate and natural hazard resilience of vulnerable communities. FEMA will engage with state, territorial, Tribal, and local emergency management partners to identify how the designation of the zones can benefit these government entities.

Despite these and other actions, several gaps limit the efficacy and volume of adaptation finance in the US, including the following:

- **Challenges in tracking and assessing adaptation finance flows:** As previously stated, sparse data on public and private adaptation-related investments inhibit the ability to track finance flows and overall investment levels within the US. Work to establish a process for tracking these data would be an important first step in better understanding the sufficiency and efficacy of adaptation investments. Adaptation finance gaps are also generally assessed in terms of aggregated finance volume (e.g., a country or regional average of adaptation finance), which does not capture the efficacy of finance.[301] Impact metrics are crucial for a full accounting of adaptation finance.
- **Upfront or operational costs of adaptation are, or are perceived to be, high or are inhibited by other factors:** Many interventions that could strengthen adaptation have, or are perceived to have, high up-front costs or uncertainty in total costs (especially if the costs or benefits are difficult to quantify) and may not be viewed as viable within many institutions' or communities' financial capacity. Local adaptation plan cost estimates sometimes exceed local governments' entire municipal budgets,[302] leaving very little budget to implement the actions identified in the plan.
- **Private entities have historically lacked incentives to invest in adaptation, but this may be changing:** Investments in adaptation can be perceived as public goods, limiting private-sector involvement.[57,286] Many private financiers have faced difficulties incorporating the economic benefits from avoided losses into their investment decision-making.[303] Emerging evidence points to increased investor, insurer, and credit rating agency attention to climate risk and the associated financial impacts or cost of capital for borrowers vulnerable to climate risk.[304,305] More publicly traded companies are estimating and disclosing the financial impacts of climate change and the investments made to reduce climate-related risks and to maximize the opportunities.[306] These evolutions may cause a shift in perspective by private investors if investment returns are perceived to be at risk from climate change.

- **Unsupportive legal and regulatory environment:** Although there are examples of regulatory mandates for adaptation planning (e.g., California Public Utilities Commission Rulemaking R.18-04-019[307] and New York State Senate Bill 7802[308]), in many contexts, the legal and regulatory institutions and infrastructure that support adaptation investment are insufficient, either because they are themselves underfunded (KM 31.3) or because political support is lacking (or both). Insufficient, weak, or nonexistent regulatory and policy frameworks (e.g., lack of or delayed adoption of forward-looking infrastructure codes and standards; KM 12.3) create barriers to action and investment. Such policy decisions limit incentives to address physical climate risk and reduce the likelihood of mobilization of finance.

Traceable Accounts

Process Description

Adaptation to climate change has the potential to affect people from all walks of life, so the author team was selected to represent people from a diverse range of disciplines including social sciences and engineering, as well as professional practitioners focused on adaptation. Care was taken to ensure that the team included both early-career and senior professionals from across industry, academia, and government who come from varying geographic areas and personal backgrounds. The authors were selected from the list of individuals who responded to the Federal Register Notice or otherwise directly contacted the US Global Change Research Program to volunteer. Authors met virtually on a weekly or bi-weekly basis throughout the assessment to build consensus, incorporate feedback from stakeholders received during the public workshops and comment periods, and collaborate and cross-reference other Fifth National Climate Assessment chapters where relevant.

It is important to note that while the terms "adaptation" and "resilience" are complementary concepts, there are distinct and important differences between the meanings of these terms, and confusion arises since they are often used interchangeably in policy and academic discourse. "At its most basic, adaptation refers to a process or action that changes a living thing so that it is better able to survive in a new environment, whereas resilience describes the capacity or ability to anticipate and cope with shocks, and to recover from their impacts in a timely and efficient manner. However, in practice, the distinctions and relationships between resilience and adaptation are more complicated and less easily defined."[309]

Historically, resilience was referenced as "bouncing back" and involved a return to baselines—such as a community recovering to its pre-disaster state after an acute climate-related event, such as an earthquake or hurricane.[310] More recently, however, the disaster planning and adaptation communities have realized that "bouncing back" to the status quo can be harmful. Therefore, the term "resilience" has recently been discussed as "bouncing forward"—changing a system or community to be better prepared for future conditions, whether those are sudden shocks like hurricanes or long-term stressors like drought and sea level rise. Bouncing forward implies that there has been reflection, growth, and learning, which does not always occur and is not always captured and evaluated after shocks and stresses have occurred. There are also communities that are forced to be resilient and can either bounce forward or bounce back depending on their access to the resources and support that meet their specific needs in both the short and long term. This chapter focuses on actions that help communities "bounce forward" to prepare for and thrive under future conditions.

Key Message 31.1

Adaptation Is Occurring but Is Insufficient in Relation to the Pace of Climate Change

Description of Evidence Base

The state of climate adaptation in the US has been somewhat well-documented through literature and organizations capturing publicly available adaptation actions to date at multiple scales, such as the Georgetown Climate Center, the Intergovernmental Panel on Climate change,[150] the Global Adaptation Mapping Initiative,[15] and this National Climate Assessment. In addition, there are numerous studies documenting diverse barriers to adaptation, including psychological, regulatory, financial, and political barriers.[43,44,45,48] The chapter authors, as adaptation practitioners and researchers, understand in depth the current state

of adaptation and progress—or lack thereof—being made across the US from the local to the national scale and wove that into the evidence base. The authors were able to capture evidence of progress and barriers along the various stages of the adaptation cycle from recent research and literature, public comments, and their professional experience. Although there is progress being made across the US, there are still significant barriers to overcome for Americans to adapt to climate change now and into the future. The chapter documents these barriers further in the Key Message narrative and highlights some on-the-ground examples to illustrate these barriers.

Major Uncertainties and Research Gaps

Given the lack of research on evaluating the effectiveness and sufficiency of adaptation actions across multiple sectors, scales, and regions, the authors focused on evaluating the current status of and barriers to adaptation across the five stages of the adaptation cycle. Authors felt as though the previous graphics[4,19] that illustrate progress along the adaptation cycle do not accurately reflect the varying levels of progress from the national to local scale. For example, a rural town in Kansas may be at the awareness stage, whereas the City of New York is in between the implementation and monitoring and evaluation stages of the cycle. Given this disparity in the level of progress along the cycle, authors included examples—captured from literature and author experience—of progress and barriers to each stage of the adaptation cycle.

Description of Confidence and Likelihood

Very high confidence in the diversity of adaptation actions occurring across the US stems from widespread and well-documented academic and policy reports about adaptation. While there are few documented examples of fully implemented adaptations, a lack of systematic studies of adaptation implementation that enable a comparison over time and the difficulty of comparing across regions and sectors yield *medium confidence* that adaptation is moving from the planning to implementation phase. Available research agrees that few implemented adaptations are being evaluated (*high confidence*) and that organizations face numerous barriers to developing and implementing adaptations (*high confidence*). Most available sources agree that current adaptation efforts and investments are incremental in nature and are insufficient to address future climate risks (*high confidence*). However, projecting and evaluating actual levels of risk reduction remains difficult, which leads to our statement of *medium confidence* related to current adaptation efforts and investments being unlikely to keep pace with future changes in the climate.

There is no consistent or regularly updated and tracked source for adaptation actions across the US at multiple scales, regions, or sectors, and many actions that may be considered adaptation may not be publicly known or captured through sources currently available that do track adaptation actions (e.g., the Intergovernmental Panel on Climate Change [IPCC] and the Georgetown Climate Center [GCC]). Therefore, the chapter's authors can provide confidence levels but not likelihood assessments.

Key Message 31.2

Effective Adaptation Requires Centering Equity

Description of Evidence Base

A substantial number of peer-reviewed papers, government data and reports, and accounts from extreme weather and climate events illustrate the uneven effects of climate change (Chs. 16, 18, 20).[62,63,64,65,66] Specifically, there is mounting evidence of the ways climate change disproportionately impacts low-income communities with higher percentages of Black, Indigenous, and Latin people, women, and younger or older adult populations, among others. Research and government reports document numerous ways in which government and private-sector systems contribute to differential effects through discrimination, displace-

ment, or underinvestment in hazard mitigation, other public infrastructure, or disaster response (e.g., Frank 2020;[69] Wilson et al. 2021;[70] Howell and Elliott 2019[68]). Some disparities are better documented than others, but the finding that climate change affects populations differently and that some of these differences are driven by government (in)actions and social systems is not disputed in the literature.

There is a converging body of evidence that demonstrates that individual and social factors play a significant role in whether people have the resources to reduce or avoid climate impacts (e.g., adaptation), as is the case in other areas of society (e.g., access to education as a limiting factor to job security).[84,85,86,87] The specific reasons why individuals and communities adapt the way they do remains an area for research, but there is robust evidence and high consensus that psychological, cultural, historical, geographical, and social factors play a role and that individual or community values are important drivers in the adaptation process.[95,96,311,312]

Maladaptation is a well-established concept in the adaptation literature, and cases of maladaptation have been well documented in numerous cases by a range of author teams,[106,107] although the exact criteria used to determine when an action is maladaptive often differ according to context. A growing body of research documents the ways that centering equity in the design, planning, and implementation stages of adaptation leads to improved outcomes.[40,113,117]

Major Uncertainties and Research Gaps

A source of uncertainty is the lack of standardized methods to evaluate the social justice or equity implications of climate adaptation. Numerous studies have documented inequities and injustices in adaptation or hazard risk-reduction programs and actions (e.g., Frank 2020;[69] Wilson et al. 2021;[70] Howell and Elliott 2019[68]), but different author teams use different metrics and concepts, including participatory, distributive, or recognition justice. The different methods make comparative analyses challenging, although notably the many methods and teams reach similar conclusions about the desirability of centering equity and justice to both improve quality of life for affected communities and reduce climate-related risks.

Description of Confidence and Likelihood

There is strong evidence from a wide range of academic studies and government reports, with high levels of agreement across numerous research teams, that people are affected by climate change in different ways and to different degrees and that these differences are affected by historical and contemporary social systems. This statement therefore warranted *very high confidence*. Similarly, there is widespread, robust evidence with strong consensus that adaptation choices are influenced by preferences, capacity, and access to resources as well as personal and community values, so this statement was also considered to have *very high confidence*. The statement that adaptation actions that do not center equity and underlying causes of injustice can exacerbate inequity and increase climate risk is considered *high confidence* because there is widespread consensus about this claim, but the evidence is slightly less robust due to a lack of standardized methods to assess the social justice of adaptation outcomes. Studies documenting maladaptation when equity is not centered also bolster this conclusion.

Key Message 31.3

Transformative Adaptation Will Be Needed to Adequately Address Climate-Related Risks

Description of Evidence Base

There is a significant and robust literature documenting the occurrence and type of adaptation practices globally and in the United States.[15] Technical contributors to this chapter reviewed adaptation actions as

documented in government reports and adaptation plans, as collected by the GCC Adaptation Clearinghouse and a systematic review. Researchers use several frameworks to assess transformative adaptation actions, but core principles relate to the depth or novelty of the change, the scale of the change (e.g., geographic or across multiple sectors), and the ability to address fundamental traits of systems or to challenge constraints of adaptation.[40,90,122,123] The IPCC Sixth Assessment Report, Working Group 2, for example, reviewed the relative frequency of incremental and transformative adaptation in over 1,800 studies using a modified version of the Termeer et al. (2017)[123] framework.[150]

Determining whether transformative adaptation is necessary in a particular case or whether incremental adaptation is sufficient for a given location or sector requires evaluation of not only individual adaptation actions but also suites of actions. Adaptation actions are difficult to evaluate, as the goals of adaptation are often contested, and the effectiveness or sufficiency of actions may not become apparent for a long time[16,313,314] (see discussion below in "Major Uncertainties and Research Gaps"). Nevertheless, a common finding within the literature is that most adaptation actions are incremental, small in scale, and limited by soft and hard constraints on adaptation.[1,15] Studies that assess the sufficiency of adaptation actions to address future climate change impacts routinely find that current incremental actions may be insufficient,[27,120] where sufficiency is determined based on projected climate change effects and limitations of adaptation actions (e.g., the ability of irrigation systems to handle future droughts). While the degree to which future actions will need to be transformative is uncertain (e.g., whether some, most, or all actions will need to be transformative), the literature supports *high confidence* that more actions will need to be transformative in the future than is current practice. That is, the US adaptation portfolio will need to include more transformative adaptation to adequately address future climate risks.

Major Uncertainties and Research Gaps

The major source of uncertainty is a lack of consistent, high-quality methods to evaluate the sufficiency of adaptation actions to address future climate-related risks. Methods are being developed (e.g., Parker et al. 2020[27]), but lack of consistency across the field makes comparative studies difficult and complicates efforts to pin down optimal adaptation portfolios. Methods for decision-making under uncertainty are growing for this reason, as are methods to identify actions and portfolios of actions that are robust under numerous climate futures. Efforts to evaluate both the effectiveness of adaptation actions and portfolios in addressing current climate-related risks and the sufficiency of actions and portfolios to address future climate risks are areas for continuing research.

Description of Confidence and Likelihood

There is *very high confidence* that climate adaptation actions in the United States to date have been incremental, because numerous information sources reporting adaptation actions in academic and government literature document these results and generally agree on the incremental nature of the adaptation actions. Although there is evidence of a few examples of transformative action, the overall statement that actions are generally small in scale and incremental remains robustly supported with strong evidence and high consensus. The necessity of transformative adaptation is assigned *high confidence* because numerous author teams and government reports reach this conclusion, but there is less robust evidence to support the extent of transformation that will be necessary. Similarly, numerous research teams conclude that monitoring and evaluation of adaptation will need to improve, both in terms of the methods used and the data collection and processes, to better understand what adaptation actions are effective to deal with current risks or sufficient to address future climate risks. However, not all teams agree on the nature of these monitoring and evaluation methods, so the need for improvement is assigned *high confidence*. The finding that adaptation actions in the United States (both the type and extent of actions) are generally insufficient to deal with future climate risks is not controversial in the literature. Likelihood

statements were not provided because they represent probabilistic assessments of uncertainty that are inappropriate for this type of analysis.

Key Message 31.4

Effective Adaptation Governance Empowers Multiple Voices to Navigate Competing Goals

Description of Evidence Base

Research on adaptation governance and how adaptation decisions are made is a less developed topic relative to research on mitigation policy and governance,[156,158] especially for papers empirically focused on the US. Over the last five years, an increasing number of case studies have focused on adaptation governance in specific locations and sectors, such as sea level rise in San Francisco[159] or flood risk in the Upper Mississippi basin.[48] Existing case studies of adaptation governance display a high level of agreement with respect to its multi-actor, fragmented nature, wherein actors working in distinct organizations and sectors make independent decisions related to adaptation in an uncoordinated fashion.[48,49,50,159,165,166] This literature also highlights that these organizations have distinct goals, values, risk perceptions, and capabilities that lead to inconsistent and sometimes conflicting adaptation choices.[160,161,162,163,164] Both theoretical and empirical literature on adaptation governance also emphasize the benefits of increased coordination and collaboration across organizations, sectors, and levels of government.[1,51,165,172,173]

Major Uncertainties and Research Gaps

The major source of uncertainty is a lack of systematic, cross-case research comparing adaptation governance approaches across multiple sectors, types of adaptation, or geographies. The majority of evidence stems from single case studies or comparisons of two or three city or community cases. The lack of larger comparative studies creates uncertainty about the specific contexts in which governance approaches work and more universal challenges in implementation. Comparative research has assessed the use of specific policy tools to promote adaptation[315,316] but rarely focuses on broader governance arrangements, such as who is involved in decision-making and the roles they play (an exception is Fastiggi et al. 2021[165]). Likewise, there is minimal research evaluating the outcomes of governance approaches on adoption of adaptation actions, risk reduction, or equity.

Description of Confidence and Likelihood

High confidence about the diversity of actors involved in adaptation governance and the challenge of balancing competing goals signals that these statements rely on many high-quality papers that show the same general trends. *Medium confidence* about the need for collaboration and diversity of values and knowledge signals that there is a lower overall number of papers showing empirically the value of these approaches.

Key Message 31.5

Adaptation Requires More Than Scientific Information and Understanding

Description of Evidence Base

Many integrated, science-based approaches are used to help manage decisions under uncertainty and decisions spanning future social–economic–environmental futures.[162,163,210] Even though some future uncer-

tainties cannot be reduced (Ch. 18) for particular strategies, many other strategies can take advantage of computing power and artificial intelligence to reduce future uncertainty, hedge against uncertainty by selecting actions that work across multiple possible futures, or approach adaptation decisions as a long-term process to be revisited over time.[195,235,317,318,319,320,321,322,323,324,325,326,327,328,329,330,331,332,333,334,335] Tools include modifications to traditional approaches like cost–benefit analysis, scenario planning, and multicriteria decision analysis; more participatory versions such as participatory mapping and serious gaming;[240,244] computational methods such as robust decision-making, probabilistic decisions, and real-options analysis; less computationally intense options such as heuristics, a growing area of research; and flexible options such as dynamic adaptation policy pathways[235] and adaptive management and governance systems.

A wealth of peer-reviewed literature over at least the past two decades provides formal and informal evaluation of specific climate service efforts and examines the use of climate information for a variety of decision-making contexts and applications. Recent research in this body of literature made strides by illustrating that equally important to whether climate information is used is how climate information is used. Specifically, it is important to acknowledge that any one specific climate service effort need not change a specific policy or real-world condition to benefit progress toward those or other outcomes.

Climate services can have numerous societal benefits and support diverse outcomes (see, for example, the Pacific Islands Regional Climate Assessment Evaluation[336]).[246,248] Over the past two decades, social science has improved the development of climate services by evaluating the usability of services,[337] prescriptively improving public data products,[338,339] and, more recently, expanding the degree to which various service efforts support adaptation and related societal benefits. Social science, including formal and informal evaluation of climate services, has improved our ability to generate usable and actionable climate information.[151,228,247,337,340] Additionally, social and behavioral science illustrate that actionable climate information can be complemented with new models of participatory, adaptive decision-making geared toward long-term behavior change.[162,231,232,234,337,341,342,343,344,345,346,347]

While the aforementioned literature evaluating climate services speaks to trust, legitimacy, and other important indications that dimensions of equity (e.g., procedural) may or may not have been achieved in different climate service efforts, the body of research only recently has started to examine equity as a critical component of climate services, as an intentional or deliberate part of both the evaluation and the climate service effort itself. Furthermore, equity in adaptation is a relatively new area of literature, and efforts to link the two bodies of work may also be limited by ambiguity over the definition of what constitutes a climate service. Additionally, attribution remains a thorny problem for evaluation research and investigations into the use of climate information, as well as for equity in adaptation. More work will be needed to determine the relative influence of a climate service effort alone versus the combination of a climate service effort and preexisting community organizing efforts to make a difference in catalyzing equitable adaptation. Nevertheless, of the climate service efforts proven to have a range of societal impacts leading to positive social and environmental outcomes and/or adaptive decisions, many have drawn on foundational work by Cash et al. (2003),[221] rooted in the concepts of legitimacy and saliency defined from a stakeholder perspective.

Major Uncertainties and Research Gaps

Additional research would be beneficial to evaluate how well different models of climate service 1) align with different decision contexts, 2) contribute to societal benefits/impacts and outcomes, and 3) support dimensions of equity, particularly around racial and economic disparity. Spanning all three issues related to climate services, more research would be needed to more fully investigate the efficacy of various forms of engagement and collaborative decision-making and how they factor into coproduced climate services. More institutional research would also be needed to determine ways that for-profit services can generate value (e.g., empowerment, revenue) for lower-income communities.

Description of Confidence and Likelihood

High confidence stems from a wealth of literature that climate services do provide a range of benefits and have met a range of needs. *Medium confidence* stems from less literature on equity in adaptation and climate services specifically, and, where that research exists, definitional ambiguity and problems with attribution of societal outcomes directly to climate services, as opposed to a combination of factors.

Key Message 31.6

Adaptation Investments and Financing Are Difficult to Track and May Be Inadequate

Description of Evidence Base

The author team reviewed the literature by searching databases, inviting technical contributions from subject-matter experts, and soliciting feedback during public meetings.

Economic analysis of the costs and benefits of adaptation is a significant research field with numerous studies covering a range of sectors and geographies. Relevant studies include Melvin et al. (2017);[277] Reguero et al. (2018);[278] Martinich and Crimmins (2019);[273] Fant et al (2020);[128] Lorie et al. (2020);[281] Neumann et al. (2021);[274] Wobus et al. (2021);[279] LeRoy et al. (2019);[348] and Clavet et al. (2021).[349]

The peer-reviewed literature abounds with studies estimating the costs of adaptation, although these examples tend to coalesce around a subset of climate hazards, mostly flooding and other hydroclimate-related hazards (e.g., Clavet et al. 2021;[349] Lorie et al. 2020;[281] Melvin et al. 2017;[277] Neumann et al. 2021;[274] Reguero et al. 2018;[278] Wobus et al. 2021[279]); around a subset of sectors, historically agriculture, energy, and water; and in specific geographies, although there are several recent studies that evaluate the economics of adaptation for the continental US.[273,274,276,279] Time horizons for implementation of adaptation options vary across studies (e.g., next decades versus midcentury versus end of century), which can make it difficult to compare cost and benefit estimates. Recent studies (e.g., Neumann et al. 2021[274]) have attempted to incorporate estimation of the indirect costs of climate change on different sectors (e.g., train delays resulting from effects of temperature on rail lines) and these estimates' effect on evaluation of adaptation options.

Since the publication of the Fourth National Climate Assessment, there has been increased research into the effects of different adaptation implementation scenarios (e.g., proactive, reactive, and no adaptation) on damages associated with climate change (e.g., Martinich and Crimmins 2019;[273] Fant et al 2020;[128] Neumann et al 2021[274]), with much of this work supported by the EPA's Climate Change Impacts and Risk Analysis project.

Many organizations have climate investment tracking initiatives and publish regular reports on investment levels and flows (e.g., Climate Policy Initiative, World Bank, United Nations Environment Programme). This tracking is most robust at the international level and at monitoring investment and finance flows between countries, specifically transfers from developed nations to developing nations or transfers to international adaptation funding mechanisms.[284] Specific statistics on investment levels within countries, including the US, are more challenging to find. This is due in part to the fact that adaptation-related investments are not always labeled as such, especially when compared to climate change mitigation–related investments. Finally, tracking of public sector climate investment flows (e.g., from governments or multilateral institutions such as development banks) is also more robust than tracking of private-sector climate flows.

Major Uncertainties and Research Gaps

Despite the multiple case studies of individual examples of adaptation, evidence is unclear about how coordinated or transformative these activities are. The lack of detailed information on adaptation-related investment does not indicate that it is not occurring but rather that it may be uneven, uncoordinated, or underreported. Thus, a major source of uncertainty in assessing the current state of adaptation is assessing the extent to which it is being adequately funded and financed in a coordinated way. Research gaps center on improved tracking of within-country and private-sector adaptation investments; identifying methods to track investment needs or levels when it is difficult to categorize adaptation-related investments; and developing improved metrics and methods for justifying adaptation-related investments.

More finance options have emerged to assist communities with covering the costs of adaptation. The chapter briefly cites four examples: the Louisiana's Strategic Adaptations for Future Environments, a fund administered by the State of Louisiana to provide community-driven adaptation support to residents, targeting the housing, transportation, and energy sectors; the DC Water's Environmental Impact Bond, an environmental impact bond to share with investors the financial performance risk associated with projects to respond to water stress facing the systems; investments from community development financial institutions, such as Coastal Enterprises Inc. in Maine; and a parametric insurance program for the Miami–Dade School District, developed by reinsurer Swiss Re. More research, specifically in the US, investigating the rates of uptake and share of different financing types utilized compared to others would be valuable.

Description of Confidence and Likelihood

Multiple sources[275,284,290,291,295] consistently call out the lack of data on private-sector investments in adaptation, especially when compared to data on public-sector investments and financing. New et al. (2022)[284] note that progress has been made in tracking climate finance internationally but identify tracking of domestic public-sector and overall private-sector investments as critical gaps. For these reasons, there is *high confidence* that more investment in adaptation and improved tracking of domestic adaptation-related investments would be significantly beneficial.

Where adaptation may be occurring, the literature does cite evidence of underinvestment. Lorie et al. 2020[281] cite studies that reported that observed adaptation is lower than what would be expected from traditional cost–benefit analyses. There are many factors that influence the decision to adapt, including finances, lack of incentives, and technological unavailability, suggesting barriers to the decision to invest. Without a full picture of where adaptation investments are occurring and the nature of adaptation investments across sectors and communities, it is difficult to determine the adequacy of these investments. For these reasons, the authors decided to assign *medium confidence* to the statement that investments may be inadequate.

Studies that evaluate differences in aggregate costs of climate change across different scenarios consistently project higher economic costs under very high scenarios (e.g., RCP8.5) compared to intermediate (e.g., RCP4.5) or lower scenarios. Estimates of adaptation costs, which can translate into future investment needs, are consistently in the hundreds of millions to billions of dollars.[273,274,276,277,278,279] As many of these estimates are for specific sectors (as opposed to a comprehensive national-level assessment) and do not evaluate all possible climate impact pathways (for example, Fant et al. 2020[128] does not account for the impact of floods, hurricanes, and ice storms on transmission and distribution infrastructure), they may underestimate the total costs of climate change–related damages and total benefits of adaptation. For these reasons, there is *high confidence* that future investments needs will be significant but still substantial uncertainty as to what those figures will actually be.

Proactive adaptation has been shown to reduce costs compared to reactive and no adaptation scenarios,[128,274] with most benefits accruing in the later decades of the 21st century as warming levels increase under

high scenarios. The choice of discount rate influences the additional cost reductions of proactive adaptation relative to reactive adaptation. Because of this and the fact that analyses of the effects of different adaptation scenarios are limited to select sectors, there is *medium confidence* in this part of the Key Message.

Multiple examples of events in recent decades that have caused significant economic damages and loss of life suggest that communities are not well adapted to face current climate conditions, including ways in which current climate conditions have changed with global warming. Events such as the Texas winter storm in February 2021, where cold temperatures were extreme but not unprecedented in the historical record, demonstrate that many communities are unprepared for current climate conditions. Similarly, Wobus et al. (2021)[279] report that current flood-related risk is serious enough in many locations to justify adaptation-related investments now. For this reason, there is *high confidence* that adaptation is needed to address the risks posed by current climate conditions.

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Fifth National Climate Assessment: Chapter 32

Mitigation



Chapter 32. Mitigation

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Introduction

Mitigation refers to efforts to reduce emissions or to remove carbon from the atmosphere with the goal of avoiding or reducing the effects of climate change, which is different from adapting systems and activities to a changed climate (Ch. 31). To meet international climate goals, global carbon dioxide (CO_2) emissions would need to reach net zero by around 2050 (KM 32.1).[1]

Mitigation is the most cost-effective response to climate change, with potentially large benefits to economies (Ch. 19), social and economic equity (Ch. 12), human health (Chs. 13, 14, 15), food security (Ch. 6), and ecosystems (Chs. 7, 8). Modeling studies agree that large near-term decreases in greenhouse gases (GHGs) in the United States are feasible by improving energy efficiency, electrifying end uses of energy, and generating electricity from non-emitting energy sources such as solar and wind (KM 32.2). However, the optimal mix of technologies to reach net-zero emissions is not yet clear, and further research and development is needed to determine the best options for long-duration energy storage, non-emitting and dispatchable (sometimes called firm) sources of electricity, and net-zero options for aviation and long-distance freight transport, as well as carbon dioxide removal (KM 32.3). Actions to immediately and substantially reduce emissions are available, and can be supported by individual choices and decisions by multiple stakeholders (KM 32.5). Further, racial, economic, demographic, and geographic inequities and injustices are embedded within existing infrastructure and social systems, and mitigation will both influence and be influenced by equity, environmental, and economic factors (KM 32.4).

Key Message 32.1

Successful Mitigation Means Reaching Net-Zero Emissions

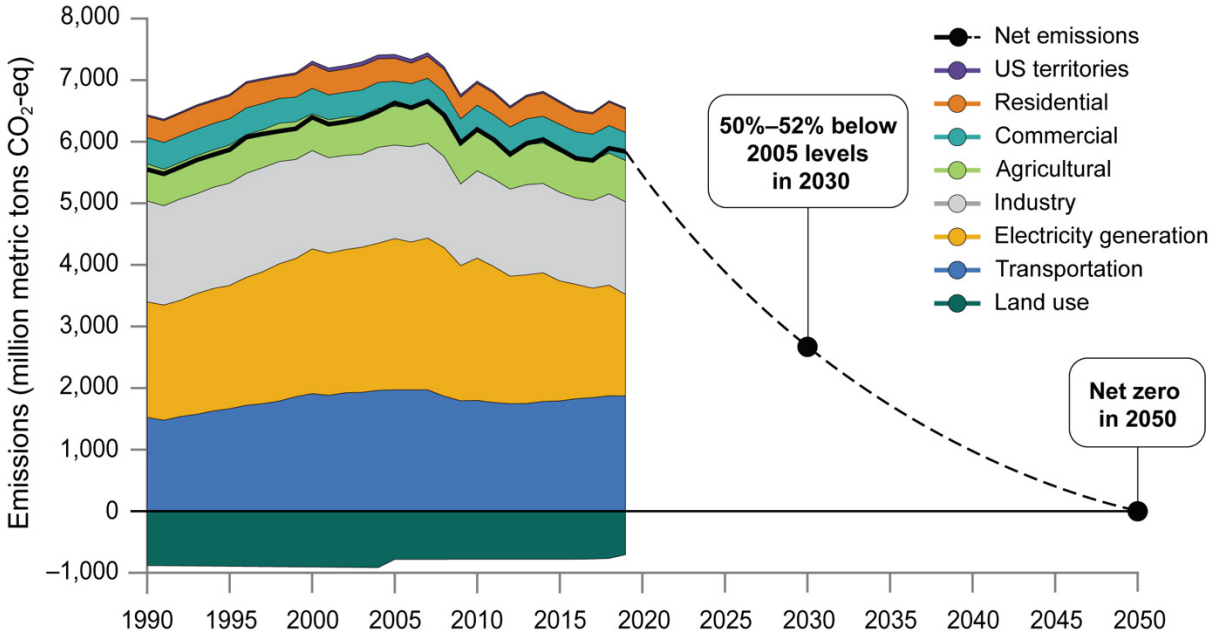
Greenhouse gas emissions in the United States decreased by 12% between 2005 and 2019, mostly due to replacing coal-fired electricity generation with natural gas–fired and renewable generation (*very high confidence*). However, US net greenhouse gas emissions remain substantial and would have to decline by more than 6% per year on average, reaching net zero around midcentury, to meet current national climate targets and international temperature goals (*very high confidence*).

Mitigation Goals

To achieve the Paris Agreement (an international treaty on climate change) goal of limiting global warming to well below 2°C above preindustrial levels and pursuing efforts to limit global warming to 1.5°C above preindustrial levels, global CO_2 emissions need to reach net zero around 2050 and remain net zero or net negative afterward.[2] Thus, US CO_2 emissions reaching net zero around midcentury would be consistent with Paris goals, although a wide range of trajectories is possible based on considerations of international equity, burden-sharing, costs, and policy assumptions.[3,4,5] This chapter addresses pathways and options for mitigation of US emissions from all sectors consistent with national and international climate goals.

As part of the Paris Agreement, countries communicate nationally determined contributions (NDCs)—emissions-reduction targets that they intend to achieve. The latest NDC communicated by the United States to the United Nations Framework Convention on Climate Change (UNFCCC) Secretariat sets an economy-wide target of reducing all its net GHG emissions (not only CO_2) by 50%–52% below 2005 levels in 2030, or roughly –6% per year beginning in 2022, putting the country on a path to achieve the goal of reaching net-zero GHG emissions by no later than 2050 (Figure 32.1).[6] In addition, 24 states and Washington, DC, have their own reduction targets (KM 32.5).

US Greenhouse Gas Emissions by Sector with 2030 and 2050 Goals Added



US emissions will need to decrease rapidly to reach levels consistent with international climate targets.

Figure 32.1. Figure shows US annual greenhouse gas emissions and sinks from 2005 to 2019, as well as future targets for achieving the US nationally determined contribution under the Paris Agreement. US territories—including American Sāmoa, Commonwealth of the Northern Mariana Islands, Federated States of Micronesia, Guam, Republic of the Marshall Islands, and Republic of Palau—contribute minor emissions (not visible) that are not broken down by sector. CO_2-eq = carbon dioxide equivalent. Adapted from DOS and EOP 2021.[6]

Major Trends

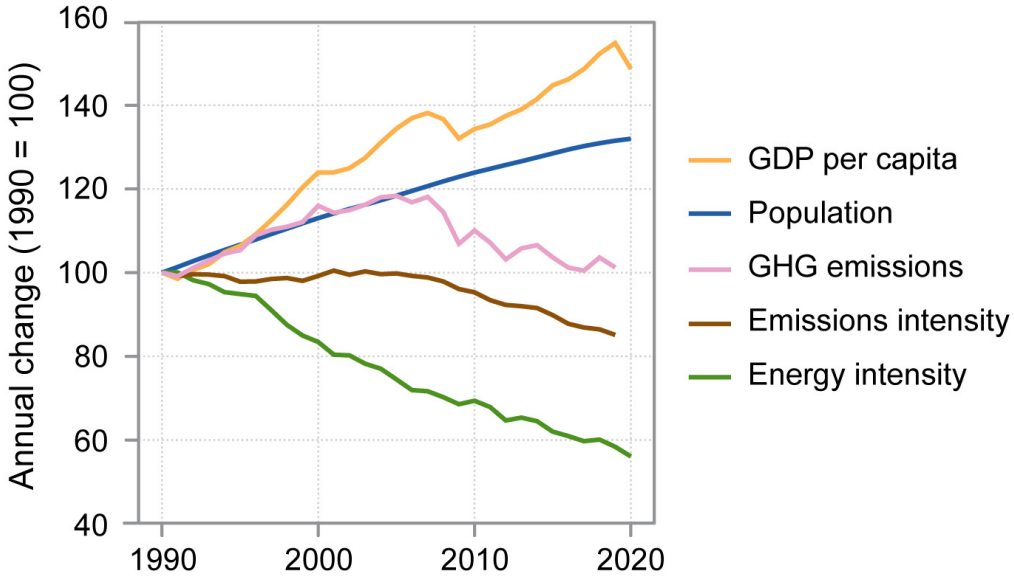
Between 1990 and 2019, US CO_2 and nitrous oxide (N_2O) emissions increased by approximately 3% in each case. Emissions of fluorinated gases increased by 86%, and methane (CH_4) emissions decreased by 15%.[7] Although the latest EPA inventory reports emissions through 2021,[8] this chapter focuses on trends in emissions to 2019 because the COVID-19 pandemic caused substantial but largely temporary changes in energy-related emissions worldwide (see, e.g., Davis et al. 2022;[9] Liu et al. 2020[10]). The EPA estimates that US carbon dioxide equivalent (CO_2-eq) GHG emissions were about 6.6 billion metric tons (or gigatons; Gt) in 2019, 2% more than in 1990.[7,11] The sources of these emissions are primarily electricity generation, transportation, and combustion of fuels in other sectors (i.e., commercial, residential, and industrial), with smaller contributions from agriculture, industrial processes, and waste (Figure 32.1). Major sinks were land-use change and especially forests, which resulted in net uptake of 0.7 Gt of CO_2 in 2019. Net GHG emissions from all sources and sinks were thus 5.8 Gt of CO_2-eq in 2019.[7,8,11]

Between 2005 and 2019, US GHG emissions decreased by 12%, mainly because of reductions in electricity generation emissions. Indeed, since 2017, the largest share of GHG emissions has come from the transportation sector (Figure 32.1). Estimates include emissions occurring within all US territories, as annually reported to the UNFCCC Secretariat by the EPA. Independent estimates by other scientific bodies and researchers are similar but not identical.[12,13,14,15]

Sector-Specific Trends and Drivers

Between 1990 and 2019, economic and population growth have acted to increase US energy-related emissions but have been counterbalanced by reductions in both the energy used per dollar of GDP (or "energy intensity of economic activity") and the CO_2 emissions per unit of energy used (or "emissions intensity of energy").[16] In particular, decreases in energy emissions since 2007 were driven by a steady and substantial fall in CO_2 emissions per unit of energy consumed from a maximum of 59 million metric tons (megatons; Mt) of CO_2 per exajoule (10^{18} joules) of energy consumed in 2007 to 51 Mt per exajoule in 2019 (Figure 32.2).

Changes in Drivers for Energy-Related Greenhouse Gas (GHG) Emissions



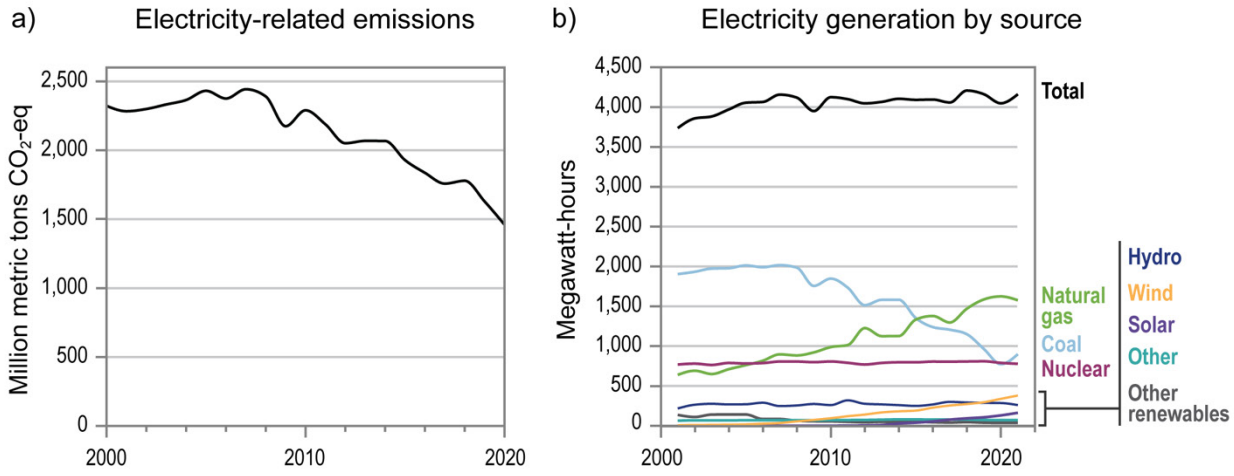
US greenhouse gas emissions have dropped even as population and economic activity (as measured by GDP) have climbed.

Figure 32.2. Energy-related greenhouse gas (GHG) emissions in the United States have declined since 2007 (pink) despite rising population (blue) and economic activity measured by the GDP (orange). Behind the decreasing trend are gradual reductions in energy use per dollar of GDP (energy intensity, green) and large decreases in GHG emissions per unit of energy produced (emissions intensity, brown). Figure credit: Stanford University.

Electricity Sector Emissions

GHG emissions from the electricity sector in 2019 were 1,629 Mt of CO_2-eq, or 30% of energy-related emissions.[7] Decreases in US energy-related emissions since 2007 mostly reflect changes in the electricity sector, especially the retirement and reduced use of coal-fired power plants and corresponding increases in lower-cost electricity from natural gas–fired power plants (and to a lesser extent renewable technologies; Figure 32.3b). US emissions from electricity generation in 2019 were roughly 40% below 2005 levels (Figure 32.3a).

Trends in Electricity Generation by Source and Related CO_2 Emissions



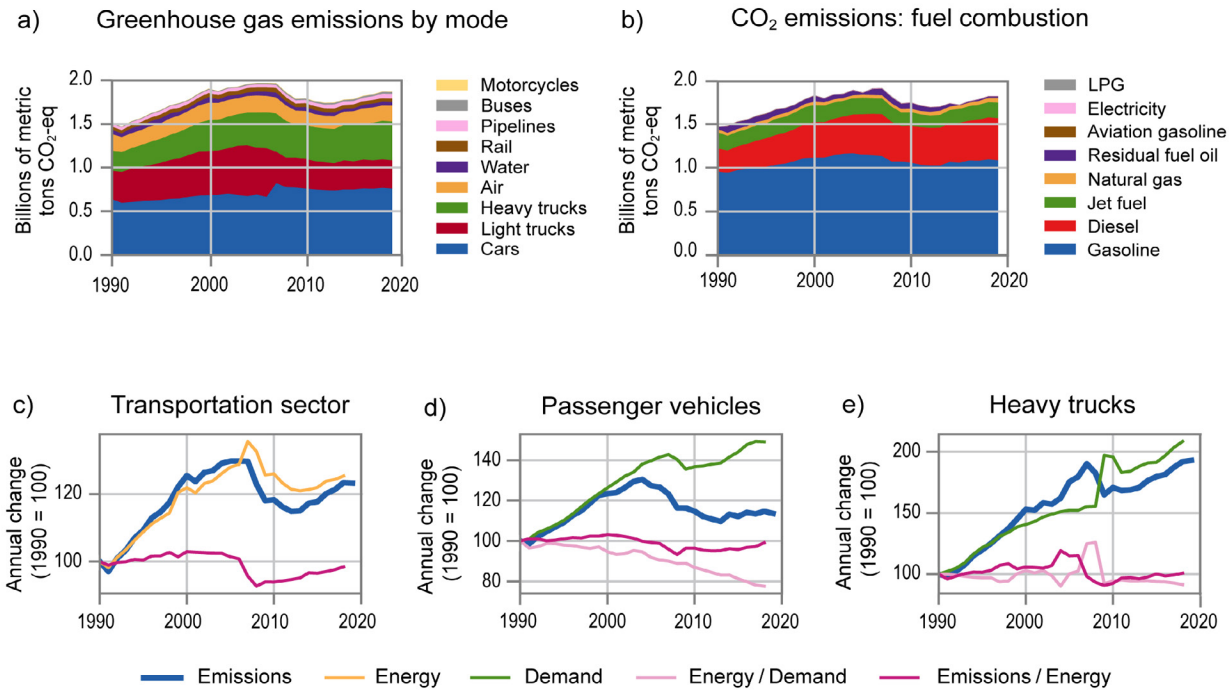
Carbon dioxide (CO_2) emissions from electricity generation decreased by almost 40% between 2005 and 2020.

Figure 32.3. The decrease in electricity-related emissions between 2000 and 2020 (**a**) can be explained by the decline in high-emitting coal generation and the growth in generation from lower-emitting (natural gas) and non-emitting (wind and solar) sources (**b**). CO_2-eq = carbon dioxide equivalent. Adapted from Scott Institute for Energy Innovation 2017[17] [CC BY-SA 4.0].

Transportation Sector Emissions

GHG emissions from the transportation sector in 2019 were 1,874 Mt of CO_2-eq.[7] Most transportation emissions are CO_2 emissions from combustion of gasoline (59.6%, mostly for light trucks and cars), diesel (26.4%, mostly for heavy trucks, buses, and trains), and jet fuel (9.8%; Figure 32.4). In contrast to electricity sector emissions, transportation emissions increased by 23% between 1990 and 2018, largely reflecting 49% growth in demand for passenger vehicle transport over the period (measured in passenger-kilometers, or the distance traveled in km multiplied by the number of passengers), which was partially offset by a 22% decrease in energy required per passenger-kilometer. Over the same 1990–2018 time period, demand for heavy trucks (measured in vehicle-kilometer, or the total distance traveled by the truck fleet) more than doubled, and improvements in energy per vehicle-kilometer were more modest (an 8.6% decrease in energy required per vehicle-kilometer).

Trends in Transportation Emissions and Underlying Drivers



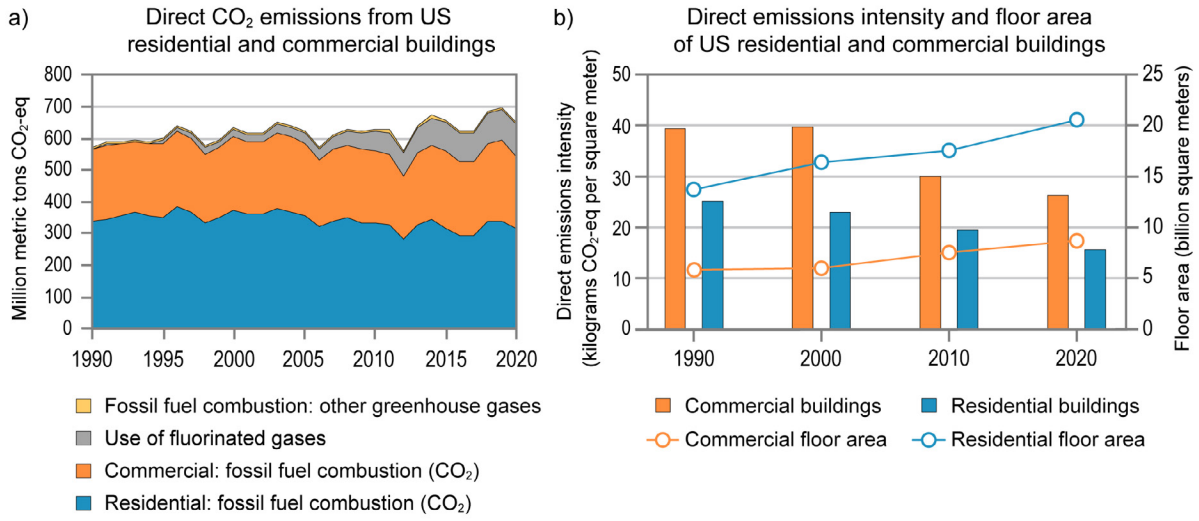
Transportations emissions fell from 2007–2012 but have climbed since then.

Figure 32.4. The figure shows US greenhouse gas emissions by transportation mode. Emissions from transportation decreased starting in 2007 (**a**), reflecting decreases in carbon dioxide (CO_2) emissions from fuel combustion (**b**), but both have increased again since 2012. The trend was consistent across different types of vehicles, driven by a drop in demand during a period of recession and high fuel prices (**c**, **d**, **e**). Passenger vehicles include cars, light trucks, and buses. LPG refers to liquified petroleum gas or propane; CO_2-eq = carbon dioxide equivalent. Figure credit: Stanford University.

Residential- and Commercial-Building Sector Emissions

Direct GHG emissions from residential and commercial buildings were 699 Mt CO_2-eq in 2019. Since 1990, direct emissions from US residential and commercial buildings (i.e., excluding electricity) have risen by roughly 14% (Figure 32.5a). The increase is primarily related to steady growth of fugitive emissions of fluorinated gases from building cooling systems.[8] Over the same period, energy efficiency improvements and increasing electrification have kept flat direct CO_2 emissions from onsite fuel combustion despite 50% increases in both residential and commercial building floor area (Figure 32.5b).[18,19]

Trends in Residential- and Commercial-Building Emissions and Intensities



Overall greenhouse gas emissions from buildings have climbed despite small declines in CO_2 emissions from onsite combustion of fossil fuels.

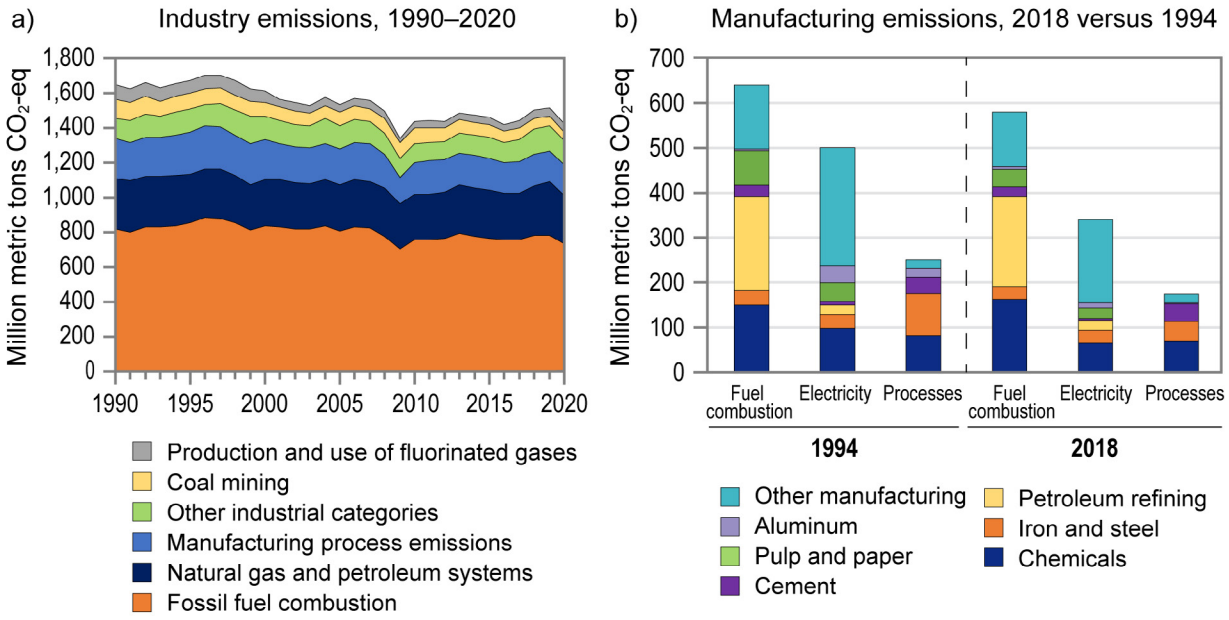
Figure 32.5. Carbon dioxide (CO_2) emissions from onsite fuel combustion in US buildings have decreased modestly since 2005 (**a**), driven by decreasing fuel-related emissions per building floor area (**b**), but overall related greenhouse gas emissions from buildings have increased over the same period due to both growth in the size of floor area (lines in panel b) and increasing levels of fluorinated gases escaping from building cooling systems (gray area in panel a). CO_2-eq = carbon dioxide equivalent. Figure credit: University of California, Santa Barbara.

Industrial Sector Emissions

GHG emissions from the industrial sector were 1,568 Mt of CO_2-eq in 2019.[8] Direct emissions from the industrial sector, including onsite fuel combustion as well as all process and fugitive GHG emissions (e.g., emissions from calcination of limestone in cement production and methane leakage from oil and gas infrastructure), decreased by 14% between 1990 and 2020, primarily due to decreases in total fossil fuel combustion, fluorinated gas production and use, and metals-related process emissions (Figure 32.6). The manufacturing sector (i.e., production of goods and materials) is the largest source of direct emissions within the overall industrial sector and accounts for substantial electricity sector emissions related to purchases of power and heat (Figure 32.6b). Six key manufacturing subsectors (petroleum refining, chemicals, cement, iron and steel, aluminum, and forest products) account for around 70% of all emissions attributable to the manufacturing sector (Figure 32.6b).

Between 1994 and 2018, electricity-related emissions from US manufacturing have decreased by about 32% due to improved process efficiencies, deployment of combined heat and power systems, and decarbonization of purchased electricity. However, direct emissions from onsite fossil fuel combustion have decreased by only 10% over the same period and now account for about three-quarters of direct manufacturing emissions (Figure 32.6b).

Trends in Industry Emissions



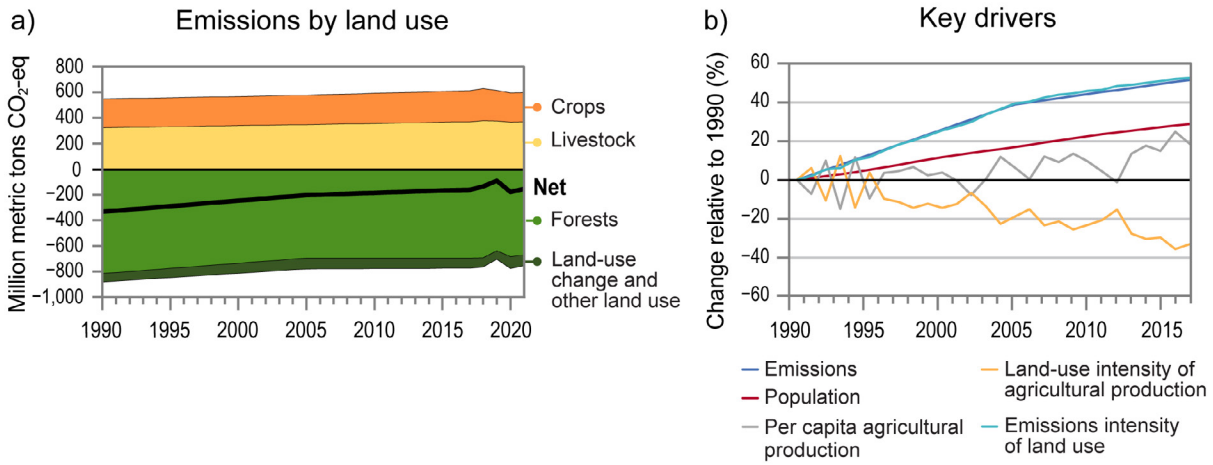
Greenhouse gas emissions from US industry, including manufacturing, have declined in recent decades.

Figure 32.6. Greenhouse gas emissions from US industry have declined modestly since 2005 across all sources (**a**). Panel **b** shows the breakdown of industry emissions in 1994 and 2018 by key manufacturing subsectors such as chemicals, iron and steel, pulp and paper, and aluminum. Data on intensity of industry emissions over time are not available. CO_2-eq = carbon dioxide equivalent. Figure credit: University of California, Santa Barbara.

Land-Related Emissions

Annual US GHG emissions related to land use in 2019 can be split into emissions of 615 Mt of CO_2-eq from agriculture and uptake of 704 Mt of CO_2-eq by other land use and land-use change (including forests; Figure 32.7). Thus in 2019, there was a net land-related uptake (i.e., negative emissions) of 90 Mt CO_2-eq. Forests take up carbon, but the amount of carbon sequestered by US forest land has decreased from 816 Mt CO_2 in 1990 to 638 Mt CO_2 in 2019[8] due to a combination of drought, wildfire, and disturbances by insects and disease (Box 7.2; KM 6.1).[20,21,22] Agricultural emissions (excluding fuel combustion) increased slightly from 548 Mt CO_2-eq in 1990 to 615 Mt CO_2-eq in 2019. The net uptake of 90 Mt CO_2-eq from US lands in 2019 represents a 73% decrease from the uptake of 333 Mt CO_2-eq in 1990.[8]

Trends in Land-Use Greenhouse Gas Emissions and Underlying Drivers



US forests sequester more carbon than is emitted by agriculture, but the forest sink has weakened in recent decades.

Figure 32.7. Net greenhouse gas emissions from US land use are negative, meaning the carbon taken up by forests is greater than agricultural emissions (**a**). However, this net sink has weakened since 2005, driven by increases in the emissions intensity of land use (light blue curve in panel **b**) and despite decreases in the land-use intensity of agricultural production (yellow curve in panel b). CO_2-eq = carbon dioxide equivalent. Figure credit: University of California, Irvine.

Key Message 32.2

We Know How to Drastically Reduce Emissions

A US energy system with net-zero emissions would rely on widespread improvements in energy efficiency, substantial electricity generation from solar and wind energy, and widespread electrification of transportation and heating (*high confidence*). Low-carbon fuels would still be needed for some transport and industry applications that are difficult to electrify (*high confidence*). Land-related emissions in the US could be reduced by increasing the efficiency of food systems and improving agricultural practices and by protecting and restoring natural lands (*high confidence*). Across all sectors, many of these options are economically feasible now (*high confidence*).

Established Opportunities to Reduce Energy-Related Emissions

In modeling studies, deeply decarbonized and net-zero-emissions energy systems share several common characteristics, but regional approaches may depend on differences in resources,[23,24] industrial bases,[25] existing infrastructure,[26,27] geography,[28] governance and politics,[29] public acceptance,[30] and broader policy priorities.[31]

Improve Energy Efficiency

Improving energy efficiency means supplying the same level of end-use services or output while using less energy. Efficiency of buildings and appliances can be improved by design or retrofits (e.g., better insulation),[32] as well as by optimizing control and management of devices (e.g., HVAC and lighting; KM 12.3;

Figure 5.5).[33] Further efficiency gains are available in the transportation sector: urban design can reduce travel demands;[34,35] public and active transportation modes can greatly reduce energy use per passenger-mile;[36,37] and advanced engines, electrification, reducing the weight of vehicles, and aerodynamic improvements can reduce energy use per passenger-mile (KM 13.3).[38,39,40] In model scenarios of energy systems that successfully reach net-zero CO_2 emissions, total US energy use often decreases relative to current levels, despite economic and population growth.[41,42]

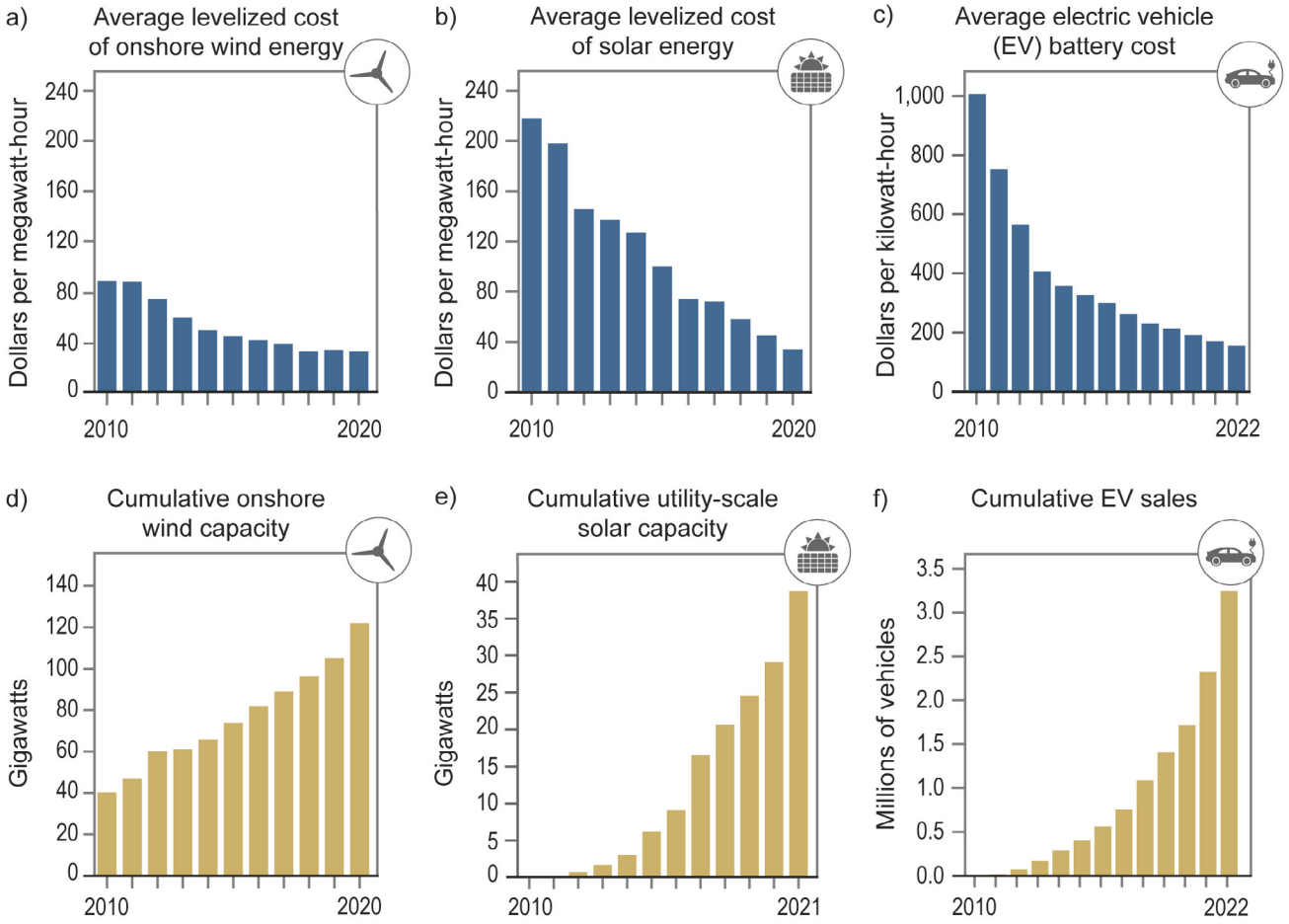
One of the concerns with energy efficiency is whether it can induce rebound effects of different types. Studies have shown that the direct rebound effect (i.e., use of more of a good or service as it becomes more affordable) is low in the context of energy goods and services, but there is more uncertainty regarding indirect rebound effects (i.e., how an increase in energy efficiency of a good or service may lead to a change in the use of other goods and services or changes in the overall economy).[43,44]

Decarbonize the Electricity Sector

Options for reducing electricity system emissions include variable renewables (e.g., solar and wind resources, which are not available on demand; KM 5.3), dispatchable or "firm" renewables (e.g., biomass, hydropower, and geothermal, which can be available on demand), and other low-emitting dispatchable resources (e.g., nuclear and carbon capture and storage [CCS]–equipped fossil-fired generators); energy storage technologies; improved transmission (both upgrading conductors and new rights-of-way); and demand management. The rate and scale at which these technologies may be deployed in the future depend on the uncertain trajectories of their costs and energy markets, as well as a host of non-economic factors (KM 32.4).[45,46,47,48,49,50,51,52,53]

However, given their plummeting costs (Figure 32.8a, b) and growing policy support (e.g., the Inflation Reduction Act of 2022[54]), variable renewable-energy resources—especially wind and photovoltaic solar generation—are expected to play central roles in decarbonizing electricity systems across the United States. Energy system models project that the capacity of wind and solar would need to increase 2 to 10 times faster each year than maximum historical rates (Figure 32.9b) to reach the 2030 target of halving economy-wide GHG emissions and midcentury net-zero targets (Figure 32.1).[41,42] In such scenarios, expansion of energy storage generally supports greater reliance on wind and solar (Figure 32.1).[41,42]

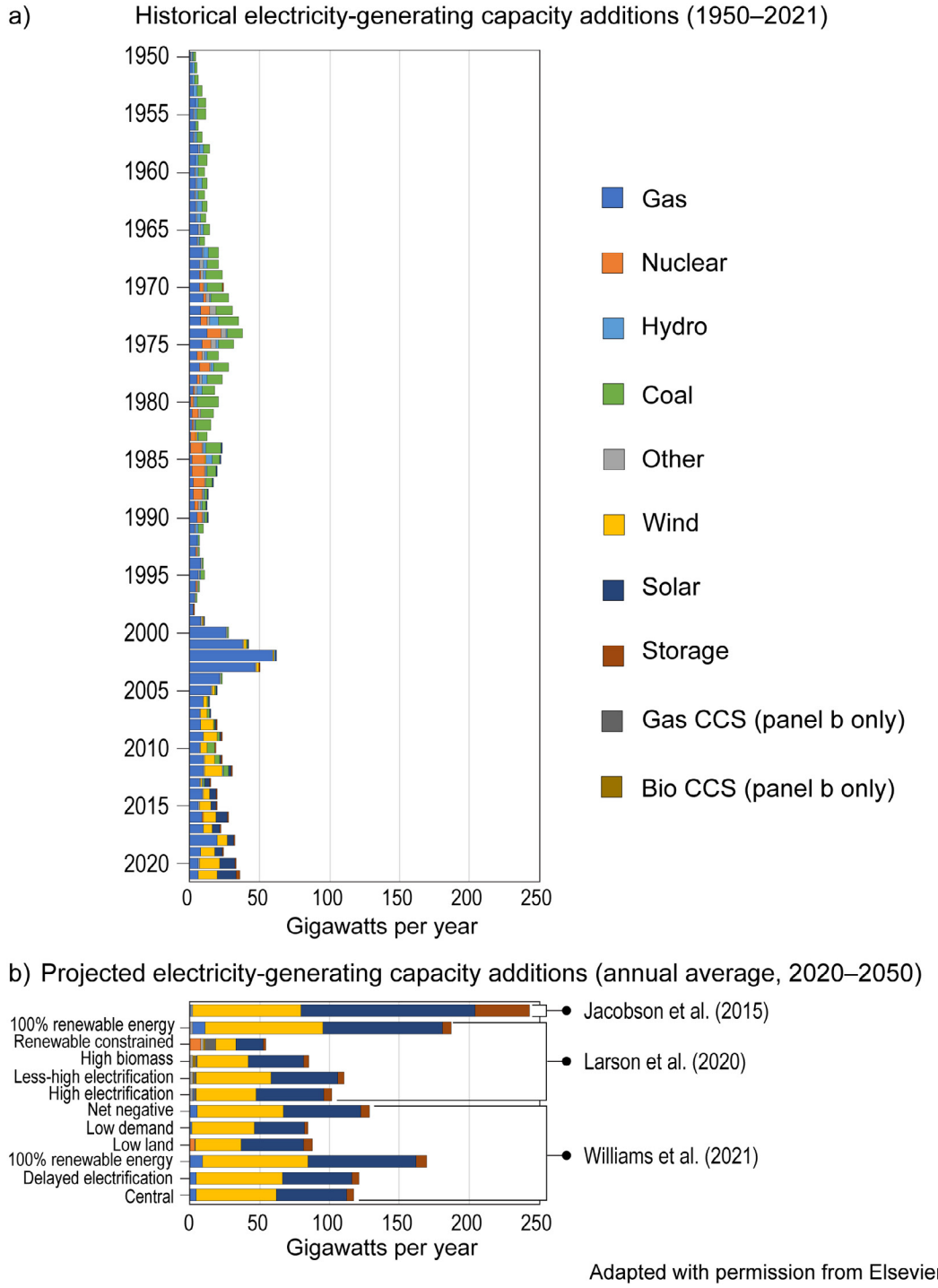
Historical Trends in Costs and Capacity of Low-Carbon Energy Technologies in the United States



Costs of renewable energy sources and electric vehicle batteries have declined as their cumulative deployment has increased.

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

Historical and Projected Net-Zero Annual Capacity Additions by Technology for the US Under Net-Zero Scenarios



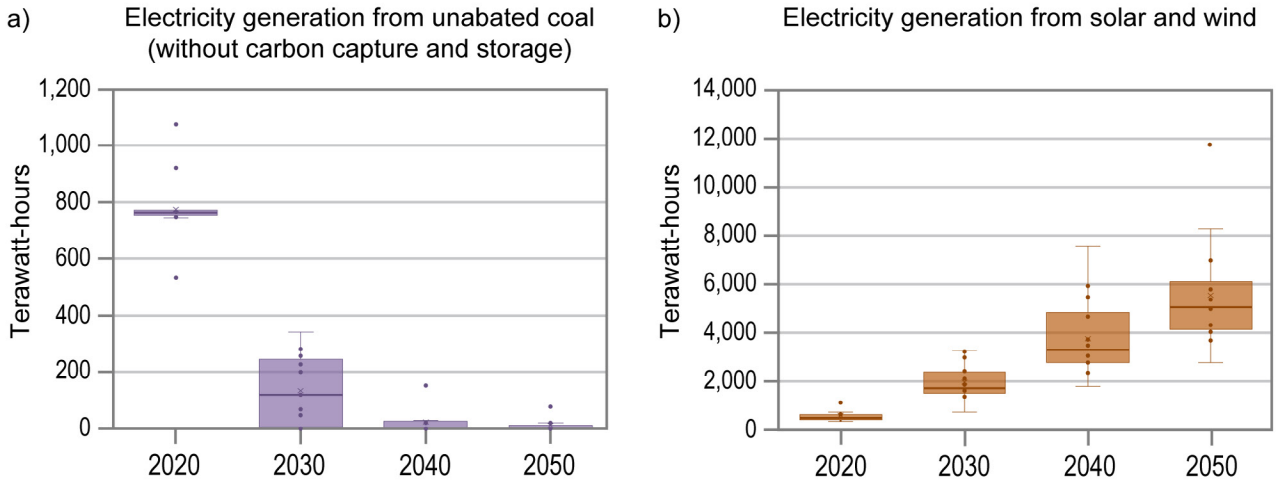
Adapted with permission from Elsevier ©2021.

To reach net zero, the US will need to add more electricity-generating capacity in each of the next 30 years than we have added historically.

Figure 32.9. Since 1950, increases in US electricity-generating capacity have exceeded 50 gigawatts (GW) in only one year, 2002 (**a**). In comparison, scenarios of net-zero-emissions energy systems produced by models project average increases in electricity-generating capacity of more than 50 GW per year every year between 2020 and 2050 (**b**). CCS refers to carbon capture and storage. See Jacobson et al. 2015; Larson et al. 2020; and Williams et al. 2021.[49,52,59] Adapted from Bistline 2021[60] with permission from Elsevier (https://www.sciencedirect.com/journal/joule).

The same model scenarios consistently project the rapid decline of coal-fired electricity generation in decarbonized systems to near zero by 2030 (Figure 32.10).[41,42] In contrast, natural gas–fired electricity generation declines more slowly in most of these net-zero emissions scenarios, facilitating penetration of variable renewables but operating less frequently over time unless equipped with CCS.[52,55,56]

Projected Coal and Solar/Wind Electricity Generation



Models project a steep decline in coal-generated electricity and increases in renewables.

Figure 32.10. Across net-zero scenarios produced by models, median US coal electricity generation (thick horizontal lines) is expected to decrease sharply between 2020 and 2030 (**a**). Meanwhile, in the same scenarios, median solar and wind generation would increase steadily between 2020 and 2050 (**b**). Plots show individual scenarios as points, the 25th–75th percentile ranges as rectangles, and the 10th–90th percentile ranges as thin vertical lines. The mean of each set of scenarios is represented by an X. Figure credit: University of California, Irvine, and Electric Power Research Institute.

Finally, net-zero CO_2 emissions scenarios often maintain—but do not greatly expand—existing nuclear and hydropower capacity in the absence of significant cost declines (such as improved economics from small modular designs; KM 5.3) and/or constraints on the deployment of other technologies.[41,42,57] In contrast, both transmission infrastructure (i.e., power lines) and international and interregional transfers of electricity often increase in decarbonization scenarios, although the scale of such increases varies.[41,42,58]

Electrify Energy End Uses

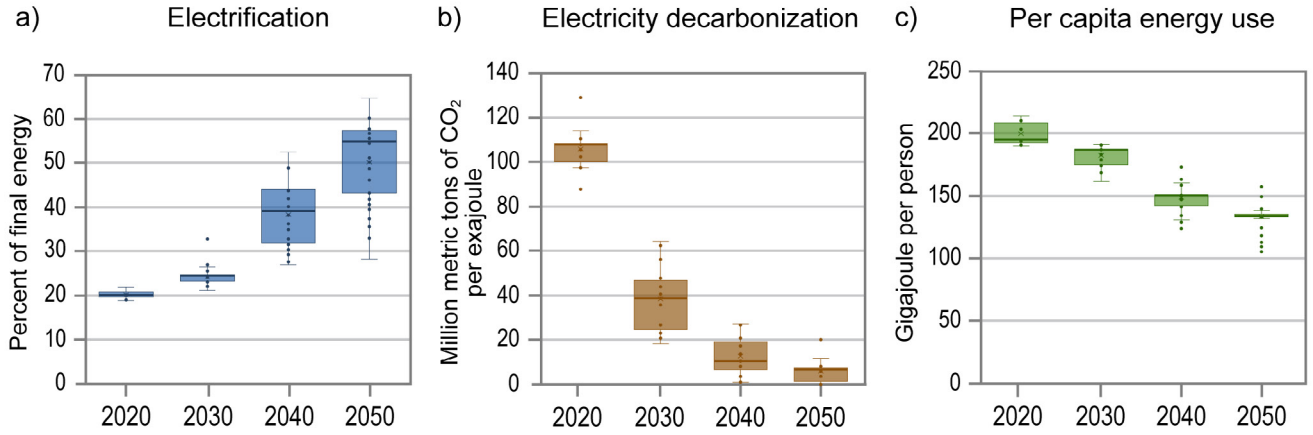
As electricity systems are decarbonized, energy model scenarios consistently project widespread electrification of energy end uses such as on-road transportation and heat for buildings and industry (KM 5.1).[41,42,49,51,52,53,61] Electricity may also be used to produce low-carbon fuels, such as hydrogen and e-fuels (liquid fuels produced by combining carbon captured from the atmosphere with hydrogen produced by electrolysis), for difficult-to-electrify applications (Box 32.1).[62] The share of US final energy demands (i.e., energy used) met by electricity in net-zero-emissions energy systems will depend on the costs of low-carbon alternatives such as biofuels and hydrogen, but estimates range from 30%–60% in 2050, up from about 20% today (Figure 32.11).[41,42]

In transportation, light-duty electric vehicles (EVs) have had policy support (e.g., tax refunds) at both the state and federal level for a long time, and new EV sales have increased in recent years (Figure 32.8).[63,64,65,66] The EV share of new light-duty vehicle sales in the US is expected to grow quickly,[66,67] which is the case in model scenarios that reach net-zero emissions by midcentury.[41,42] Many medium- and heavy-duty

vehicles can also be electrified,[68] although some applications (e.g., long-distance trips) may present special challenges.[69,70,71,72,73] Decarbonization of the most difficult-to-electrify transportation sectors (e.g., aviation, international shipping) may require liquid biofuels or fuels synthesized using electrolytic hydrogen and carbon captured from the atmosphere.[74,75]

Insofar as electricity is generated from non-emitting sources, electrification of space and water heating would drastically reduce direct emissions from residential and commercial buildings in the United States (where these end uses account for the bulk of natural gas and oil consumption).[76,77,78] Similarly, most industrial energy demand could be electrified using existing technologies,[79] although achieving net-zero emissions in some industries may present special challenges[80,81,82,83]—particularly related to the costs of supplying high-temperature heat with electricity[84] and/or fundamental changes in processes such as switching to direct reduction of iron ore with electrolytic hydrogen or installing carbon capture and storage on thousands of cement kilns worldwide.[85]

Characteristics of US Energy Systems in Climate Mitigation Scenarios



Net-zero model scenarios show large increases in electrical energy, accompanied by decarbonization of electricity sources and modest decreases in overall energy use per person.

Figure 32.11. Across net-zero model scenarios, between 2020 and 2050 the median share of all energy used (thick horizontal lines) by end consumers that is electricity increases (**a**), the median carbon intensity of electricity decreases (**b**), and the median energy per capita decreases modestly (**c**). Plots show individual scenarios as points, the 25th–75th percentile ranges as rectangles, and the 10th–90th percentile ranges as thin vertical lines. The mean of each set of scenarios is represented by an X. CO_2 = carbon dioxide. Figure credit: University of California, Irvine; Electric Power Research Institute; and Evolved Energy Research.

Established Opportunities to Reduce Land-Related Emissions

Despite increasing demand for food and the headwinds of climate change impacts on agriculture, there are multiple options for decreasing land-use emissions and protecting and enhancing terrestrial carbon sinks (Ch. 11).

Use Most-Productive Land for Agriculture

Agriculture requires more land, by far, than any other human activity.[86] One way to reduce the land required to grow food is to continue farming the most productive lands (those that grow more crops per land area). Removing the most productive areas from cultivation would lead to an increase in the overall land area required for agriculture.[87] Loss of productive US farmland to sprawl or even restoration could thus lead to substantial land-use change and related GHG emissions elsewhere (e.g., if demanded agricultural goods

are imported from other regions).[88,89] For these reasons, studies have suggested mitigation efforts should prioritize restoration of marginal (i.e., not the most productive) lands.[90]

Reduce Food Waste

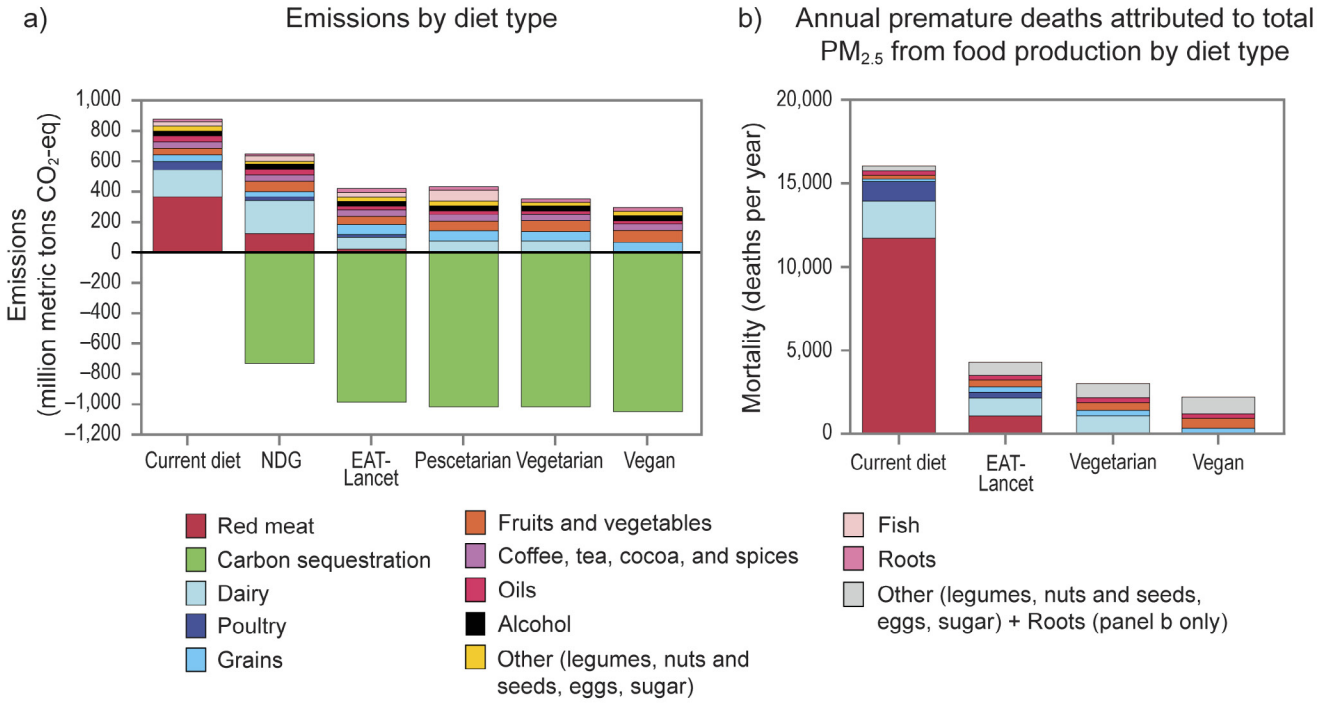
More than a third of all food in the US is currently wasted, more than 40% of which is food discarded by retailers and consumers (Box 11.2; Figure 11.12).[91,92] Multiyear campaigns (from 4 to 11 years long) in five other developed countries successfully reduced food waste per person by 8%–29% through public education and public and private initiatives.[91] Assuming similar reductions could be achieved, US agricultural land and land-related GHG emissions could be reduced by 4%–13%.

Shift Diets

GHG emissions produced during food production, distribution, transportation, and sale at retail or restaurants vary across different foods, so that different diets will entail different levels of life-cycle GHG emissions.[93,94,95,96] In particular, although meat is a good source of protein and micronutrients, it generally produces more emissions per calorie than plant-based foods because energy is lost at each trophic level.[93] Emissions related to meat production also vary: for example, ruminant animals usually produce much more GHG emissions per calorie of meat and per gram of protein than poultry (Figure 11.8).[97] By reducing demand for emissions-intensive food, shifts to pescatarian, vegetarian, vegan, Mediterranean, or "flexitarian" (less meat consumption but not strictly vegetarian) diets can reduce land-related GHG emissions while providing direct health benefits (Figure 32.12),[94,98,99,100] although analyses and models differ as to the level of future food demand related to such diets and other socioeconomic changes.[101] Shifting diets and associated changes in agricultural practices have implications for land-use change as well as supply chains, air pollution, and human health.[102] Consideration of energy and other inputs per unit of production and the resulting impacts on net GHG emissions is important for comparison of different dietary choices.

However, 10.4% of American households are food insecure (Box 11.1),[103] so any approach to reduce the consumption of higher-emissions foods that results in higher food prices could disproportionately harm these households. Instead, policies might encourage less emissions-intensive diets while also reducing food costs and increasing consumer choice by making a diversity of plant-based and other lower-emissions, nutritious, and affordable options more widely available.

Emissions Reductions and Related Health Benefits from Dietary Shifts



Changes in American diets could decrease US land-use greenhouse gas emissions, increase carbon sequestration, and reduce air pollution.

Figure 32.12. Studies have estimated potential reductions in greenhouse gas (GHG) emissions (**a**) and air pollution-related deaths (**b**) if the shares of foods in Americans' current (average) diet were to shift. Although the specific changes in diet vary across studies, all would reduce GHG and pollution emissions as well as enhance carbon sequestration relative to the current diet. EAT-Lancet refers to a "flexitarian" diet that is mostly plant-based but includes modest amounts of fish, meat, and dairy foods. NDG refers to government-endorsed national dietary guidelines. $PM_{2.5}$ refers to particulate matter 2.5 micrometers or smaller in diameter. CO_2-eq = carbon dioxide equivalent. Figure credits: (a) University of Minnesota, NOAA NCEI, and CISESS NC; (b) adapted from Domingo et al. 2021[102] [CC BY-NC-ND 4.0].

Improve Management of Croplands and Pasture

There are numerous opportunities to decrease the intensity of emissions (and/or increase sequestration; see Box 32.2) of croplands and pasture, including 1) improving soil health, 2) improving nitrogen fertilizer management, 3) increasing the number of trees and other perennials on the landscape (e.g., by agroforestry; see Ch. 11),[104,105,106] and 4) avoiding methane emissions. Soil health and carbon sequestration can also be improved by amendments (including biochar; Figure 11.5), cover crops, reduced tillage,[107] and diversification of crop rotations.[108] Careful and sustained implementation of these practices can increase not only soil carbon but also yields, resilience, and profitability.

Better aligning the timing and amount of fertilization with plants' needs can reduce fertilizer use[109,110] and thereby also reduce both nitrous oxide (N_2O) emissions from the soil and fossil fuel emissions from fertilizer production. Fertilizers with synthetic nitrification inhibitors can further reduce N_2O emissions.[111] Increased fertilizer efficiency and inhibition of nitrification processes in soil together can reduce N_2O emissions by roughly 50%.[112,113]

There are also feasible options for reducing agricultural (livestock and rice) and waste (landfill and wastewater) sources of methane emissions.[114] Methane is a relatively short-lived GHG that has contributed

to at least 25% of climate warming to date.[115,116] Consequently, technically feasible near-term methane emissions reductions could slow global decadal warming by 30%, avoiding a quarter degree Celsius of warming by midcentury.[114] In addition to land-related sources of methane, there are large reductions possible from the oil and gas sector,[117] primarily by repairing leaks at little or no net cost[114] and ideally prioritizing disproportionately large sources (i.e., super-emitters).[118,119,120]

Avoid Conversion and Monitor Carbon Fluxes on Unmanaged Land

Between 50 and 150 Mt of annual CO_2 emissions could be avoided by stopping conversions of unmanaged land in the United States (i.e., natural forests, grasslands, wetlands, or other ecosystems where there has been no substantial human influence or intervention).[121] Strategies for stopping such conversions include densification of already-developed areas, zoning, and property tax incentives, as well as land protection such as conservation easements and public parks.[122,123,124,125] Related to this opportunity, the recent decrease in carbon sequestration by US forests (KM 32.1) is a concern. Further weakening of this carbon sink would make reaching net zero proportionally that much more difficult. Improved monitoring of forest carbon fluxes and their drivers is therefore important, including those on unmanaged land and in boreal Alaska (KM 7.2).[126,127,128]

Key Message 32.3

To Reach Net-Zero Emissions, Additional Mitigation Options Need to Be Explored

Although many mitigation options are currently available and cost-effective, the level and types of energy technologies and carbon management in net-zero-emissions energy systems depend on still-uncertain technological progress, public acceptance, consumer choice, and future developments in institutions, markets, and policies (*high confidence*). Attractive targets for further research, development, and demonstration include carbon capture, utilization, and storage; long-duration energy storage; low-carbon fuels and feedstocks; demand management; next-generation electricity transmission; carbon dioxide removal; modern foods; and interventions to reduce industry and agricultural emissions (*medium confidence*).

Potential Opportunities to Reduce Energy-Related Emissions

There are many uncertainties and outstanding questions related to mitigation of energy-related emissions. These uncertainties are reflected by the large differences in the scale and mix of energy sources and use as well as carbon management across modeled net-zero-emissions energy systems, which highlight potential mitigation opportunities.

The Mix of Electricity Sources in Net-Zero-Emissions Energy Systems

In recently modeled net-zero-emissions US energy systems, the share of electricity demand met by variable renewables—as opposed to firm sources—varied from 45%–89% depending on the availability of energy storage, transmission, and the mix of solar and wind.[41,42] Although grid managers are gaining experience planning and operating electricity systems with large amounts of solar and wind generation, questions persist as to the maximum share of these resources that should be included in reliable and resilient decarbonized systems[129] and the best approaches for dealing with their natural variability.[130] Large shares of variable renewables can be incorporated in electricity grids through the use of 1) batteries, hydrogen, and other types of energy storage; 2) transmission and interregional transfers of electricity; 3) firm low-carbon electricity sources; and 4) greater demand-side responses. The costs and effectiveness of these approaches for managing variability differ and are related to the spatial and temporal variability of solar and wind

resources,[24,75,131,132,133,134,135,136] in addition to a host of non-cost factors (KM 32.4). Moreover, energy sources and technologies will interact in complex ways to fulfill the different functions in electricity systems (e.g., providing energy, capacity, and ancillary services over different timescales), depending on their relative costs and system benefits, policy stringency and design, geophysical resources and infrastructure, environmental co-benefits, and societal preferences.[55,56,137] Further research, development, and demonstration of technologies and approaches are needed to resolve uncertainties, identify key sensitivities, and clarify the most attractive options for providing reliable, resilient, and affordable electricity in net-zero-emissions energy systems (Figure 5.6).

Alternative Fuels for Difficult-to-Electrify Sectors

As with electricity, there is considerable uncertainty about the scale and mix of other energy carriers (e.g., hydrogen, bioenergy, e-fuels) that may be needed by difficult-to-electrify sectors such as long-distance transportation of freight, long-haul aviation, high-temperature industrial heating, and space heating in very cold climates.[75,84,138,139,140] Hydrogen, ammonia, alcohols, and carbon-based fuels (e.g., methane, petroleum, methanol) can all be produced with low and eventually net-zero CO_2 emissions (Box 32.1). However, it is not clear whether producing and burning these fuels would be lower in cost and more sustainable than continuing to use fossil fuels and managing the related emissions through CCS or carbon dioxide removal (CDR; removal of CO_2 from the atmosphere).[62] Here again, further research, development, and demonstration of technologies will help reveal critical dependencies and trade-offs and clarify the most sustainable and cost-effective pathways to net-zero-emissions fuels.

Box 32.1. Hydrogen

Hydrogen is an energy carrier that could link together multiple energy sectors (known as sector coupling) and facilitate high shares of variable wind and solar generation in electricity systems.[141,142] Multiple processes can produce hydrogen—including electrolysis, which uses electricity to split water into hydrogen gas (H_2) and oxygen gas (O_2). These processes represent potential links between the electricity sector, fuels for transportation and industry, and feedstock for chemical materials.

Some electrolyzers (e.g., proton exchange membrane) can also be ramped up and down in seconds[143,144] to help manage electricity demand in energy systems with variable electricity sources.[142,145] Other means of producing hydrogen with low or no CO_2 emissions, such as methane or biomass pyrolosis and steam methane reforming (SMR) with carbon capture, utilization, and storage (CCUS),[142,146,147] may also contribute to decarbonization if life-cycle GHG emissions can be kept low,[148,149] but these will not facilitate sector coupling or act as flexible electricity demand.

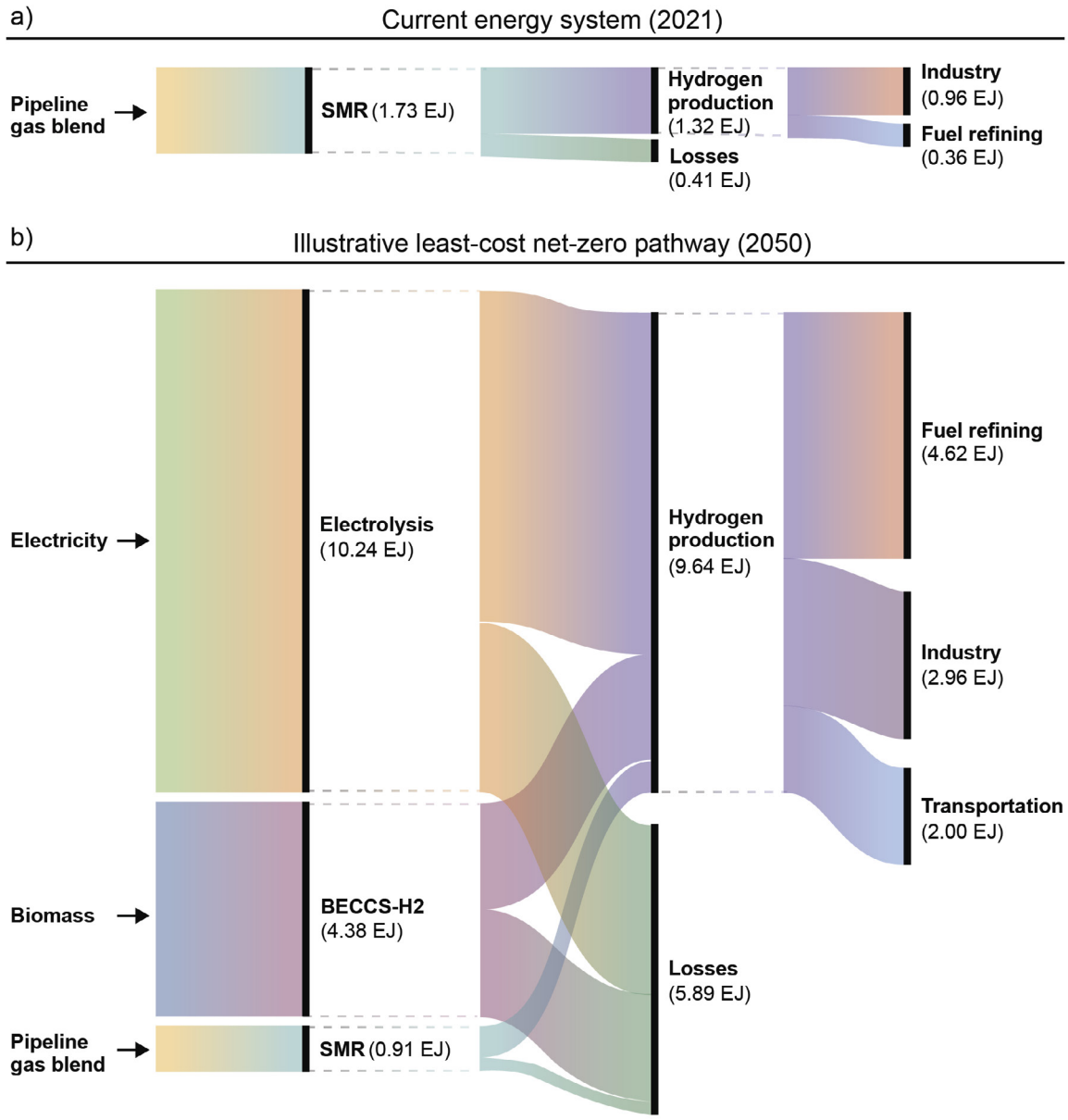
Global hydrogen demand was 90 Mt in 2020 and was supplied almost exclusively by fossil fuel feedstocks: 59% by natural gas without CCUS, 19% by coal, 21% from by-product processes that often contain a mixture of other gases, and less than 1% each of natural gas with CCUS, oil, and electricity (Figure 32.13).[150] Petrochemical processes were the largest sources of by-product hydrogen. Reflecting its fossil origin, hydrogen production in 2020 accounted for 900 Mt of CO_2 emissions.[150] Of all hydrogen produced in 2020, 44% was used in refineries, 37% in ammonia production, 14% in methanol production, and 6% in the direct reduction of iron, with other demands accounting for less than 1%.[150]

As noted in the discussion of alternative fuels (KM 32.3), hydrogen may help to decarbonize difficult-to-electrify end uses such as long-distance transport of freight and aviation, for which energy density is critical.[74,75] However, pressurizing or storing hydrogen in liquid phase for transport and storage adds additional costs and requires heavy storage tanks.[75,142] When used, hydrogen can either be oxidized in fuel cells or combusted in gas turbines[151,152] to produce electricity (or thrust) in a power-to-gas-to-power loop. Although substantial energy is lost in this loop, it allows shifting electricity in time from when it is readily available to when it is needed most.[131,134]

A key challenge is the current high cost of producing hydrogen from zero- or low-emitting processes. Hydrogen produced from carbon-emitting SMR can cost in the range of \$1–\$2.50/kg H_2, much lower than the more than \$4/kg H_2 achievable with current electrolysis technology and wind or solar power.[153,154] The US Department of Energy's Hydrogen Shot program has set a goal of achieving clean hydrogen production for \$1/kg H_2 within a decade by reducing both electrolyzer and

wind- and solar-electricity costs (KM 5.3).[153] There are also challenges of leakage from and embrittlement of infrastructure not originally designed for hydrogen, such as natural gas pipelines, which create concerns about safety,[142,155] the potential for increases in air pollutants such as nitrogen oxides if hydrogen is combusted,[156,157] and the climate-warming influence of fugitive hydrogen.[158,159] However, at low concentrations, hydrogen can be safely injected into natural gas pipelines and used in conventional home appliances.[160,161,162,163,164]

Hydrogen Production by Source and End Uses in 2021 and 2050



Energy model scenarios show that the magnitude, sources, and uses of hydrogen will change substantially by 2050.

Figure 32.13. Curves in the figure show how hydrogen is produced (left), lost to waste (middle) and used (right) currently (**a**) and in an illustrative 2050 scenario (**b**). The thickness of the curves represents the amount of hydrogen in each category. Today, most hydrogen is produced by steam reforming of natural gas (SMR) and used by the chemical industry (especially for making fertilizer). In the depicted net-zero emissions scenario, by 2050 the largest source has become electricity, and fuel refining has become the largest use. BECCS-H2 refers to hydrogen produced from biomass feedstocks with carbon capture and storage; EJ = exajoule. Adapted with permission from Haley et al. 2022.[165]

Carbon Management

Most model scenarios that reach net-zero emissions in the United States entail substantial use of CDR technologies, not as a replacement for emissions reductions but instead to offset continuing emissions from the most difficult-to-decarbonize sectors and processes, such as aviation and cement making (sources of emissions that may be much more expensive to eliminate), to offset non-energy GHG emissions, and to reduce GHG concentrations in the atmosphere. The degree and form of CDR deployment, including the balance between industrial carbon capture and intentional enhancement of natural carbon sinks, remain highly uncertain, however, and depend on technological readiness, economics, public acceptance, and institutional and political considerations (Box 32.2).

Box 32.2. Carbon Dioxide Removal

The most recent modeling studies of net-zero emissions scenarios for the United States consistently project that some quantity of carbon dioxide removal (CDR) from the atmosphere will be needed to offset any residual greenhouse gas (GHG) emissions.[41,42] The scale of CDR called for in these scenarios ranges from 0.8–2.9 gigatons (Gt) of carbon dioxide (CO_2; median is 1.6 Gt) in scenarios that reach net-zero CO_2 emissions by 2050 (Figure 32.14).

CDR options fall into two categories according to whether they enhance uptake of atmospheric CO_2 by biological processes or by chemical processes, each of which can be further disaggregated depending on where the processes occur (e.g., on land, in the ocean, or in industrial facilities).[166,167] Different approaches have different biophysical and economic limits to scale,[168] as well as different concerns related to equity and environmental justice,[169,170] environmental impacts,[171] permanence or durability of removal (i.e., the timescale of sequestration and its reversibility),[172,173,174] and additionality (i.e., the removal would not have occurred without human intervention).[166,175]

Current energy models are relatively simplistic in their representation of CDR, typically including only 1) bioenergy with carbon capture and storage (BECCS), 2) afforestation/reforestation, and 3) industrial direct air capture (DAC). Among these methods, the on-land biological options (BECCS and afforestation/reforestation) are the most prevalent in net-zero emissions scenarios; BECCS dominates if underground carbon sequestration is allowed (Figure 32.14).

Most scenarios use DAC sparingly, owing to its cost and energy requirements (Figure 32.14), but recent studies have highlighted potential cost reductions.[176] Evaluations of natural climate solutions meanwhile suggest that reforestation represents the largest opportunity for land-based mitigation.[177] Up to 128 million acres of land in the US are reforestable and could sequester 200–500 million metric tons (Mt) of CO_2 per year[178,179] given substantial investments in the reforestation supply chain.[180]

However, a variety of other biological CDR options are being explored and could be cost-effective at carbon prices of \$50–\$100/Mt CO_2: improved management of rangeland and pasture might sequester 0.05–0.74 Mt of CO_2 per acre per year, or a total of 49–490 Mt of CO_2 per year, given the roughly 655 million acres of US grazing land.[121,181,182,183,184] Improved management of cropland soil (e.g., applying biochar, cover crops, or no-till) might sequester 150–250 Mt of CO_2 in the United States each year.[121,185,186,187,188] In forests, extending timber rotations, removing competing vegetation, and selective harvesting could remove 160–315 Mt CO_2 per year.[179,189,190,191,192,193,194,195,196] Finally, rewetting drained US wetlands[197,198] and reconnecting salt marshes to the ocean (which reduces methane emissions)[199] could remove 9 Mt of CO_2 per year.[121] These options are discussed further in other chapters (KMs 6.3, 9.2, 11.1; Boxes 7.2, 30.5; Focus on Blue Carbon).

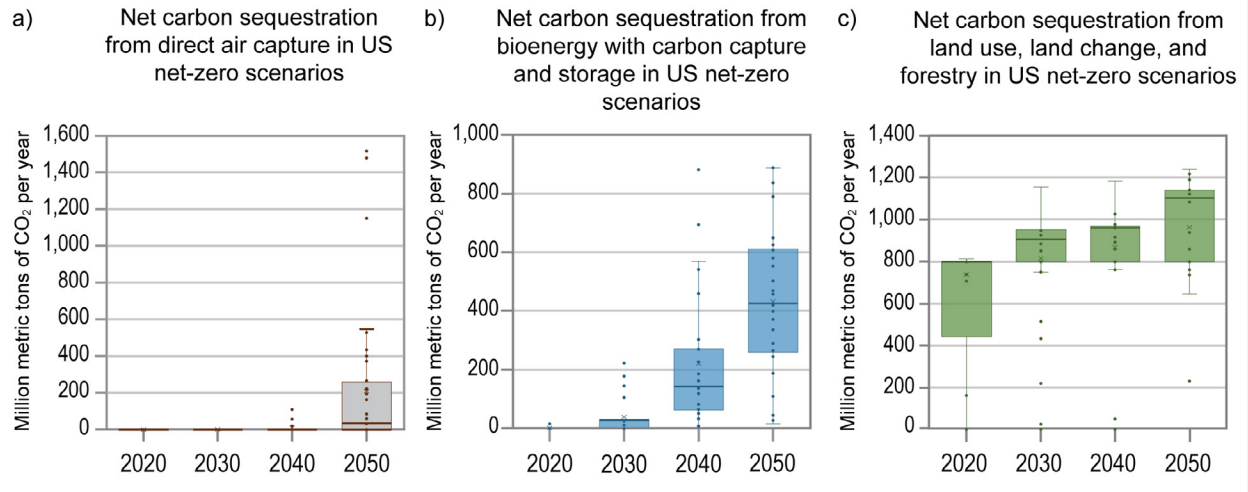
Although less mature, a growing body of research is also focusing on ocean-based CDR,[200] including ocean fertilization,[201] artificial upwelling and downwelling, seaweed farming,[202] marine restoration, ocean alkalinity enhancement,[203] and electrochemical engineering approaches (see, e.g., KM 10.3).

Additional research could reduce the uncertainty related to these estimates; establish robust monitoring, reporting, and verification protocols; and help to prioritize types and locations for CDR based on co-benefits and trade-offs. A related area of research is the Earth system response to large-scale CDR (i.e., negative emissions); a growing body of literature has shown that emitting GHGs and then removing them from the atmosphere is not the same as not emitting the GHGs at all.[204,205,206]

Reducing sunlight reaching the Earth's surface, or solar radiation modification (SRM), is sometimes discussed alongside CDR because both are intentional interventions in the climate system.[166,207] SRM is not mitigation as defined in this

chapter; the effectiveness, costs, environmental trade-offs, and geopolitical implications of SRM are uncertain, and further research on these topics is either underway or may be merited (KM 17.2). Moreover, some scientists and policymakers emphasize that the risks of SRM should be considered in the context of the many risks of continued climate change.[208]

Scale and Type of Carbon Dioxide Removal in US Net-Zero Emissions Scenarios



Net-zero emissions scenarios project substantial carbon dioxide removal by 2050, although the type and quantities used in the scenarios vary considerably.

Figure 32.14. Annual carbon dioxide (CO_2) removals increase between 2020 and 2050 in scenarios that reach net zero by 2050, including nature-based sequestration on land (**c**), bioenergy with carbon capture and storage (**b**), and—after 2040—direct air capture (**a**). Median sequestration (thick horizontal lines) by land use, land-use change, and forestry increases less dramatically in scenarios. Plots show individual scenarios as points, the 25th–75th percentile ranges as rectangles, and the 10th–90th percentile ranges as thin vertical lines. The mean of each set of scenarios is represented by an X. Figure credit: University of California, Irvine.

Changes in Transportation Modes and Behavior

Uncertain changes in mobility and travel behavior could facilitate or hinder mitigation. For example, autonomous vehicles are rapidly evolving but still need to overcome challenges of consistent safety measures, standardization of technology liability, and security and privacy concerns.[209,210] Studies have shown that autonomous vehicles could increase or decrease energy use and GHG emissions depending on the conditions of adoption and use.[211,212,213] New mobility services (e.g., ride-hailing or transit services with a monthly subscription) are becoming widespread and have the potential to transform current patterns of travel behavior, but they still face challenges of cost-competitiveness and consumer acceptance.[214,215,216] And as with automation, these mobility services may reduce emissions under a limited set of conditions (e.g., electrification and shared use cases).[213,217,218,219]

Sector Coupling

The integration of different parts of energy systems, sometimes referred to as sector coupling, involves coordinated planning, operations, and markets for electricity, fuels, and thermal resources to meet end-use service demands. Linking energy industries, processes, and geographies could lower costs, reduce environmental impacts, and increase the reliability of low-carbon energy systems.[75,220,221]

Potential Opportunities to Reduce Land-Related Emissions

Modern Foods

Recent innovations aim to increase food choices with plant-based and cultured meat[222,223,224] and foods synthesized chemically without photosynthetic inputs[225,226] that may be able to displace demand for foods with substantially higher emissions per calorie. However, the potential benefits will depend on the scalability and public demand for such products.

Interventions to Reduce Methane and Nitrous Oxide Emissions

There are a number of options for reducing non-CO_2 GHG emissions from agriculture whose potential remains uncertain. Ruminant feed supplements may suppress methane emissions (although some such supplements have not yet been approved for use in the United States).[227,228] Methane from manure lagoons can be captured and used for bioenergy or reduced through flaring.[229] Seasonally flooded rice paddies can undergo temporary drainage to reduce emissions by about 40%.[230] And crops may be bred to produce root exudates that inhibit nitrification and thereby reduce N_2O emissions from croplands.[231]

Key Message 32.4

Mitigation Can Be Sustainable, Healthy, and Fair

Large reductions in US greenhouse gas emissions could have substantial benefits for human health and well-being (*high confidence*). Mitigation is expected to affect pollution, the use of land and water resources, the labor force, and the affordability, reliability, and security of energy and food (*high confidence*). An equitable and sustainable transition to net-zero-emissions energy and food systems in the United States could help redress legacies of inequity, racism, and injustice while maximizing overall benefits to our economy and environment (*high confidence*).

A number of important dimensions rarely represented in mitigation scenarios may nonetheless determine the pace, feasibility, likelihood, efficacy, and cost-effectiveness of mitigation opportunities.

Air Pollution

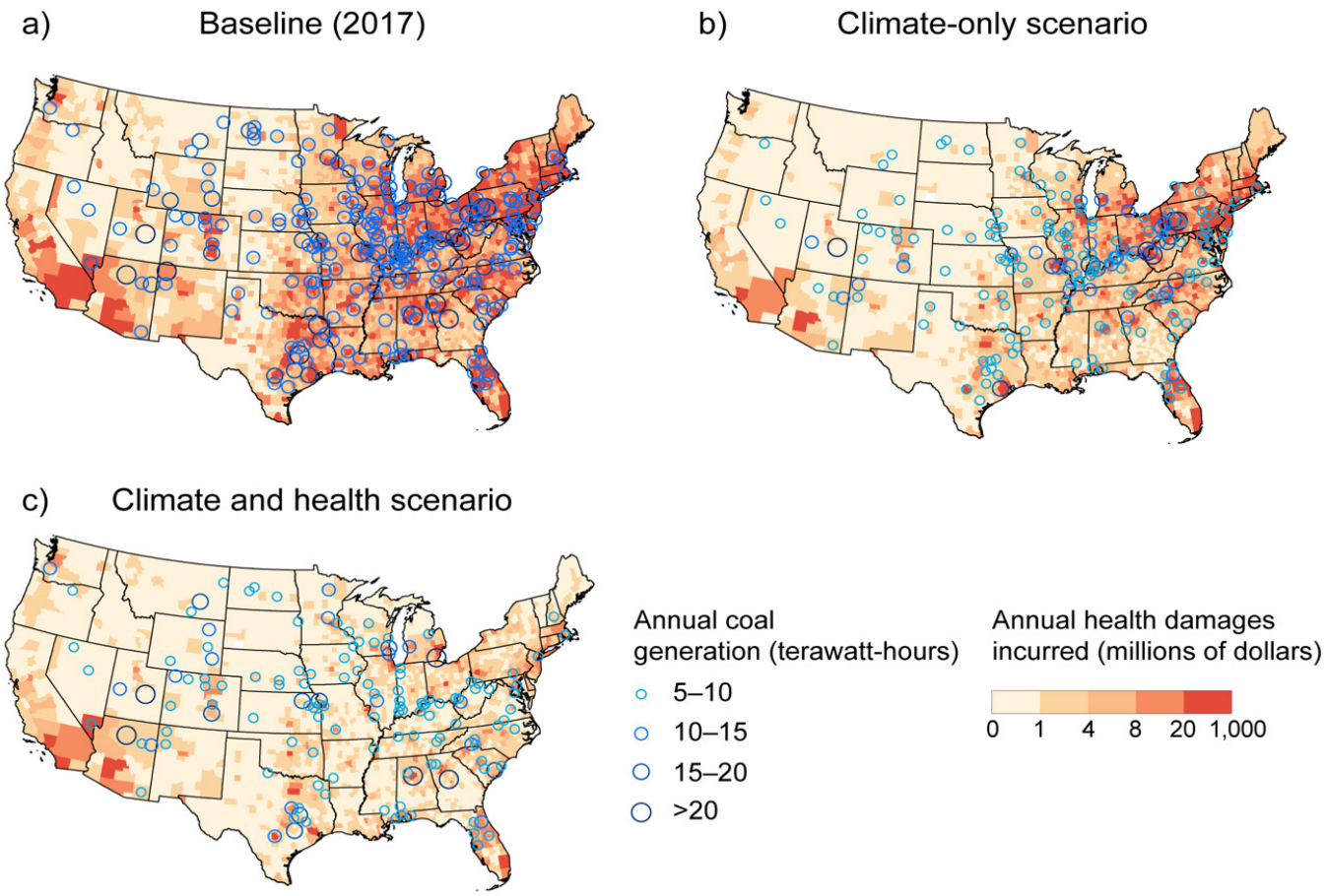
Air pollutants that impact human health are often co-emitted with greenhouse gases. Exposure to ambient fine particulate matter ($PM_{2.5}$) and ozone, which are among the largest risk factors for disease, causes 60,000–300,000 excess deaths per year in the United States (KM 14.5),[232,233,234,235,236,237,238] with health effects observed at concentrations below the current national standard.[239,240,241] Racial, ethnic, and socioeconomic disparities in air-pollution exposure are well documented[234,242,243,244,245,246,247] and have persisted despite overall decreases in air pollution.[234,240]

Transitioning to a net-zero-emissions energy system has the potential to generate substantial air pollution benefits. Estimates of cumulative net benefits by 2050 range from roughly 200,000 to 2,000,000 avoided deaths,[233,248,249,250] the monetized value (i.e., statistical value) of which could exceed the total expected costs of the transition to net zero.[49,251] However, the distribution and magnitude of air pollution benefits over the transition period depend on the pace of electrification, technology selection, and siting decisions,[49,252,253,254] especially regarding retirement of fossil fuel power plants (Figure 32.15)[254,255,256,257,258,259,260] and vehicle electrification.[261,262] Electrification of heating,[256,263] reduction in fossil fuel production, electrification of the industrial sector, and shifting diets[102] can also all generate meaningful air pollution benefits. Carbon

capture and hydrogen technologies may also reduce air pollutant emissions, although it is not yet clear by how much.

It is also possible that mitigation efforts could increase air pollution at local and regional scales, for example, due to increases in bioenergy, residential wood heating, and domestic manufacturing to meet demands for materials and products (e.g., Gallagher and Holloway 2020;[252] Commane and Schiferl 2022[264]).

Health Co-benefits of Strategic Power Plant Retirements



Shutting down coal-fired power plants would produce both health and climate benefits.

Figure 32.15. Blue circles show the location and size of US coal-fired power plants in 2017 (**a**) and in two scenarios: one in which the fewest plants are retired to reduce CO_2 emissions by a fixed amount (**b**) and one in which plants are retired not only to achieve the same CO_2 reduction but also to avoid health damages as much as possible (**c**). Not surprisingly, estimated health damages (red shading) are greatly reduced in the future scenario that prioritizes health. Annual generation from coal power plants (in terawatt-hours) and corresponding annualized health damages (in millions of dollars) from each scenario are both summarized by county. Baseline shows results based on 2017 continuous emissions monitoring systems data, while optimization results shown represent the climate-only and climate-plus-health scenarios. Health damages are shown by the county in which those damages occur; legend breaks are based on quintiles of the data. Although this analysis included only the continental US, its conclusions are consistent with similar analyses in other regions: substantial health benefits would be expected from retiring coal electricity anywhere. Adapted with permission from Sergi et al. 2020.[254]

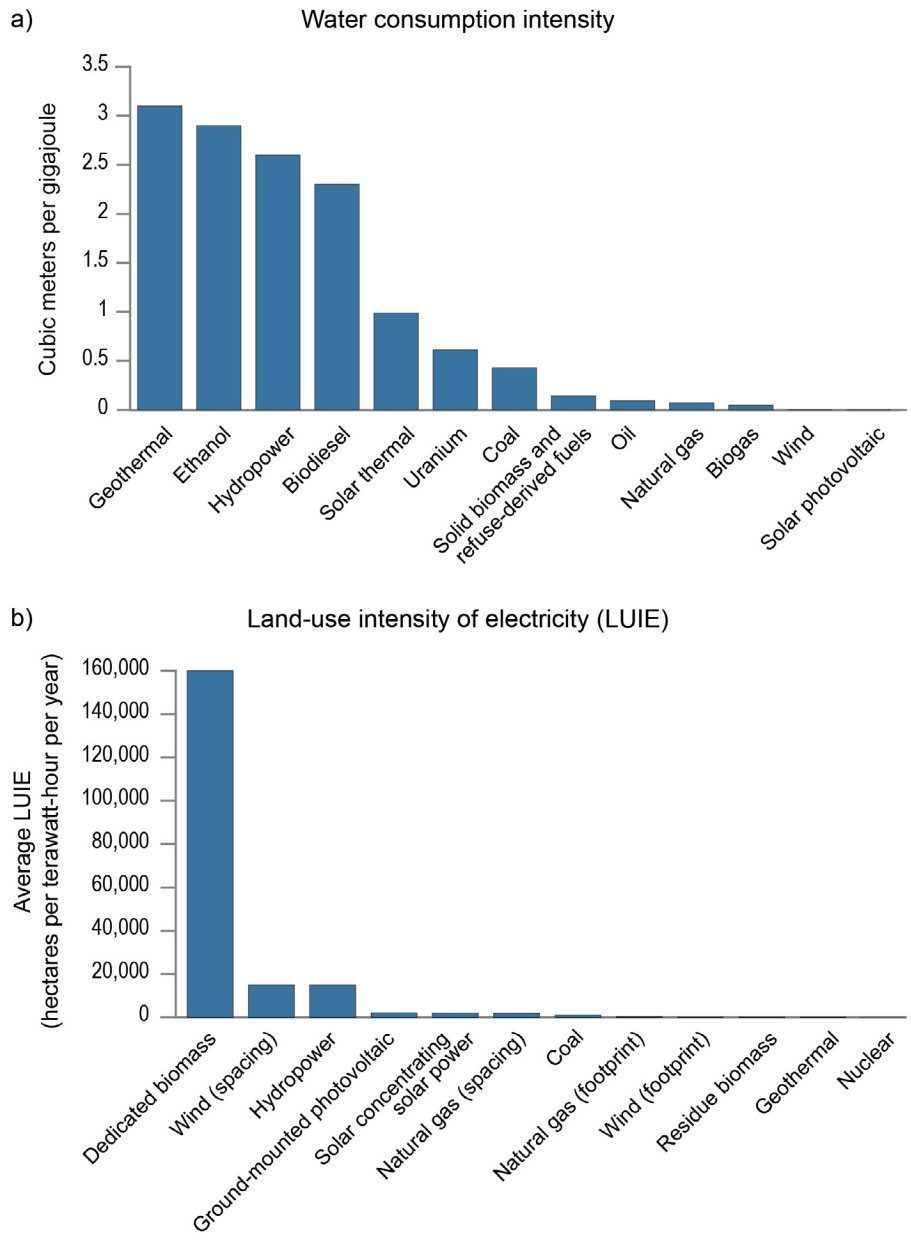
Siting and Land Use

Net-zero-emissions energy systems may require large land areas, with land requirements in rough proportion to the share of wind and solar energy. Cumulative US land use for solar and wind energy in recent net-zero scenarios ranges from about 250,000 to more than 1 million square kilometers (including the entire area of solar and wind farms),[41,42,52] with solar concentrated in the Northeast and Southeast and wind in the Midwest, Great Plains, and Texas (KM 6.3).[49] Even at the low end of this range, the projected scale of land use is massive, and may face public opposition. For example, the visual impact and competition for land of such extensive systems would need to gain and maintain the support of many communities; this recently has been a challenge in the siting of solar and wind projects.[265,266] Similar challenges may apply to siting and demonstration of other infrastructure regardless of its land footprint, such as new electricity transmission,[265] CCS,[267] and CDR.[268] Others express concern over the potential environmental impacts of solar and wind farms, including land-cover change, loss of plant and animal habitats, barriers to migration and collision deaths of birds and bats,[269,270,271] and competition for land between agriculture and renewables.[272] Notably, competition with agriculture has also long been a concern about bioenergy, which may be alleviated if demand for corn ethanol decreases due to electrification of transport.[273,274] Researchers have thus begun developing pathways that take some of these concerns and constraints into account,[49,275] as well as identifying changes in governance and administrative law that may help streamline siting processes;[276] however, siting may prove a key obstacle for renewables-based net-zero-emissions systems.[277] Engagement with community groups and stakeholders early in the planning process has the potential to reduce project delays and cancellations.[278]

Water Use

The water requirements of net-zero-emissions energy systems could be lower than current consumption,[279] largely because wind and solar require little water (Figure 32.16; KM 5.1).[280,281,282,283] However, some processes for energy conversion and carbon management, such as electrolysis for hydrogen production, chemical synthesis of hydrocarbons (e.g., by the Fischer-Tropsch process), and CCS, are water intensive and could offset water savings from fuel switching. Ultimately, water use (and related quality), temporal, and locational needs, depend heavily on the mix of resources and processes used to achieve net-zero emissions.[284,285,286]

Land and Water Requirements of Energy Sources



Different sources of energy entail more or less water and land use.

Figure 32.16. Bars depict water-consumption intensity (**a**) and land-use intensity of electricity (LUIE) for the US in 2014 (**b**) related to different electricity sources. Wind and solar use less water than any of the other energy sources but more land area than nuclear, geothermal, or fossil sources. (a) Adapted with permission from Grubert and Sanders 2018;[280] (b) adapted from Lovering et al. 2022[287] [CC BY 4.0].

Labor

The productivity, supply, and disposition of labor, in addition to national discourse and community-level support and concern regarding labor, has the potential to accelerate or constrain mitigation efforts. Nearly 8 million Americans were directly employed in energy-related jobs in 2021, comprising roughly 5% of the total labor force.[288,289] Of those 8 million energy-related jobs, approximately 41% were in net-zero-emissions-aligned areas in 2022.[290] Energy-related jobs tend to be geographically concentrated in certain states and

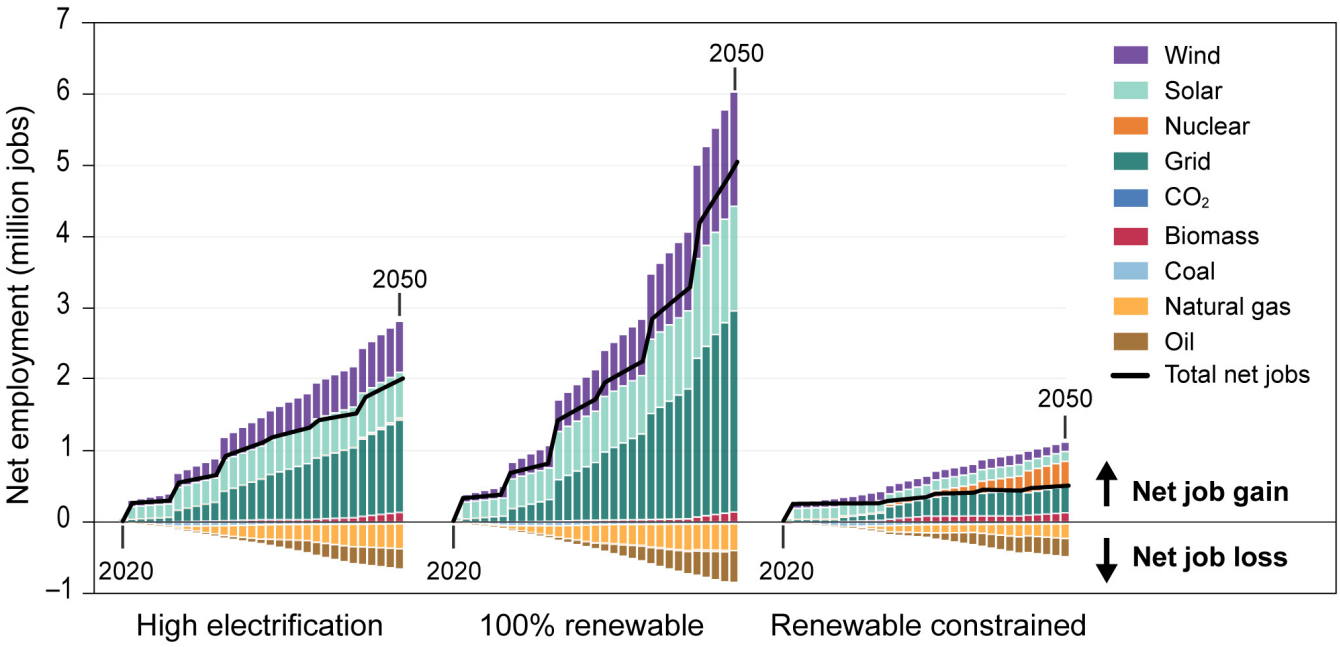
communities (Figure 32.17). More than 10% of the labor force in 150 counties (of 3,142) is directly employed in energy-related jobs[288,291,292]—often the production of coal, oil, and gas—but employment in mitigation-related activities is growing and is already high in many counties (e.g., energy efficiency in Vermont, wind installations in the Southern Great Plains; KM 26.2).

Reaching net-zero emissions in the United States by 2050 would generate jobs related to manufacturing and deployment of new infrastructure but reduce fossil fuel–related jobs.[293] Many analyses find that employment and wage losses in fossil fuel sectors would be entirely offset (in aggregate) by increases in low-carbon resource industries.[293,294,295,296,297] The number and local distribution of mitigation-related jobs will depend on the ultimate mix of energy sources, siting and investment decisions, labor supply constraints, the extent of domestic manufacturing, and political bargaining; however, decarbonization could lead to long-term expansion in the energy workforce in most states, even when accounting for increased worker productivity (which is often an underlying assumption in technology cost projections). Large-scale and sustained workforce development programs, high-road labor practices and policies, and corresponding federal support could accelerate a transition to net-zero emissions.[293,298]

However, there is already evidence of hiring difficulties in energy labor markets,[291] portending labor supply bottlenecks in the absence of counteracting policies. Although there is public support for employment benefits related to climate mitigation,[294] there is also evidence of mistrust associated with historical energy-related job creation narratives.[299] Moreover, there are existing racial and gender disparities in the energy workforces.[291]

Meanwhile, despite policy and political discourse regarding just transitions for fossil fuel workers,[294,300,301] many fossil fuel–dependent communities have experienced large declines in employment.[26,302,303] Moreover, former fossil fuel workers often relocate because their skills are not always transferable to other local industries, and nearby communities lose tax revenues that support public infrastructure and social services (KM 26.2).[304,305] Going forward, domestic policies that consider when and where workforces in declining energy industries could fill new jobs in emerging energy sectors (e.g., natural gas and carbon capture supply chains; coal mining; and solar manufacturing) have the potential to moderate labor supply bottlenecks, concentrated unemployment, and low-carbon boom-and-bust cycles. Where there is flexibility in siting of infrastructure and allocation of funding, such funds might also be leveraged to build political support and more equitably distribute costs and benefits. For example, provisions in the Inflation Reduction Act of 2022 offer enhanced tax credits to clean energy projects that pay prevailing wages to workers and use registered apprentices,[290] that manufacture and source materials domestically,[306] and/or that are located in "energy communities" defined by thresholds in the share of fossil fuel–related jobs.[307]

Energy Employment from 2020 to 2050 for Alternative Net-Zero Pathways



A shift toward renewables is projected to increase the total number of jobs in the energy sector.

Figure 32.17. Despite decreases in the number of fossil fuel–related jobs, the overall number of energy jobs (specifically those involved in the supply of energy) is generally projected to increase in net-zero-emissions energy scenarios between 2020 and 2050, although by much more in some scenarios than in others. These particular scenarios are from Larson et al. 2021[49] and span a range of energy futures in which nearly all buildings and transport are electrified but there are no constraints (**a**), renewables produce 100% of energy (**b**), or renewables produce much less energy and nuclear and fossil energy with carbon capture and storage are prevalent (**c**). CO_2 = carbon dioxide. Adapted with permission from Jenkins et al. 2021.[308]

Energy Equity and Environmental Justice

Social inequities in the United States are rooted in systemic discriminatory practices, such as redlining, that marginalize communities based on race or socioeconomics. Social equity involves several energy- and climate-related aspects of recognition, procedural, and distributional justice (KMs 23.4, 27.3).[309,310] In the context of energy and climate decision-making, recognition justice refers to an understanding that certain individuals and groups are presently bearing, and have historically borne, disparate burdens related to our collective energy systems and may therefore require extra resources or mitigation efforts. Procedural justice considers who is involved and has influence in energy and climate decision-making processes, with the goal of ensuring that those who want to be included in decision-making processes—and especially those who will be affected by the outcomes—are meaningfully engaged through fair and inclusive procedures (see, e.g., KM 30.3 regarding mitigation informed by Indigenous Knowledge). Distributional justice refers to the allocation of benefits and burdens based on geography and sociodemographics, with the objective that no single population receives a disproportionate share of energy or climate harms (e.g., energy-related air pollution; KM 14.3) or benefits (e.g., access to low-carbon and efficient energy technologies or clean-tech jobs).

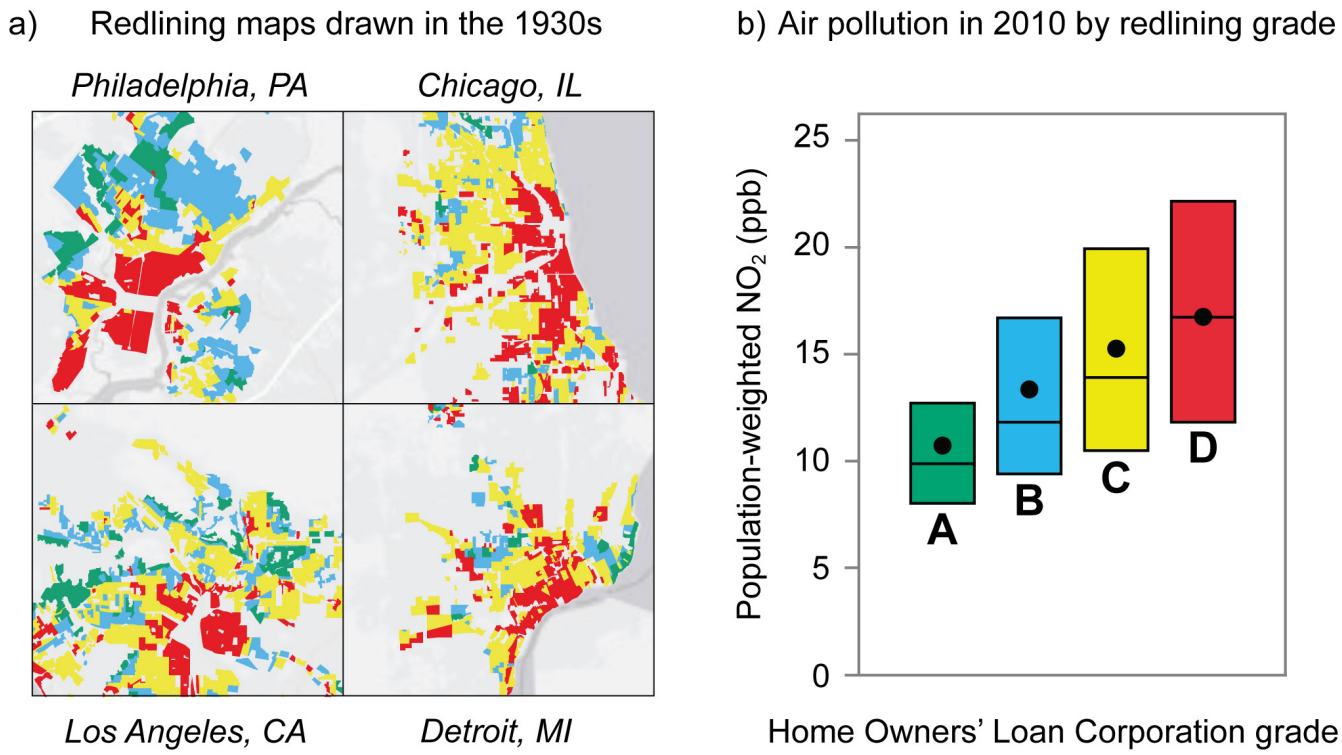
The disproportionate public health burdens of energy systems on communities of color and/or low-income communities, such as from vehicle emissions and power plants, have been extensively documented (Figure 32.18).[311,312,313,314] Energy insecurity (e.g., regularly struggling to pay energy bills) also disproportionately affects low-income households, communities of color, rural and Indigenous communities, families with children,

and older adults (Ch. 16).[313,315,316,317,318,319,320] This disproportionate burden of energy insecurity reflects that Black Americans, for example, are more likely to live in older homes that are less energy-efficient.[317,318,321] Moreover, redlined areas often lack trees and green spaces to mitigate the urban heat island effect and thus experience higher summer temperatures than surrounding urban areas,[322,323,324] which in turn increases energy demands and burdens[325] and makes residents more susceptible to the adverse health effects of extreme heat (KM 15.3).[325,326]

Although environmental impacts and energy insecurity are not borne proportionately across social groups, it is possible to pursue mitigation options that also redress current and historical injustices. For example, low-income communities and communities of color could experience disproportionate improvements in air pollution.[251,259] Energy equity considerations also include access to sufficient energy services,[327,328] as well as reductions in energy burden or energy poverty,[321,329,330] and the upfront costs of energy efficiency and low-carbon technologies.[331] Mitigation efforts that increase the availability and affordability of energy services (including safe and comfortable temperatures) could improve energy equity outcomes. For example, improving thermal efficiency of buildings would both reduce energy costs and help to maintain safe indoor thermal temperatures in the absence of functional air-conditioning.[332]

Studies have found that low-carbon and efficient technologies (e.g., electric vehicles, solar panels, battery storage, and LED lightbulbs) tend to be disproportionately owned by—and the financial incentives for such are received by—higher-income, more educated, and White households.[311,312,313,333] Job opportunities in clean energy have also tended to exclude women and people of color.[334] Moreover, insofar as mitigation increases energy costs, more households will experience energy poverty, and energy inequities may get worse.[335,336] In addition, changes in the type, timing, and cost of energy needed to provide safe and comfortable temperatures under climate change and anticipated electrification patterns may exacerbate health risks, financial energy burdens, and other measures of energy equity.[327,335]

Inequitable Air Quality Within Historically Redlined Neighborhoods



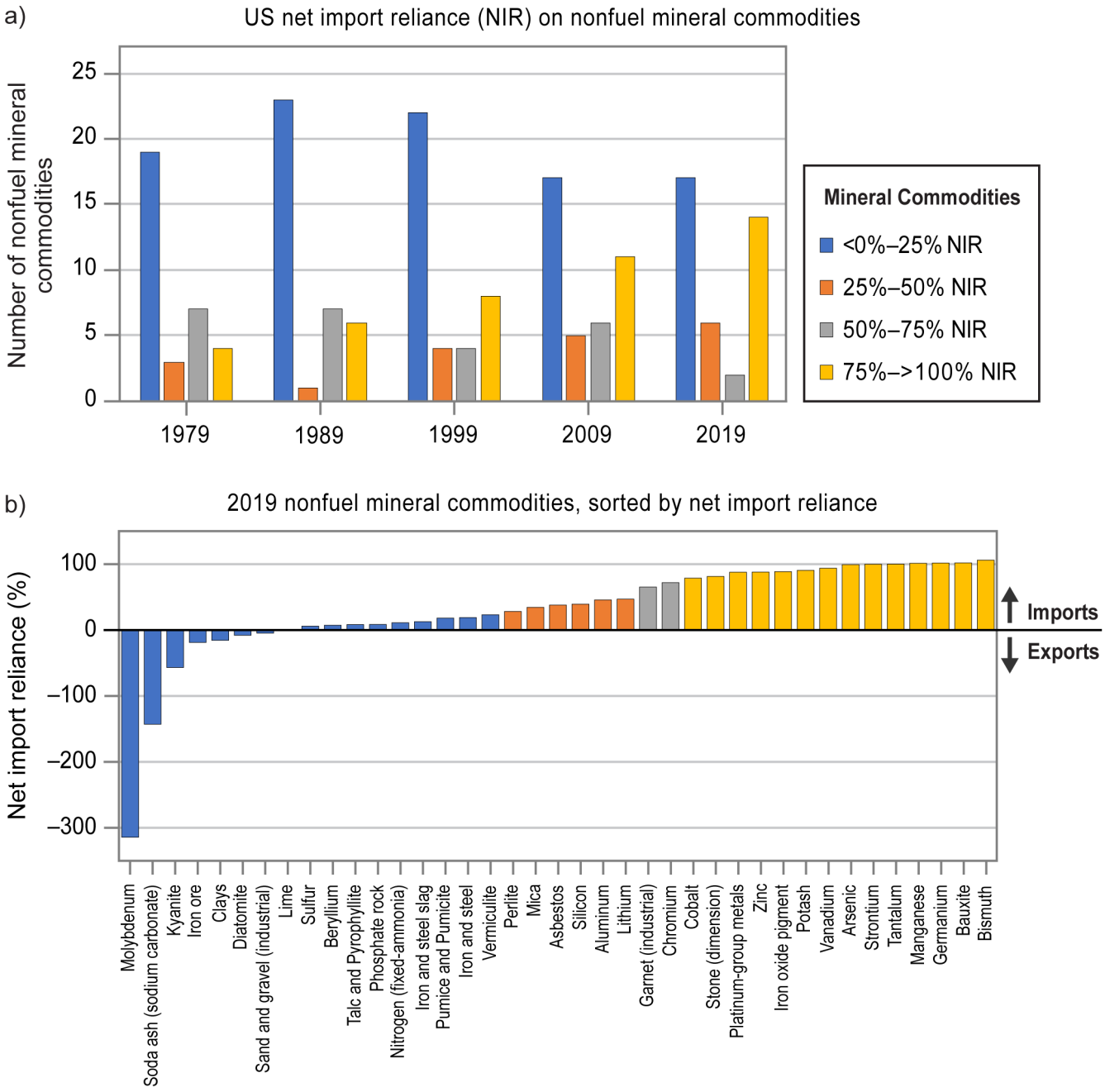
Communities redlined in the 1930s experience more air pollution today.

Figure 32.18. The Home Owners' Loan Corporation (HOLC) grades (A ["best"], B, C, and D ["hazardous," i.e., redlined]) from the 1930s (which effectively denied Black and minority groups access to lending institutions) still corresponded to greater levels of air pollution in 2010. Panel (**a**) shows redlining maps of neighborhoods based on 1930s HOLC grade classifications for four US cities. Panel (**b**) shows the population-weighted distribution of nitrogen dioxide (NO_2) levels (measured as concentration in parts per billion [ppb]) for 2010 across 202 census tracts in the contiguous US. Horizontal lines indicate medians, points indicate averages, and bars indicate 25th to 75th percentiles. Adapted with permission from Lane et al. 2022.[314]

Supply Chains, Energy Security, and Geopolitics

Climate mitigation efforts may drastically increase domestic and global demand for products (e.g., solar photovoltaics, batteries, electric motors, wind turbines) and metal and mineral resources (e.g., lithium, nickel, cobalt, copper), which may have implications for supply security, markets, advanced manufacturing (e.g., robotics and EVs), geopolitics, and mining (Focus on Risks to Supply Chains).[337,338,339,340] Moreover, in the United States there are currently 50 listed critical minerals (up from 35 in 2018),[341,342] defined as those essential to economic or national security and whose supply chains are vulnerable to disruption (Figure 32.19). With increased demand as the system decarbonizes, there could be near-term shortages in several minerals and metals. Note that a series of executive orders anticipates this challenge and calls for monitoring and reduction in US dependence on imported critical materials, for example, by increased recycling (e.g., Executive Order 13817, "A Federal Strategy to Ensure Secure and Reliable Supplies of Critical Minerals,"[343] and Executive Order 13953, "Addressing the Threat to the Domestic Supply Chain from Reliance on Critical Minerals from Foreign Adversaries and Supporting the Domestic Mining and Processing Industries"[344]) and more resilient supply chains generally (Executive Order 14017, "America's Supply Chains";[345] see also Focus on Risks to Supply Chains; KMs 17.2, 18.1).

Increasing Reliance on Imported Nonfuel Minerals



The US has grown increasingly dependent on imported minerals.

Figure 32.19. Panel (**a**) shows that the US has become increasingly dependent on imports of 39 nonfuel mineral commodities since 1979; commodities of which 75%–100% is imported (yellow bars) are increasing in number, and commodities of which less than 25% is imported (blue bars) are decreasing in number. Panel (**b**) shows the specific commodities and the degree of import reliance for each in 2019. Figure credits: (a) adapted from Fortier et al. 2015;[346] (b) University of California, Irvine.

Key Message 32.5

Governments, Organizations, and Individuals Can Act to Reduce Emissions

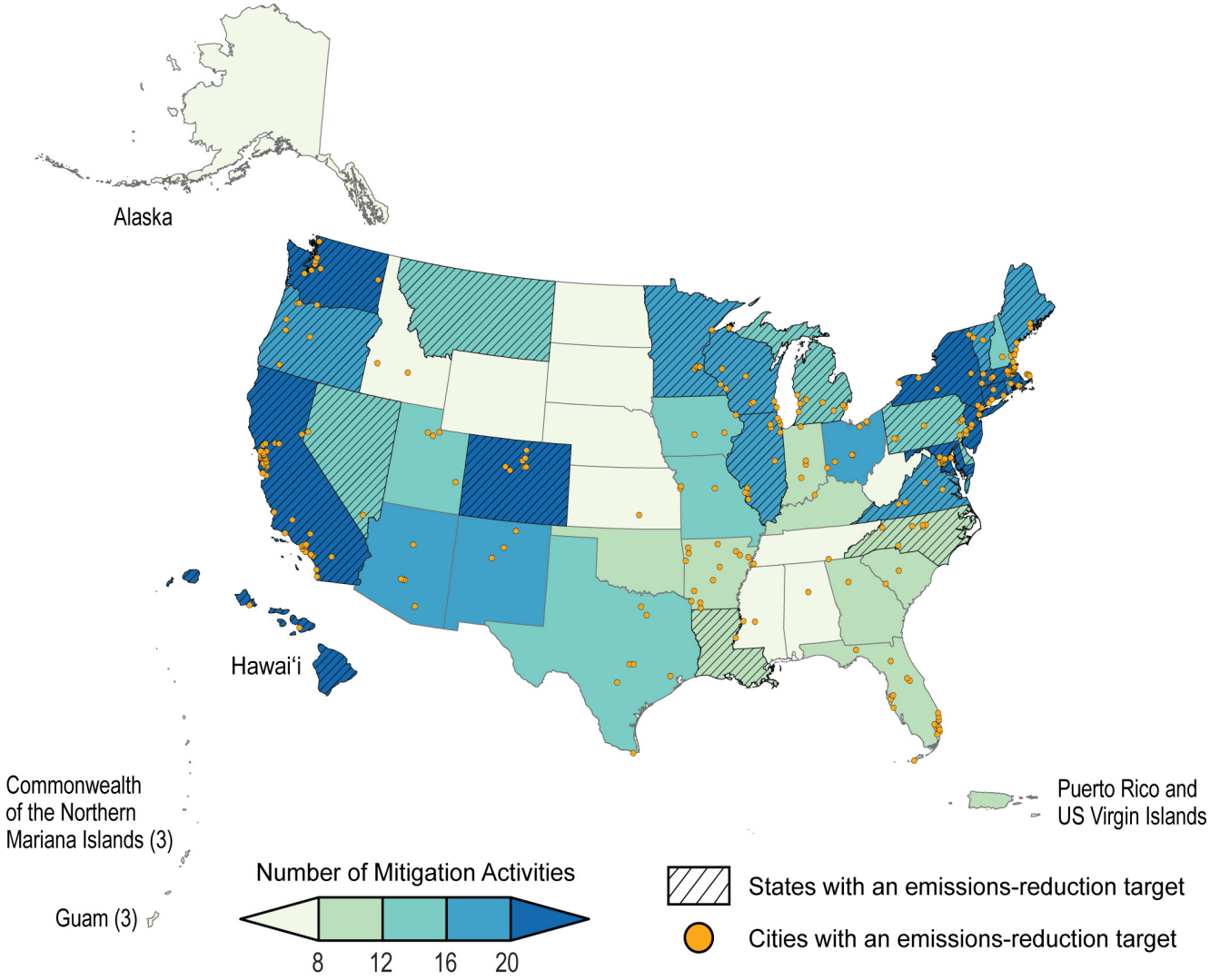
Mitigation efforts can be supported by a range of actors and actions, from choices made by individuals to decisions made by businesses and local, Tribal, state, and national governments (*high confidence*). Actions with significant near-term potential include sector-based policies accelerating deployment of low-carbon technologies, city-level efforts to promote public transportation and improve building efficiency, and individual behavioral changes to reduce energy demand and meat consumption (*high confidence*).

A wide range of actors across the US have been involved in efforts to accelerate clean energy transition and mitigate GHG emissions, including new legislation; rules, regulations, and executive orders; and voluntary actions. For example,

- the US has committed under the Paris Agreement to reduce GHG emissions by 50%–52% in 2030 relative to 2005;
- through the Bipartisan Infrastructure Law and the Inflation Reduction Act and relevant programs, there are federal subsidies to clean energy businesses and for household purchases of EVs and heat pumps;[347]
- 25 states,[348] 675 cities, 300 universities, and hundreds of companies have announced net-zero-emissions targets; and
- bottom-up coalitions such as the America Is All In initiative have support from subnational leaders who represent a constituency of more than half the US population (see, e.g., KMs 21.4, 30.3).

Since 2018, the total number of state-level mitigation activities has increased by 83%, and 169 more cities have introduced emissions reduction targets since then (Figure 32.20; see also Ch. 12).[349]

Mitigation-Related Activities at the State and City Levels

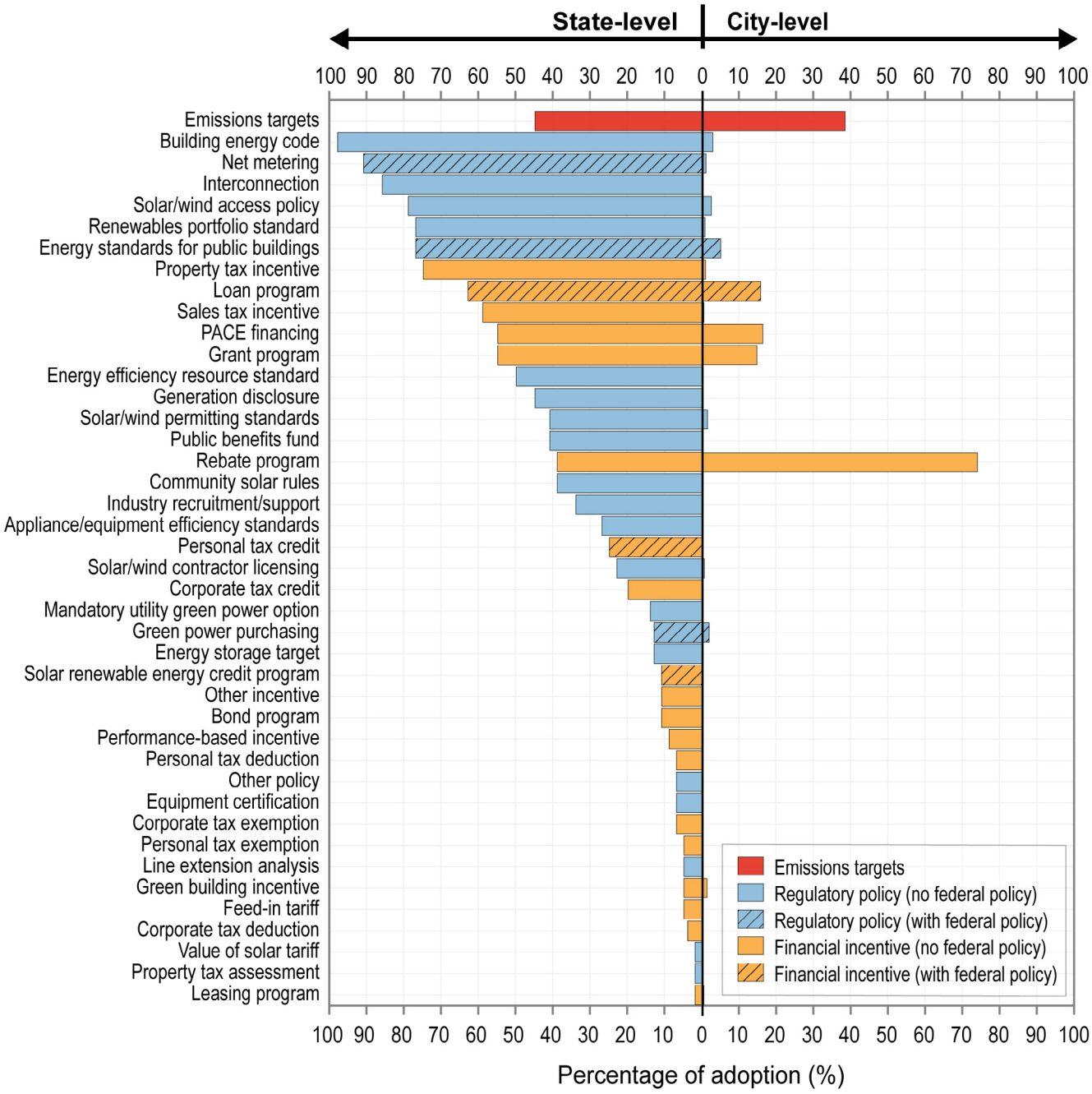


Many states and cities have taken action to reduce greenhouse gas emissions.

Figure 32.20. Shading indicates the number of mitigation activities taken by each state, and orange circles indicate cities with emissions-reduction targets (as of April 2023). Almost every region has taken some action, with hotspots of activity in the Northeast, Southwest, Colorado, Hawai'i, and along the West Coast. See Figure 32.21 for examples of the types of actions taken. Figure credit: The Pennsylvania State University, NOAA NCEI, and CISESS NC.

The pathways toward achieving these goals often include a broad collection of measures and policies, including investments in infrastructure and clean technologies that will require substantial capital, financial backing, and resource allocation. The feasibility and impact of these measures are dependent on local and regional factors, which are often reflected in more granular sector- or economy-specific mitigation targets and actions (see Figure 32.21).[350]

Adoption Rate of Various Forms of Policy Instruments and Climate Action



States and cities have adopted a range of climate actions and policies.

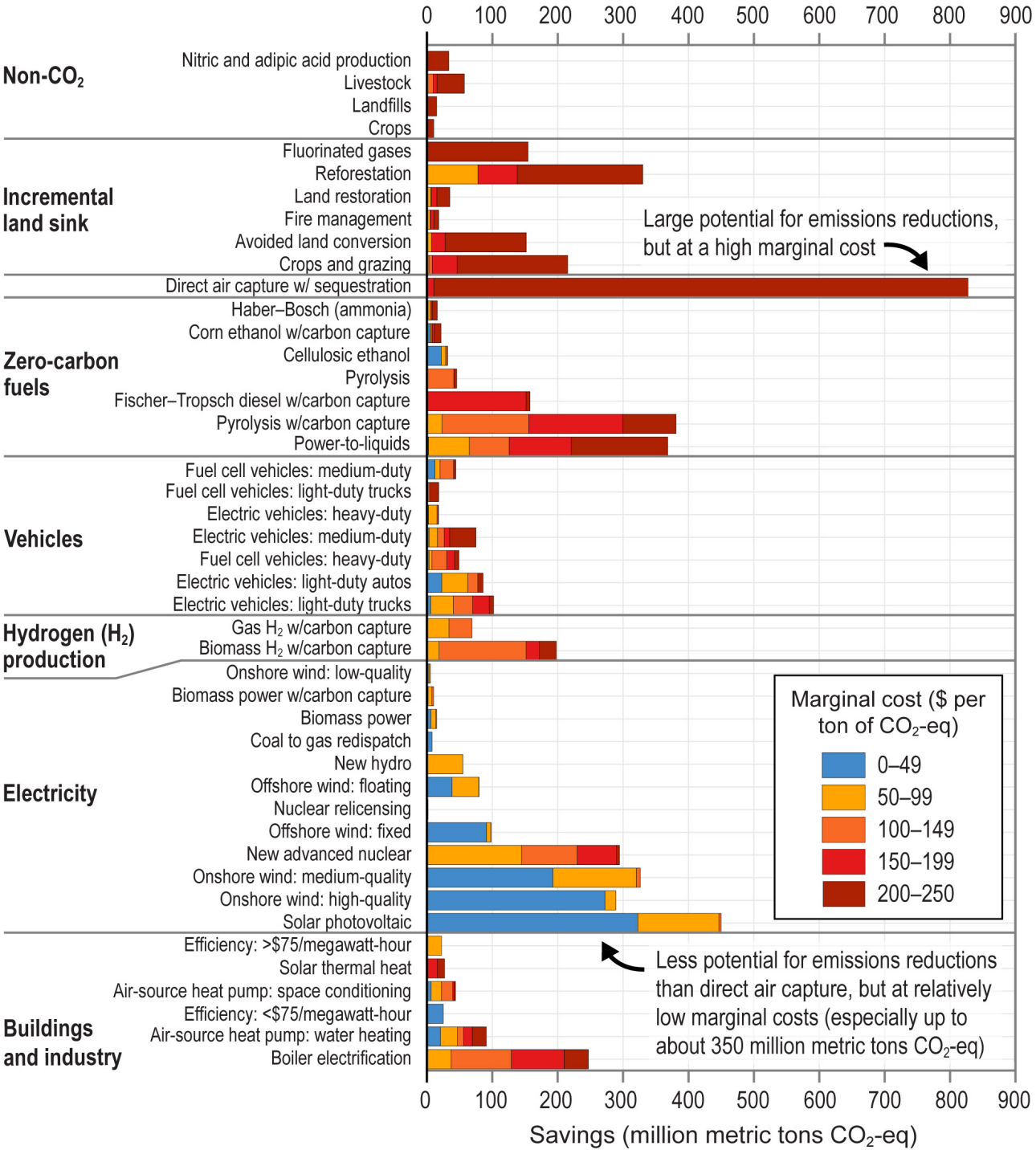
Figure 32.21. Bars show the percentages of states (**left**) and cities (**right**) that have announced emissions targets (tracked by the United Nations Framework Convention on Climate Change Non-state Actor Zone for Climate Action dataset) or adopted the selected clean energy policies (tracked in North Carolina State University's Database of State Incentives for Renewables & Efficiency dataset) as of April 2023. The color of the bars indicates the type of policy, and hashing denotes that the policy action is also being adopted or announced by the Federal Government. PACE stands for property assessed clean energy. Figure credit: The Pennsylvania State University, NOAA NCEI, and CISESS NC.

To this end, nearly 40 states have introduced renewable portfolio standards or voluntary renewable energy goals, which further guide and codify decarbonization efforts within the energy sector and induce incremental shifts toward increased penetration of renewable electricity (KM 32.1). Similarly, more than 30 local governments have enacted requirements for energy efficiency, ranging from building codes and benchmarking ordinances to establishing performance standards (see, e.g., KM 12.3). With federal corporate average fuel economy (CAFE) standards in place for vehicles, local transportation-sector efforts are often focused on behavioral mode-shift goals, such as promoting clean and public transport options and reducing vehicle-miles traveled. The proposed federal Agriculture Resilience Act is designed to address the adaptive needs of US farmers and consumers as a result of a changing climate, as well as to reduce the emissions associated with agricultural production.[351] In addition, the Securities and Exchange Commission is in the process of finalizing new rules that would require public companies to disclose greenhouse gas emissions related to their operations and supply chains, as well as climate risks to their business.[352] Such rules would build on the voluntary reporting and reduction efforts of corporations under the Carbon Disclosure Project; Science Based Targets initiative; and Environmental, Social, and Corporate Governance frameworks and will need to be supported by improved accounting protocols and focused scientific research.[174,353,354,355,356]

Beyond goal-setting and implementing regulatory measures, the enabling of financial mechanisms is often a core element of mitigation strategy. Regional cap-and-trade programs utilize a system of accountability and performance to incentivize emissions reductions at the electricity-generation level. Meanwhile, federal subsidies, such as those provided to clean energy businesses and tax credits for electric vehicle purchases, can bolster behavior change.[54] By enabling access to financial capital—whether within the government, commercial, or residential sectors—investments in infrastructure and the built environment, as well as research and development, may further drive these advances.

Available mitigation strategies vary in terms of emissions-reduction potential and costs (Figure 32.22), as well as in environmental, technical, and social implications (Figure 32.23). However, with the advancement of measurement technologies and insights gained from the deployment of various actions taken in vastly different environments, there is now more empirical evidence to inform strategy design for a given community (see regional chapters for examples of state, city, community, and Tribal mitigation actions; e.g., Box 21.1; KM 30.3). Additionally, more jurisdictions are adopting community-driven and holistic approaches to climate action planning, incorporating practices that address equitable access to information (including considerations for languages used and internet access) and events (including transportation vouchers, food and childcare provisions, and payment for subject-matter expertise to community members with lived experience), with a goal of improving and increasing capacity and ability to influence decision-making and, ultimately, assisting elected leaders in making the best-informed and most-impactful decisions for their unique communities.[357,358,359]

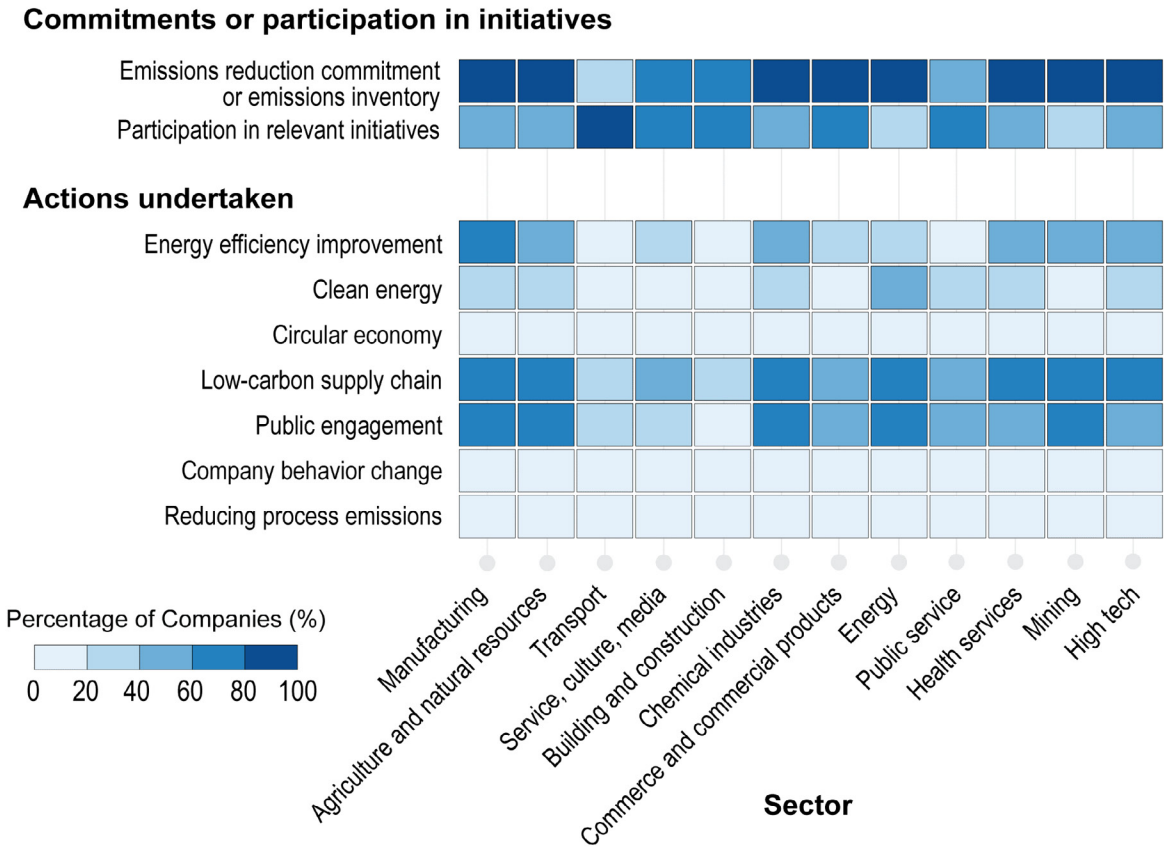
Potential Emissions Reductions by Action, for the Year 2050



The size and cost of emissions reductions depend on available technologies and the source of related emissions.

Figure 32.22. Energy system, land-sector, and non-CO_2 (carbon dioxide) mitigation options for the year 2050 are shown along with estimated marginal costs, excluding the impact of policy incentives. The sum of the mitigation options shown results in net-negative CO_2-eq (carbon dioxide equivalent) emissions in the United States, not only demonstrating the possibility of reaching net-zero emissions using a combination of these actions but also highlighting a large range of costs for such actions (costs as of 2021). Mitigation options from conservation and lifestyle change are not assessed due to the difficulty in assessing costs for these measures. H_2 = hydrogen. Adapted with permission from Farbes et al. 2021[360] and Figure SPM.7 in IPCC 2022.[361]

US Company-Level Mitigation Actions



A majority of US companies have made mitigation commitments, inventoried emissions, or participated in initiatives, but fewer are taking action.

Figure 32.23. As of April 2023, a majority of US companies across many sectors have committed to reducing emissions or conducted emissions inventories, and many have participated in mitigation initiatives (**top**). Percentages are smaller in terms of actions taken (**bottom**). For example, many companies are involved in energy efficiency improvements, efforts to reduce supply chain emissions, and public engagement efforts. But 20% or fewer across all sectors are reported as reducing process emissions or effecting company behavior changes. Figure credit: The Pennsylvania State University, NOAA NCEI, and CISESS NC.

Box 32.3. Orlando Case Study: Mitigation in the Country's Most Visited City

In the five decades since the opening of Walt Disney World, Orlando has become the most highly visited city in the United States. As a result, this community faces the unique challenge of managing the costs, demands, and emissions of more than 75 million annual visitors, or nearly 300 visitors for each individual resident.[362,363] To address these impacts, local governments have adopted an ambitious, socially inclusive, and innovative climate strategy.

The prevalence of resort and multifamily developments, for example, has led to the adoption of energy efficiency requirements for commercial buildings and a community-wide commitment to 100% renewable energy to drive the decarbonization of the local building stock. Meanwhile, to address the needs of local residents, many of whom work in lower-wage jobs associated with the tourism industry, an energy-burden analysis was conducted to identify the neighborhoods most in need of assistance.

As the largest rental car market in the world, the region has served as a proving ground for enhanced electric and autonomous vehicle piloting,[364,365] as well as the adoption of an electric vehicle readiness policy.[366] Research efforts have focused on public safety when various modes of transportation, such as single-passenger vehicles (more likely to be utilized by visitors and more affluent residents), are active in the same vicinity as buses, cyclists, and pedestrians.

Enhanced waste-reduction efforts previously included an anaerobic digestion facility that utilizes the gray water and food scraps from the Disney parks and resorts to generate biogas, a renewable energy source that is used to power these same facilities. In tandem with this localized solution, waste avoidance and gleaning programs (e.g., improved collection of excess produce and perishables from farms, retailers, and restaurants)[367] provide options for those who are food insecure.

Together, these mitigation strategies serve to protect the local environment, enhance the quality of life for local residents, and showcase a variety of solutions to the nearly 76 million guests who visit the region each year.

Traceable Accounts

Process Description

Based on their own experience, nominations, and relevant recent literature, the chapter lead author and federal coordinating lead author discussed and selected a set of experts to invite as authors, seeking diverse representation of topical expertise, disciplinary perspectives, career stages, professional backgrounds, geographies, and demographics. Of 25 invitations, 16 were accepted, forming an author team with the requisite expertise to cover the chapter topics and provide a good balance of other characteristics. The author team began meeting regularly as a group and then divided into smaller working groups focused on different key topic areas, which also met regularly (all meetings were virtual, except for the in-person All-Author Meeting held in Washington, DC, in April 2023). During these meetings, the team worked together to develop key topic areas for the chapter, identify key literature and sources, and plan syntheses and figures for the chapter. The team also planned the public engagement workshop for the chapter and afterward discussed inputs and feedbacks from that workshop.

Key Message 32.1

Successful Mitigation Means Reaching Net-Zero Emissions

Description of Evidence Base

The assessment and summary of the sources and trends of US greenhouse gas emissions relies primarily on inventories and estimates from the EPA,[7,8] supplemented by socioeconomic, energy activity, and agricultural production data from official sources such as the US Energy Information Administration (EIA)[18,368,369,370,371] and the World Bank.[372,373] EPA estimates of energy-related emissions are primarily based on tracked masses and volumes of combusted fuels (and in some case continuous emissions monitoring at point sources) publicly reported to the EIA, EPA, or Bureau of Transportation Statistics. EPA estimates of land sector (i.e., land use, land-use change, and agricultural) emissions are primarily based on activity data (e.g., area of land converted, number and kinds of livestock, mass of fertilizer applied) and associated emissions factors that have been developed based on numerous case studies.[11,374] Federal- and state-level greenhouse gases (GHG) targets were compiled from publicly available sources and are not uncertain.

Major Uncertainties and Research Gaps

Although there is no uncertainty as to the current emissions targets and it is well-established that global warming will be proportional to cumulative carbon dioxide (CO_2) emissions (e.g., Matthews et al. 2009[375]), there is relatively little scientific literature and relatively few national and international goals that address long-term management of the climate after net-zero emissions have been achieved and into the 22nd century.[376]

Estimates of agricultural and fugitive non-CO_2 GHG emissions have greater uncertainty because they are spatially heterogenous "area" sources that are more challenging to measure directly,[97,377] as evidenced by discrepancies between "top-down" estimates of global methane emissions based on measurements of the atmosphere and "bottom-up" estimates based on activity data such as number and kinds of livestock and extent of rice cultivation.[378,379] For this reason, these are active areas of research, and analysts are bringing to bear a variety of different and innovative tools and methods to reduce the uncertainty and prioritize mitigation efforts (e.g., Liu et al. 2022;[380] Norooz Oliaee et al. 2022;[381] Conrad et al. 2023[382]).

Description of Confidence and Likelihood

Based on the multiple sources of high-quality energy system data, the authors have *very high confidence* in both the overall magnitude of energy-related US GHG emissions from each major source and their relative changes over time. There is also broad agreement among dynamic vegetation models, bookkeeping models of land-use change, and atmospheric observations as to the magnitude of the US land sink in recent years,[51] but the sink has been decreasing[22] and future uptake by US forests will depend on management and climate change impacts, both of which are uncertain.[21,180,383,384] Given current emissions levels and stated goals, however, the required rate of decrease is not in question. For these reasons, we have *very high confidence* in the statements made in the Key Message.

Key Message 32.2

We Know How to Drastically Reduce Emissions

Description of Evidence Base

The assessment of established options for reducing energy-related GHG emissions reflects a large body of literature and recent energy-system modeling,[60,385] including a database of 40 US net-zero emissions scenarios.[41,42] Although there are substantial differences in the cost-effective energy systems modeled in these scenarios depending on model design and key assumptions, the Key Message and text emphasize characteristics that are robust across most, if not all, of the scenarios.[47,50,130,386,387,388]

Major Uncertainties and Research Gaps

The assessment of established options for reducing land-related GHG emissions reflects a substantial literature, but there are few quantitative scenarios to support potential reductions.[96,98,121,177,185,191,389,390,391] Instead, potential reductions are often extrapolated from the localized studies that are available. Further research is warranted to test key sensitivities in energy model scenarios and to quantitatively assess factors beyond cost, such as social and political acceptance of (or opposition to) changes in use of land and water resources and adoption of energy technologies, and the associated distribution of benefits and impacts (as well as other non-cost factors discussed in KM 32.4).

Description of Confidence and Likelihood

Across 40 of the most recent and detailed energy system scenarios of net-zero US emissions, produced by 14 independent models and assuming a wide range of costs and constraints, the share of final energy met by electricity increases from about 20% today to 43%–57% by 2050 (the 25th–75th percentile range; Figure 32.11), and solar and wind are consistently major sources of energy, typically ranging from 57%–80% of primary energy by 2050 (the 25th–75th percentile range; Figure 32.10). Yet fuels continue to be used across those scenarios for some transportation and industry applications. The robustness of these numbers despite many methodological differences gives us *high confidence* in the energy-related statements in the Key Message.

A large literature also supports the opportunities for large reductions in land-related emissions, giving us *high confidence* in the land-related statement in the Key Message.[96,98,121,177,185,191,389,390,391]

Current costs of technologies such as solar, wind, and electric vehicles and the projected large-scale deployment of these technologies in cost-optimized energy system models,[41,42,45,66,392] as well as many studies demonstrating the potential cost savings of energy efficiency improvements,[393,394] optimization of agricultural inputs,[395] shifts in diet,[96,98,396] and repair of leaky infrastructure, all give the authors similarly *high confidence* that many mitigation options are now cost-effective.

Key Message 32.3

To Reach Net-Zero Emissions, Additional Mitigation Options Need to Be Explored

Description of Evidence Base

The assessment of potential options for reducing energy-related GHG emissions reflects a large body of literature and recent energy system modeling, including a database of 40 US net-zero emissions scenarios,[41,42] but this Key Message highlights that the scale and mix of energy technologies and mitigation options remain sensitive to assumed—and yet uncertain—costs and constraints. Similarly, the potential options for reducing land-related GHG emissions presented in this Key Message are not as well studied, and there is open debate about the efficacy and/or cost-effectiveness of, for example, different energy storage technologies,[397,398] advanced nuclear technology,[399,400] and carbon management options,[52,168,401,402] as well as future agricultural productivity.[403,404]

Major Uncertainties and Research Gaps

We assign *medium confidence* to the list of attractive targets for further research, development, and demonstration because existing literature either disagrees as to the potential of these technologies or only a few studies have made the case that they have great potential. Where analyses disagree, it may be because their findings depend on assumptions regarding deeply uncertain aspects of economic development, human behavior, or technological innovation. In general, additional research is needed to quantitatively assess a greater number of emerging energy technologies and land management options, and especially work that incorporates the various non-cost factors discussed in Key Message 32.4.

Description of Confidence and Likelihood

We have *high confidence* that we do not yet know which net-zero-emissions energy system will be cost-optimal (or socially and politically acceptable) and that we do not know the ideal types or scales of carbon management to support net-zero emissions and sustainability more broadly.[405,406] This is because there is substantial variation in the type and scale of energy and carbon management technologies deployed in model scenarios, long-term projections of technology costs span large ranges, and the social and political support for different mitigation efforts is unclear. Although the effectiveness and scalability of some of the approaches to reduce land-related non-CO_2 emissions remain uncertain (e.g., soil amendments, livestock feed supplements), other options are becoming clear, such as managing manure, cover cropping, and decreasing nitrogen fertilizer applications. Thus, we have *medium confidence* as to the options for reducing these land-related non-CO_2 emissions.

Key Message 32.4

Mitigation Can Be Sustainable, Healthy, and Fair

Description of Evidence Base

The assessment of historical and future impacts of energy systems on, for example, water,[279,280,283,284] air pollution,[102,234,245,246,253,254] energy security,[31,339] labor,[233,247,293,298,305] and energy equity and environmental justice[217,251,259,300,309,329] is based on a diverse and rapidly growing academic literature as cited in the chapter.

Major Uncertainties and Research Gaps

As mentioned in regard to other Key Messages, there is a lack of specific qualitative and quantitative analyses and decision-making tools regarding how mitigation may affect and be affected by energy equity, environmental justice, land use, labor, water, air pollution, and energy security in different places, times, and social, demographic, and political contexts (Carley, Evans et al. 2018). There is also a lack of analyses and tools to reflect interacting technological, social, political, and environmental uncertainties and choices to inform multistakeholder decision-making.[407]

Description of Confidence and Likelihood

An extensive literature demonstrates the potential health benefits of climate mitigation, especially in regard to related decreases in air pollution. Fewer but still numerous studies have shown that the cost and resource savings or net social benefits of many mitigation options can accrue to specific populations. We therefore have *high confidence* in the potential benefits to human health and well-being, including specific environmental and socioeconomic effects. However, the available research also gives us *high confidence* that the benefits of mitigation may be distributed unevenly in the absence of proactive efforts to ensure fairness.

Key Message 32.5

Governments, Organizations, and Individuals Can Act to Reduce Emissions

Description of Evidence Base

Our assessment of possible actors and mitigation actions is drawn from both the actions represented in models and studies by researchers,[408,409,410,411,412] as well as reports and databases that have compiled lists of past actions taken (e.g., the Center for Climate and Energy Solutions State Climate Policy Maps,[348] North Carolina State University Database of State Incentives for Renewables & Efficiency,[413] CDP States and Regions Climate Tracker,[414] and United Nations Framework Convention on Climate Change Non-state Actor Zone for Climate Action dataset[415]).

Major Uncertainties and Research Gaps

No jurisdiction has yet transitioned from a fossil-based economy to a deeply decarbonized or net-zero-emissions one. Moreover, actions to start down that road may be different from those that reach the end of it.[416,417] Future research may productively explore the limits of actions by certain groups or jurisdictions, and seek to assess where collaborations are necessary and most valuable to support mitigation.[417,418]

Description of Confidence and Likelihood

Public commitments made and actions already taken (as tracked by the sources cited in the evidence base above) give us *high confidence* that mitigation can be supported by a wide range of actors in a wide variety of ways. Historical progress in reducing emissions (e.g., US electricity emissions since 2007) and forward-looking modeling analyses give us similarly *high confidence* that substantial near-term potential in the US lies in actions to boost low-carbon technologies,[50,255,387,419,420,421] moderate use of internal combustion vehicles,[65,66,68] improved building efficiency,[32,33] and diet shifts.[96,98,396]

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Fifth National Climate Assessment

Focus on Compound Events



Focus on Compound Events

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Focus on Compound Events

Climate change is increasing the chances of multiple climate hazards occurring simultaneously or consecutively across the US and its territories. Such interactions between multiple hazards across space or time, known as compound events, exacerbate the societal and ecosystem impacts of individual hazards and hinder the ability of communities, particularly frontline communities, to respond and cope. Therefore, infrastructure design, planning, governance, and disaster preparedness for compound events are critical for building resilient systems.

What Are Compound Events?

Compound events result from the occurrence of multiple climate drivers or hazards either in an individual location or across multiple locations that, when combined, have greater impacts than isolated hazards on ecosystems, water resources, public health, energy infrastructure, transportation, food systems, and interconnected societal networks, often straining disaster response.[1,2,3] Compound events can also result from the intersection of climate hazards with other environmental hazards like pollution, non-climate hazards such as wars and pandemics, or socioeconomic stressors like poverty and lack of adequate housing that disproportionately impact overburdened communities, thereby deepening existing societal inequities (e.g., KMs 5.2, 18.2, 20.1, 23.1, 27.1, 29.2). Compound events are broadly categorized as:

- **Multivariate**: co-occurring hazards in a location, such as simultaneous precipitation deficits and extreme heat that contributed to the severe Pan-Caribbean 2013–2016 drought[4]
- **Temporally compounding**: successive hazards in a location, such as destructive wildfires in 2017 followed by heavy rainfall on burned landscapes in January 2018 that resulted in mudslides and debris flows, damaging ecosystems and infrastructure (KMs 3.5, 5.2, 6.1, 27.2)
- **Spatially compounding**: similar or disparate hazards occurring simultaneously or within a short time window in multiple locations that are connected by physical processes or complex human and natural systems, such as simultaneous megafires across multiple western states and record back-to-back Atlantic hurricanes in 2020 that caused unprecedented demand on federal emergency response resources (Figure F1.1)[5]
- **Preconditioned**: extreme events superimposed on long-term trends, such as higher sea levels, heavier precipitation, and/or changing storm seasonality causing more frequent and severe coastal flooding (KMs 4.2, 9.1, 30.1),[6,7] like during Hurricane Florence (2018) in the Southeast (KM 22.1),[8] Typhoon Surigae (2021) in Palau, and Typhoon Merbok (2022) in Alaska (KM 29.1)[9]
- **Complex events**: non-climatic stressors that exacerbate climate hazards, such as COVID-19, which exacerbated climate-driven food, water, and livelihood insecurities facing Tribes, Indigenous Peoples, and other frontline communities (KMs 5.2, 16.1; Focus on COVID-19 and Climate Change)

Recent Events

Compound events have resulted in multiple recent disasters across several US states. The following examples illustrate their cascading societal impacts (Figure F1.1):

- **Heat, drought, and wildfires**: A series of compound events between 2020 and 2021 stressed communities and ecosystems across the western US and caused economic damages exceeding $38.5 billion (in 2022 dollars; KMs 27.2, 28.1, 28.2, 28.4).[10] In 2020, co-occurring heat and drought caused concurrent destructive fires across California, Oregon, and Washington11 that resulted in infrastructure and property damage and human fatalities, threatened access to energy and water supplies, and strained firefighting resources.[10] Millions of residents were exposed to harmful pollutants in wildfire smoke, affecting public health and worsening COVID-19 related mortality.[12,13,14] Drought persisted into 2021 and amplified the record-breaking Northwest heatwave,[15] killing over 229 people in the US. Co-occurring heat, drought, low streamflow, and low tides in 2021 triggered toxic algal blooms and mass die-offs of shellfish and low survival of salmon, species important to Indigenous communities and the West Coast economy (KM 27.2; Figure 10.2).[16] West Coast crab fishery revenue losses were exacerbated by management actions implemented during earlier marine heatwaves.[17]
- **Compound flooding**: Back-to-back storms affected the Northeast in 2021, resulting in 55 deaths and more than $21.4 billion (in 2022 dollars) in damages (KM 21.1). On August 22, Hurricane Henri brought intense rainfall to the Northeast (7 inches in New York City, including 2 inches in one hour in Central Park) that caused $749 million (in 2022 dollars) in damages despite mild winds. On August 29, Hurricane Ida, which made landfall as a Category 4 in Louisiana, moved northeast, and delivered record rainfall during September 1–2 to already-saturated Northeast soils, causing catastrophic flooding. This temporally compounding event was about 30 times more deadly and more damaging than Hurricane Henri alone, straining local governance and emergency management systems.[18]

Will Compound Events Increase with Climate Change?

Compound events are expected to become more frequent with continued climate change (e.g., KMs 2.2, 9.1). The increasing frequency and severity of climate hazards such as extreme heat, heavy precipitation, and severe storms are projected to increase the chances of 1) a sequence of hazards occurring within a short time span and 2) simultaneous independent events in a location or multiple locations. For instance, increasing swings from dry-to-wet extremes in western states and Pacific Islands will increase the chances of intense rains on parched or recently burned landscapes, increasing risks of postfire flash flooding, debris flow, and contaminated drinking water supplies (KMs 4.2, 30.1).[19,20,21] Climate change is also expected to alter the physical drivers of compound events. For instance, more frequent extreme La Niñas[22] would simultaneously elevate the risk of western US droughts and back-to-back severe Atlantic hurricanes, increasing the chances of compounding disasters similar to the 2020 season (Figure F1.1).[23,24] Changes in weather patterns such as more frequent atmospheric high-pressure systems could increase the risk of co-occurring heat, drought, and marine heatwaves.[25,26]

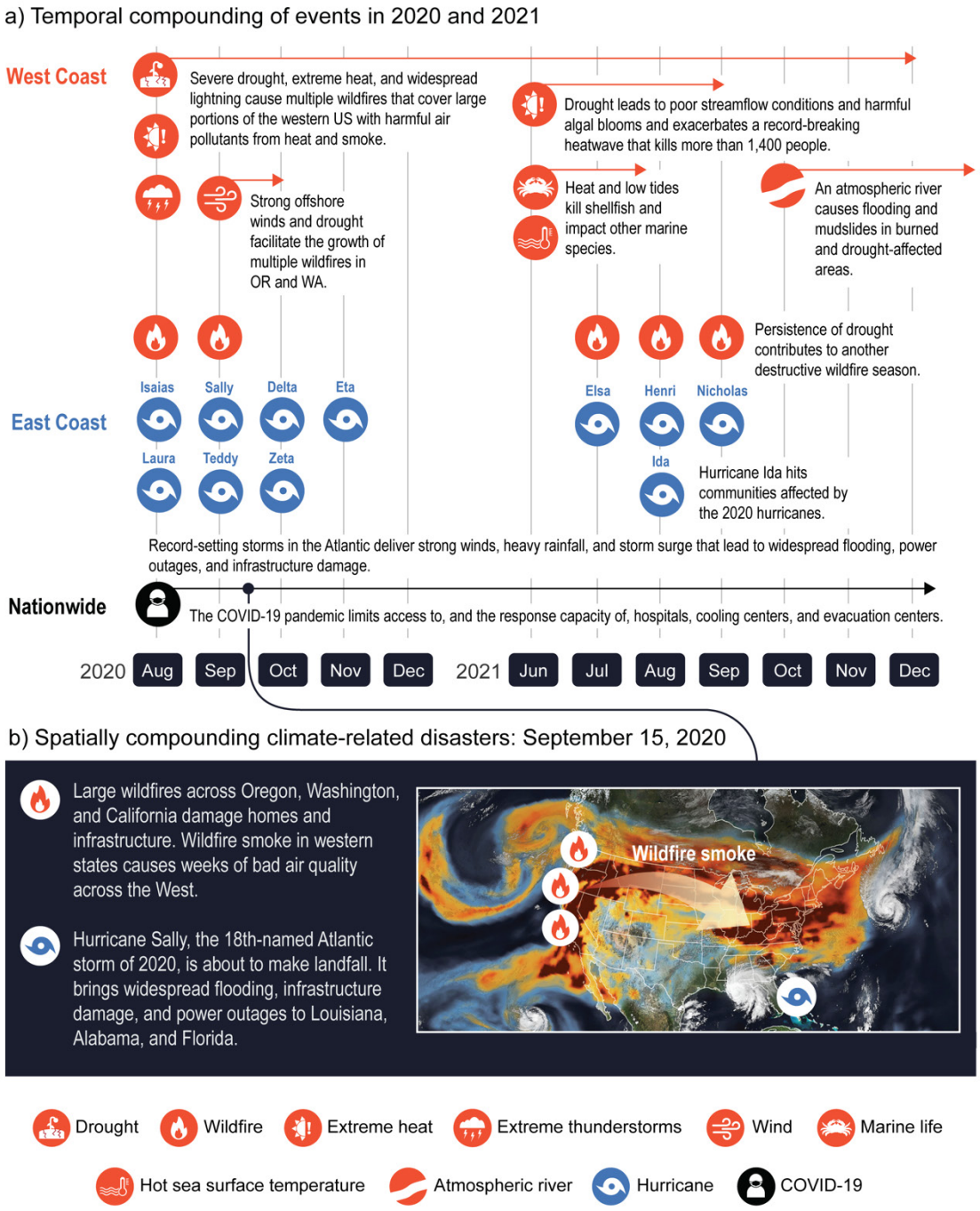
How Can We Adapt?

Low-income communities, communities of color, Tribes and Indigenous Peoples experience high exposure and vulnerability to climate hazards due to their proximity to hazard-prone areas, infrastructure deficits, limited disaster-management resources, and governance challenges, which are legacies of colonialism, redlining, and other discriminatory policies (KMs 4.2, 16.2, 18.2, 20.1).[27] Consequently, these communities could face higher risks through complex event outcomes, which can magnify existing disproportionate health risks (KM 15.2). Transformative, socially just adaptation approaches (KM 31.3), investment in emergency preparedness, and governance structures that account for the inequitable distribution of climate impacts can avoid further exacerbating such existing social disparities (KMs 12.4, 20.3, 31.2).[28,29,30] Incorporat-

ing compound event risks in infrastructure design standards and regulations, updating aging infrastructure, and planning at the community-level can improve climate resilience and protect against risks like displacement and gentrification.[28,31,32] Despite the availability of tools to evaluate infrastructure alternatives (e.g., Helgeson et al. 2020[33]), communities with limited adaptation resources face significant challenges in making such investments.

Resource allocation toward solutions that address multiple community resilience objectives can address some of these challenges.[34,35] For example, blue-green infrastructure—use of green-areas and water bodies in urban planning—and tidal marsh restoration can sequester greenhouse gas emissions and protect against floods while also providing ecosystem services like reducing heat and air pollution, creating recreational spaces, and advancing environmental justice in urban environments (KM 12.3).[36] Enhanced monitoring of adaptation actions, scenario planning activities (e.g., Gerlak et al. 2021[37]), and sharing best practices among stakeholders can alleviate planning challenges and improve management of the growing risk of compound events.

Compound Events



Compound events have amplifying impacts on ecosystems and human communities and affect their capacity to respond.

Figure F1.1. (**a**) The timeline shows temporally compounding events in 2020–2021 on the West and East Coasts and their cascading impacts on communities and ecosystems. (**b**) The satellite image shows simultaneous disasters—multiple wildfires in the US West and Hurricane Sally in the Southeast. The orange and red colors show wildfire smoke traveling across the US. Figure credit: Washington State University Vancouver. See figure metadata for additional contributors. Satellite image credit: Joshua Stevens, NASA Earth Observatory, using GEOS-5 data courtesy of NASA GSFC and VIIRS data courtesy of NASA EOSDIS/LANCE and GIBS/Worldview and the Suomi National Polar-orbiting Partnership.

Traceable Accounts

Description of Evidence Base and Research Gaps

There is broad agreement across the physical and social sciences and engineering communities that compound events are a growing threat to communities, sectors, emergency management, insurance companies, and interconnected societal systems. Recent studies have developed frameworks for studying compound events and quantified future changes in risks in several types of compound events such as hot and dry or hot and humid extremes, compound coastal and fluvial flooding, drought and marine heatwaves, marine heatwaves and ocean acidity extremes, and wildfires followed by heavy rainfall. Identification of various types of compound events has grown in recent years. Compound events are rare, and thus the short observational record for many climate variables limits the ability to quantify historical changes, characterize present-day probabilities, and evaluate the ability of climate models to simulate them. There are also gaps in the scientific understanding of the range of physical processes that lead to various types of compound events affecting many regions, communities, and sectors. Literature on their societal impacts is even more limited and challenging to quantify because compound events are still relatively rare and result from a complex set of factors. Together, these result in uncertainties and low confidence in estimates of projected changes in their risks.

Compound events span a wide variety of physical phenomena, societal impacts, and different research communities with different needs, requirements, and impacts. There is a diversity of definitions of compound events, and much of the literature consists of case studies. Compound events of multiple weather and climate variables are often treated by combining those variables into a single metric. For instance, the literature contains multiple formulations of the combined effect of high temperatures, humidity (or aridity), and winds (or stagnancy) on human health and fire risk. While such univariate formulations are more amenable to standard analysis techniques, the richness of the multivariate space can be lost. Advanced multivariate extreme statistical analysis tools have not seen widespread adoption by the scientific community. The recent development of large climate model ensembles combined with event identification analysis tools offers the opportunity to increase our understanding of the physical processes that lead to compound events and to evaluate their historical and future risks under different warming levels.

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Fifth National Climate Assessment

Focus on Western Wildfires



Focus on Western Wildfires

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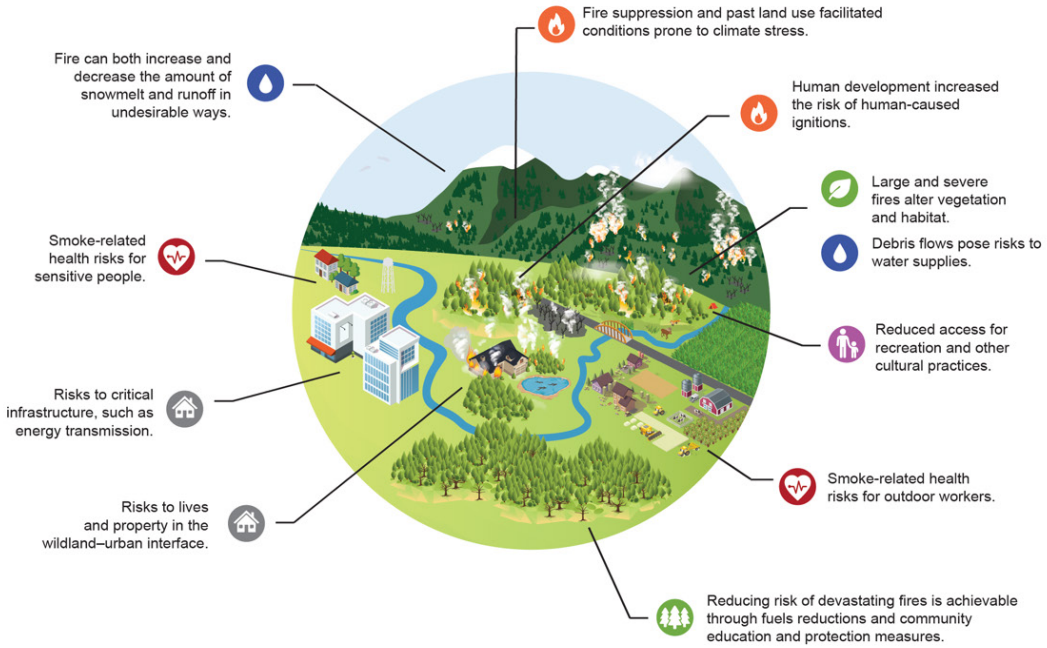
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Focus on Western Wildfires

Climate change is leading to larger and more severe wildfires in the western United States, bringing acute and chronic impacts both near and far from the flames. These wildfires have significant public health, socioeconomic, and ecological implications for the Nation.

Fire is a critical ecosystem process across the western US. In recent decades, wildfires in the western United States have become larger, hotter, and more destructive and deadly due to a suite of factors, including climate change. Prior to federal policy to suppress wildfires, natural wildfire and Indigenous burning ensured that landscapes benefited from regular fires for millennia (KM 28.5).[1] Nineteenth- and early-20th-century land-use practices, followed by a policy of fire elimination, led to vegetation fuel buildup in low-elevation fire-adapted western forests, and livestock grazing promoted highly flammable annual grass dominance in rangelands (KMs 2.2, 7.1, 28.5).[2,3,4] Development in the last 50 years has greatly expanded the wildland–urban interface (KMs 12.2, 28.5)[5] and increased human-caused ignitions, jeopardizing people, property, and infrastructure.[6,7] In recent years, climate change has contributed to very large and severe fires. While low- and moderate-severity fire with small patches of high severity can have important ecological benefits (Chs. 7, 28), large, high-severity fires often have profoundly negative long-term ecological, social, and economic consequences (Figure F2.1; KM 28.4).[8,9]

Wildfire Impacts



Wildfire: Causes and drivers

Warming, shifts in precipitation, and a drier near-surface atmosphere are increasing the frequency of large fires and the area burned (KMs 2.2, 7.1).

Fire exclusion and past management in dry forests have increased climatic stress and fire risk (KM 28.5).

Risks: Water

Particulates from wildfires reduce the albedo of snow and can accelerate snowmelt, influencing water retention and runoff (KM 28.5).

Burned areas are a debris-flow risk and threaten water supplies through erosion and particulates from smoke (KM 3.4).

Risks: Society and culture

Burned areas reduce access for recreation and other cultural uses (KMs 16.1, 28.5).

Wildfire generates substantial economic impacts, from whole sectors to individuals (KM 19.1).

Risks: Ecosystems

Large burned areas, especially with high fire severity, can promote vegetation and habitat changes (KMs 6.1, 7.2, 8.1, 8.2).

Risks: Built environment

Risks to critical infrastructure, energy, and water storage (KM 6.1).

Risks to personal safety and property and higher insurance costs for people living in the wildland–urban interface (KM 5.1).

Risks: Health

Smoke can be transported thousands of miles; airborne particulate matter creates health risks, especially for those with existing health conditions, older adults, and children (KMs 14.2, 15.1, 28.4).

Smoke and long periods of degraded air quality create health risks for outdoor workers and firefighters (KM 28.4) and disproportionately affect vulnerable populations (KM 27.5).

Opportunities: Management and adaptation

Adaptation of management strategies that create, maintain, and restore resilient forest ecosystems are critical to maintaining equitable provisioning of ecosystem services (KMs 7.3, 28.5, 31.1).

Climate change has increased the area burned and severity of wildfires and impacts on the environment, human health, and society.

Figure F2.1. Indicators and risks illustrate the drivers of, impacts from, and solutions to wildfire across a range of socioecological contexts within and beyond the western states. Considering these helps improve understanding of how impacts are experienced and how to adapt. Figure credit: USDA ARS, USDA Forest Service, University of Washington, and Montana Health Professionals for a Healthy Climate.

Climate change has produced warmer and drier conditions with prolonged droughts that stress forest vegetation, facilitating pest outbreaks and tree death, leading to the accumulation of surface fuel.[10,11] Wildfires are moving up in elevation, due to warming temperatures, reduced snowpacks and summer precipitation, and overall drier conditions (KMs 2.2, 3.5, 7.1, 28.5). Climate change has also increased vapor pressure deficit that dries fuels, altering fire behavior that results in large, hotter, and more severe fires (KMs 7.1, 28.5).[12,13,14,15] Consequently, the annual area burned and area burned by high-severity wildfires have increased in the West about eightfold since 1985 (Ch. 7).[14,16] And while the annual area burned is on par with pre-European settlement, the very large, high-severity, and deadly and destructive wildfires result in significant socioecological and economic impacts. These trends are expected to continue at least to midcentury, when fuel availability is expected to become more limited in some western forests (KMs 3.5, 28.5).[17]

In some non-forested regions, primarily arid shrublands and steppes, changes in the frequency and extent of wildfires are being driven primarily by invasive annual grasses that have benefited from climate change.[2,18] Intermountain West steppe rangelands are among the most threatened ecosystems in the US due to land use and wildfires, which have become larger and more frequent.[19] In oak savanna and chaparral shrublands, historical increases in fire are linked to changes in human ignitions and land use.[7,20]

Further increases in area burned and wildfire severity are expected to alter the distribution and abundance of plants and animals and lead to biodiversity loss (KM 7.1). In some cases, forested areas that experienced repeated severe reburns have transitioned to shrublands or other vegetation types.[21,22,23] Already, approximately 75% of vegetation type conversion in the Southwest is due to high-severity fire.[24] Continued warming, reductions in precipitation in some areas, and more frequent fire in forest and non-forest ecosystems can facilitate the establishment of invasive species, increase fuel flammability, reduce tree regeneration after wildfires,[18,25,26] and alter vegetation types (KMs 7.5, 28.5).[27] Potential reductions in forest and shrub cover due to climate-driven changes and wildfire reduce the potential for some western forestlands and steppe rangelands to function as carbon sinks (KM 7.2).

Although restored fire regimes can benefit forest hydrology in some cases,[28] wildfires can put critical infrastructure at risk by altering soil conditions and water runoff (KM 6.1). Following fire, intense rain on water-repellent soils can cause debris flows, which cause human deaths, property damage, and costly road closures (KM 6.1).[29] Chemical runoff can contaminate water supplies, and excess sediment runoff can reduce reservoir storage capacity.[30,31,32] Soot from fire emissions also darkens the surface of snow and ice, altering snow retention and melt in potentially undesirable ways.[33,34]

Human infrastructure can also affect wildfire risk. Although uncommon, fires caused by electrical transmission lines have been large and deadly. The 2018 Camp Fire nearly destroyed the entire town of Paradise, California, displacing tens of thousands of residents,[35] many of whom have not returned. To reduce such ignitions, electrical grid power shutoffs are used during windy weather.[36] However, this approach can disrupt local economies (e.g., agriculture and healthcare) and livelihoods, with disproportionately high impacts on rural and overburdened communities.[37]

Wildfire smoke can be transported thousands of miles, causing significant environmental, public health, and socioeconomic impacts across the country (KMs 14.1, 19.1, 25.1).[38,39] Smoke from burning vegetation and built structures contains fine particulate matter ($PM_{2.5}$), ozone precursors, and other toxic components (KM 14.2).[40] Although the annual average level of $PM_{2.5}$ has declined over recent decades due to air quality policies, the frequency and severity of smoke events in the western US make wildfire the largest contributor to $PM_{2.5}$ in this region, offsetting some of those improvements (KM 14.1). Exposure to wildfire smoke is associated with adverse cardiovascular and respiratory outcomes (KM 15.1), as well as increased risks of

COVID-19 mortality (Focus on COVID-19 and Climate Change).[41,42] Wildfire smoke may also affect neonatal human health, such as lower birthweights or pregnancy loss.[43,44]

Projected changes in wildfire are expected to result in a significant health burden, especially for at-risk populations.[45] Susceptibility to wildfire smoke exposure can be exacerbated by age, preexisting health conditions, socioeconomic status, occupation, and housing status (e.g., people who are unhoused experience constant exposure). Wildland firefighters are at increased risk of lung cancer mortality and cardiovascular diseases.[46] Where wildfires overlap with harvest seasons, farmworkers and other outdoor workers (frequently low-income workers from immigrant and Indigenous communities) are at risk (KMs 14.2, 15.2, 16.1, 27.1, 28.4).

Enhancing ecosystem resilience and protecting communities from wildfires is achievable through investments in both ecosystems and social systems (KM 28.5). Proactive actions include strategically placing forest fuel treatments in high-fire-risk locations and accelerating vegetation management, including the use of fire at ecologically meaningful spatial scales. These actions often require surface and ladder fuel reductions through prescribed burning or mechanical removal[47] and allowing low-intensity wildfires to burn in strategic locations (KMs 7.3, 28.5). In fire-adapted ecosystems, low- and moderate-severity wildfires reduce smaller trees, shrubs, and dead fuels, maintaining forests with fewer, more widely spaced trees (KMs 7.3, 28.5), thus increasing resilience to future climate impacts. Burned area rehabilitation efforts can reduce sediment runoff and protect water supply and hydroelectrical infrastructure (KMs 5.1, 7.1).

Efforts to strategically reduce the number of human-caused ignitions and investments in home hardening are important adaptation measures in some areas.[7,20] Fireproofing structures and other design and construction efforts can reduce the likelihood of structure ignition, lessening wildfire risk to communities.[48] Land and community planning practices—including zoning, ordinances, and building codes—influence wildfire risks to homes in wildfire-prone regions.[49] Additional measures for protecting communities involve improvements in data access and usability, emergency response planning, healthcare system preparedness, and early-warning systems for evacuation and timely communication of health impacts to the public, especially for at-risk populations and outdoor workers (KMs 14.1, 19.3).

Traceable Accounts

Description of Evidence Base and Research Gaps

This focus box examines observed and projected wildfire trends for western North America and the impacts of wildfire nationally.[3,38,50] This includes research that has used remotely sensed and modeled data, alongside field-based experimental and observational data, to demonstrate that the influence of climate change on current and future wildfire is through warming temperatures, which have reduced fuel moisture content and made the fuels more flammable.[11,12,14,22] Research demonstrates that roughly half of the increase in area burned is due to increases in fuel flammability as a result of anthropogenic climate change (KMs 3.5, 7.1).[12] Warming, lowered humidity, and atmospheric drying (i.e., higher vapor pressure deficit) have facilitated increases in the frequency of fire-conducive weather as well as of annual area burned and the proportion burned at high severity by wildfire (KM 2.2).[14,16] Similar methods have also been used to elucidate factors influencing wildfire smoke pollutant mixture and the effects on human health.[38,39,42]

There is strong and building evidence that reducing forest fuels and lowering the density of trees in forests lessens the impact of climate-mediated stress and disturbance.[4] Greater resistance and resilience to wildfire can be achieved through mechanical vegetation treatments with the use of prescribed fire and managed wildfire (KMs 7.3, 28.5). An increased and refined understanding of appropriate adaptation strategies to safeguard ecosystems, communities, and people could enhance outcomes of future investments.[4] There is evidence that planning, zoning, updating building codes, and fireproofing structures can mitigate risk and losses to infrastructure and property.[48,49] Key areas of future investigation include, but are not limited to, the appropriate suite of land-based practices (i.e., thinning, prescribed fire) as well as the ecosystem specificity (e.g., forest or vegetation type) and the appropriate spatial scale needed to meaningfully reduce risk.[15] Lastly, an increased understanding of the composition of rural populations in the western US, how different subsets of the population access information, and behavioral responses to wildfire-related alerts would allow for more targeted messaging and more informed allocation of resources during wildfire and smoke events.[45]

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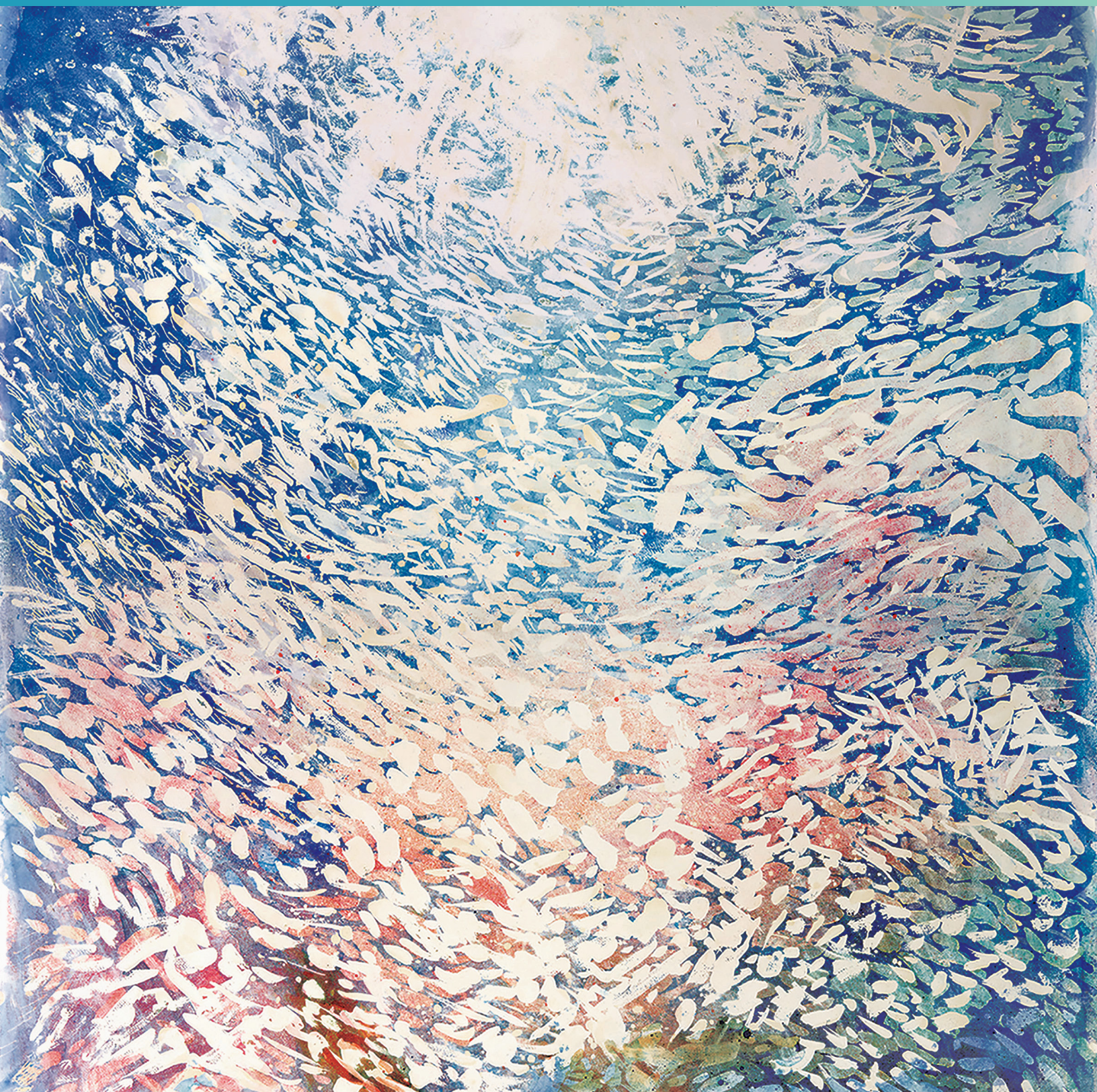
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Fifth National Climate Assessment

Focus on COVID-19 and Climate Change



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Focus on COVID-19 and Climate Change

Climate change can increase the likelihood of pandemics like COVID-19 and worsen their impacts. Climate-driven changes in ecosystems increase the risk of emerging infectious diseases by altering interactions among humans, pathogens, and animals and changing social and biological susceptibility to infection. Climate change also amplifies the risk of infection among people at the front lines of exposure, especially those with fewer resources. Addressing the challenges of climate change and pandemics requires early collective action and systemic change.

The Impact of Climate on Infectious Diseases

Over half of known human pathogenic diseases are exacerbated by climate change,[1] particularly zoonotic (originating in animals) and vector-borne diseases (KM 15.1; Table 8.1). Zoonotic diseases account for three out of every four newly emerging pathogens, including COVID-19.[2] Changes in climate alter the distribution, diversity, and abundance of vectors and non-human hosts, as well as the host's susceptibility to pathogens and pathogen replication. Climate changes can also speed the transmission of pathogens and promote the establishment of new diseases (KMs 8.2, 15.1). Coupled with global travel networks and dense urbanization, novel pathogens can rapidly spread to areas far from their origins. Our understanding of COVID-19 is evolving, but the pandemic demonstrates the global threat of emerging infectious diseases and has raised awareness of linkages between climate change and zoonotic diseases.[3,4]

Interactions Between COVID-19 and Climate Change Exacerbate Existing Inequities

Climate-related disasters have interacted with COVID-19 throughout the course of the pandemic in multiple ways (Table F3.1). Certain communities—including essential workers, older adults, low-wealth communities, and communities of color—are disproportionately impacted by these compounded exposures (KM 15.2).[5]

Table F3.1. Interactions Between COVID-19 and Climate Change Exacerbate Existing Inequities

The table shows examples of disproportionate impacts related to COVID-19 and climate change.

Climate-Related Exposures	Health Impact	COVID-19 Interactions with Climate Change
Hurricanes	COVID-19 transmission	After Hurricane Laura hit the Gulf Coast in 2020, the average number of COVID-19 hospitalizations increased, compared to before the storm, and was significantly higher in counties most affected by the storm.[6]
Drought	COVID-19 transmission	Many areas, including the Colorado River basin, experienced extreme drought—a climate-related hazard—and historic reductions in water supply during the pandemic. This highlighted the lack of access to clean water for health and hygiene for more than 2 million people living in the US, the majority of whom are people of color (KM 4.2). Tribal lands without reliable access to water had higher COVID-19 incidence.[7]
Wildfires, Hurricanes	COVID-19 transmission	Crowded housing and reduced hygiene increased disease spread during disaster-related evacuations.[5,8] COVID-19 also reduced willingness to evacuate to shelters.[9]
Wildfires	COVID-19 disease severity	Wildfires exacerbate disease risk by worsening air quality (KMs 7.2, 14.2). Breathing in tiny airborne particles magnifies a person's vulnerability to COVID-19.[10,11] Smoke from the massive 2020 fires in the West was linked with increased COVID-19 cases and associated deaths.[12]
Extreme Heat, Drought, Wildfires	Livelihoods	Farmworkers—of whom approximately 70% are born outside the US—are disproportionately vulnerable to climate change impacts that exacerbate COVID-19 risk.[13,14] Extreme heat, drought, and wildfires, combined with the pandemic, negatively affected farmworker health, farm income, and the broader agricultural economy (Figure 11.1).[13,15,16]
Air pollution	COVID-19 disparities in transmission and severity	Exposure to particulate pollution can intensify COVID-19 morbidity and mortality (KM 15.2). Disparities in exposure to particulate pollution may partially explain why Indigenous, Alaska Native, Pacific Islander, Black, and Latinx Americans have experienced higher rates of COVID-19 cases, hospitalization, and death compared to White Americans.[11,17]
Climate Disasters and Long-Term Threat	Mental-health impacts	Climate change and the pandemic may significantly increase the mental health burden in the US,[18] as current inequities in access lead to widening gaps in mental health outcomes.[19,20,21] Uncertainty, frustration, hopelessness, and helplessness, coupled with loss of livelihood, drastic lifestyle changes, and disruption of routines, are linked to COVID-19 and post-COVID conditions, as well as to acute and chronic mental health impacts of climate change (KM 15.1).[22,23]

Lessons from COVID-19 for Managing Climate Change

In 2020, COVID-19 lockdowns reduced transportation and electricity generation, decreasing annual US emissions of greenhouse gases (GHGs) by 11%.[24] At the peak of COVID-19 restrictions (April 2020), emissions decreased by approximately 32%.[25,26] While emissions reductions were not sustained and had little influence on global climate,[27] they revealed the impact climate actions might have on air quality and the carbon cycle.[25,28,29,30] The short-lived decrease in GHG emissions, despite dramatic lifestyle changes, as well as public resistance to restrictions, vaccines, and masks, suggests that voluntary lifestyle changes will not be enough to achieve GHG emissions-reduction targets. Reaching net-zero emissions is achievable and would require implementing known systemic changes (KM 32.2).

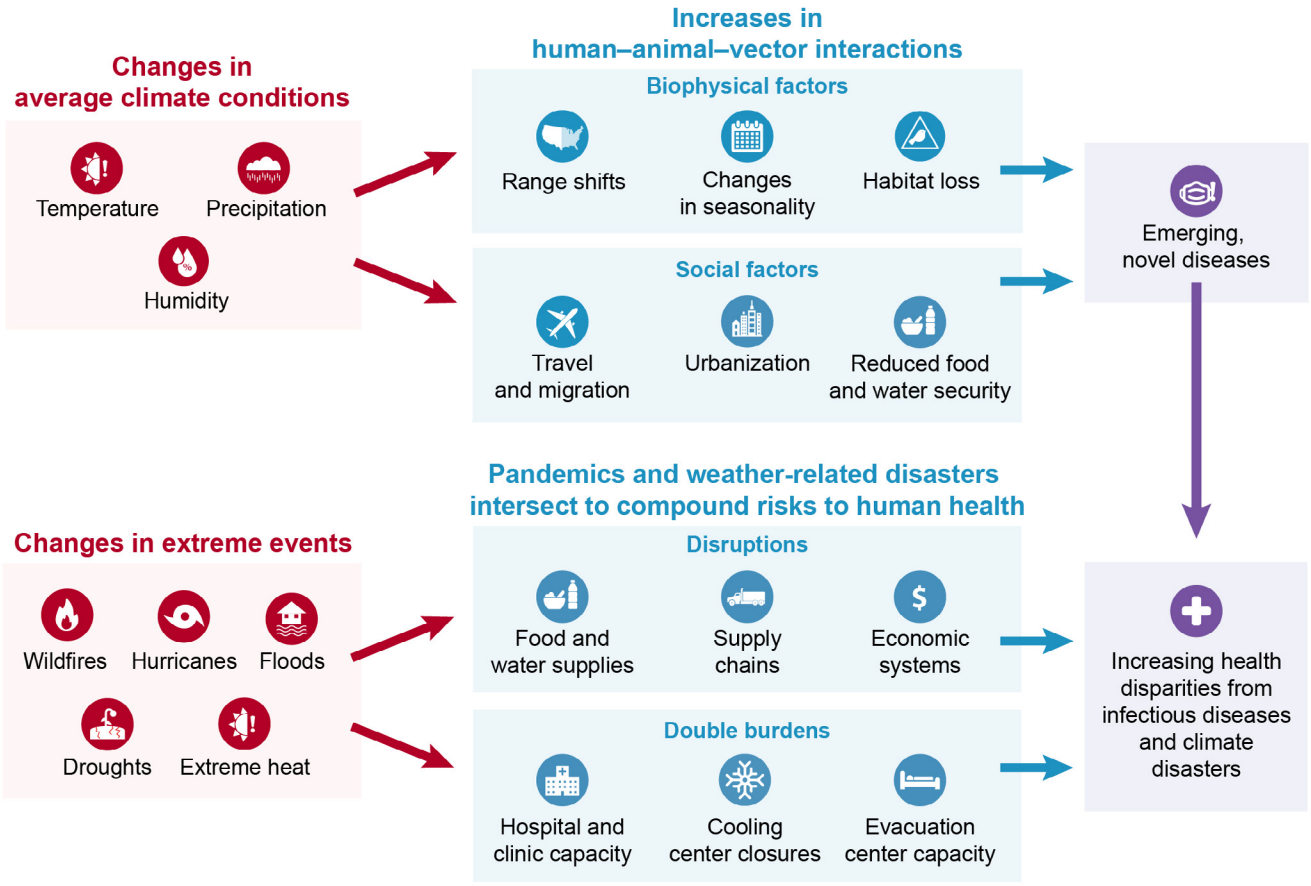
Early projections of COVID-19 costs to the US from lost economic output (i.e., income) and reduced health (i.e., premature death and long-term impairment) were calculated to be $17.9 trillion (in 2022 dollars)[31]—an underestimate given continued transmission and the high prevalence of post-COVID conditions.[32] Climate change also involves significant and inequitable direct and indirect costs, which increase with delayed response (KM 19.1). Developing solutions would help avoid significant economic costs of future pandemics and climate change.

COVID-19 and climate change have common underlying challenges and solutions.[33,34] Shared solutions include the following:

- Improved science communication that builds trust and minimizes disinformation impacts
- Collective action among nations to minimize threats
- Bottom-up and top-down programming to build community resilience
- Solutions to address stark socioeconomic, racial, and gender disparities that increase the vulnerability of those who are facing discrimination or have fewer resources
- Investments in public health and medical infrastructure that can respond to acute increases in medical burden
- Continued advancement in technology to prevent and respond to crises
- Responsive and agile systems that detect and respond to early warning signals before the worst impacts are realized

Quick action has major benefits. For COVID-19, deaths lag hospitalizations, hospitalizations lag infections, and infections lag exposures, providing time to prepare if adequate surveillance and public health systems are in place. Similarly, today's GHG emissions will affect the climate for decades to come, and delayed action has significant consequences (KM 19.1).[31] Early, preventive actions will slow or avoid the impacts of both pandemics and climate change, particularly the impacts felt by future generations. For climate change, preventive actions include achieving net-zero emissions (KM 32.1) and increasing adaptive capacity (KM 31.3). For pandemics, actions include addressing current health inequities, modernizing surveillance systems, enhancing targeted communication, mobilizing community-based prevention programs, and rapidly developing technical solutions such as vaccines. We can use the lessons learned from the COVID-19 pandemic to build resilience and to better mitigate, respond to, and recover from both the next novel pathogen and climate change.

Climate Change and Pandemic Risks



Climate change exacerbates infectious disease risk and increases health disparities.

Figure F3.1. (**top**) Climate change is projected to alter the geographic range and seasonality of disease vectors and animal hosts due to habitat loss and changes in habitat suitability. Concurrent climate-driven changes to human social systems—such as migration and travel, growing urban centers, and food and water insecurity—increase the potential for novel pathogens to spread quickly. (**bottom**) More frequent or severe extreme weather events can simultaneously interrupt supply chains, causing further economic disruption. Extreme weather events during a pandemic can reduce healthcare capacity, increase crowding in evacuation centers, and increase exposure to extreme conditions, such as exposure to extreme heat if cooling centers are closed—all of which act together to increase health disparities. Figure credit: University of Arizona and USGCRP. See figure metadata for additional contributors.

Traceable Accounts

Description of Evidence Base and Research Gaps

The author team reviewed the current science related to COVID-19 and climate change, focusing particularly on the more measurable impacts of climate change–related disasters and their compounding impacts during the COVID-19 pandemic. There is a growing body of literature that examines the compounding health effects of COVID-19 and climate change–driven disasters and extremes.[5] Primary research articles examine the links between air pollution, wildfires, and COVID-19 susceptibility, and several case studies examine hospital capacity in areas experiencing both COVID-19 and natural disasters. These include articles that demonstrate how extreme heat during the pandemic overlapped with COVID-19 to impact vulnerable populations;[35] the COVID-19 pandemic's influence on willingness to evacuate during hurricanes;[9] the potential impact of hurricane evacuation on COVID-19 transmission;[36] and the role of wildfires on susceptibility to severe COVID-19 disease. Additional parallels between climate change and the COVID-19 pandemic have been drawn extensively within the academic literature.[5] Most of these articles are reviews of the science of these two challenges that seek to identify how they interrelate. Many of the articles raise similar themes, indicating some degree of consensus among the experts who have examined these two issues.

There remain significant gaps in understanding the role that climate change has played and will play regarding COVID-19 transmission. For example, it is unclear if, and to what extent, climate change was a driver of the emergence of the novel SARS-CoV-2 virus.[37] There is no scientific consensus and low certainty of this relationship. Questions remain about the cited increase in bat species in the region, as well as about the methods for calculating vegetation change. This illustrates the challenges in directly linking the emergence of a novel pathogen with climate change, as pathogen emergence is a downstream consequence of both first-order (i.e., geophysical changes in the climate) and second-order (shifts in forests, grasslands, and oceans) impacts of increasing GHGs. There is evidence that supports higher transmission of COVID-19 in drier and colder months, but longer time trends need to be established before there can be reliable projections of how climate change will impact transmission patterns.

For disease systems with a longer history, the role of climate change in increasing the geographic range and incidence of disease is much clearer. Zoonotic and vector-borne disease systems are particularly subject to climate change impacts. Range expansion of disease vectors is already occurring.[38,39] Changing ranges will also alter interactions among species, leading to projected increases in cross-species transmission.[40] Human movement from climate change–related disasters and loss of livelihoods are also anticipated to move pathogens around the globe[41] and expose larger numbers of individuals when these pathogens are introduced into increasingly large urban populations.[42]

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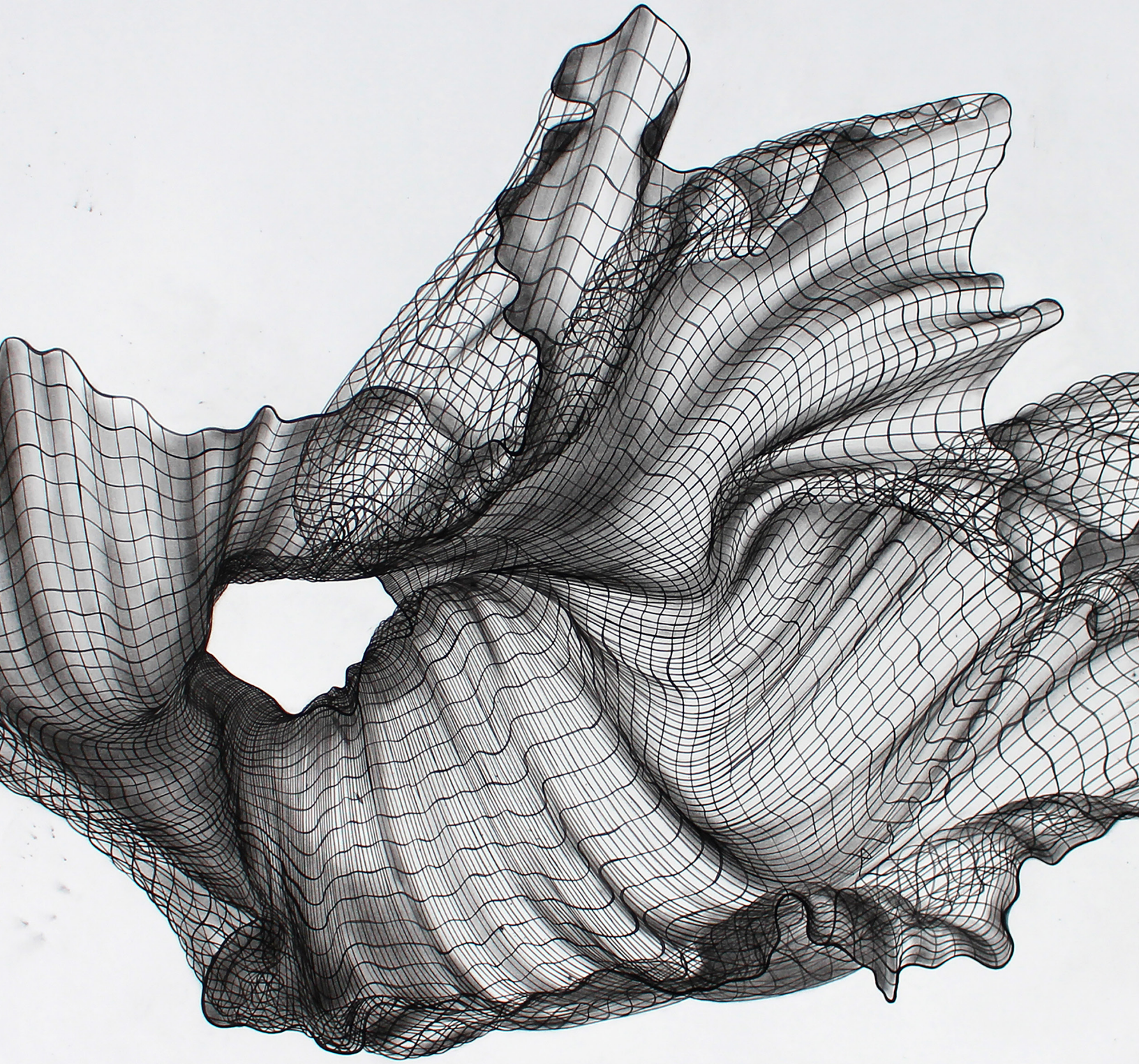
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Fifth National Climate Assessment

Focus on Risks to Supply Chains



Focus on Risks to Supply Chains

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Focus on Risks to Supply Chains

Damage to supply chain networks caused by climate change reverberates through people's livelihoods and investments in ways that threaten quality of life and security, often in lasting and inequitable ways. Coordinated efforts can mediate impacts and help communities and companies adapt to these large, interconnected, and recurring risks. However, the pace, scale, and scope of efforts that have been undertaken to transform supply chains are not yet sufficient to meet either current or expected disruptions and costs.

A supply chain represents the entire flow of goods and services, from the sourcing of raw materials to the delivery of a product or service to the customer. Supply chains operate globally across complex and interdependent networks of infrastructure, activities, and resources and include producers, manufacturers, and distributors. Upstream portions of supply chains encompass the range of activities needed to produce the product or service, while downstream portions encompass the range of activities needed to get the product or service to its final consumer. Supply chain management predominantly follows a linear model (take, make, and dispose), but a circular model is emerging that addresses sustainability by adding elements of recycling or refurbishing products.[1] Supply chains depend on the physical transportation of goods and services, as well as on digital networks to provide logistical support, to track movement of goods and services or other important information (e.g., immutable ledgers on investment and financial transactions on blockchain networks), and to deliver goods and services (e.g., telemedicine or remote education). In addition to physical and digital infrastructure, supply chains depend on networks of people to manage and service them.

Climate-driven disruptions to supply chains cascade and compound across multiple systems, underlining the need to understand and manage climate-related risks (KMs 17.1, 18.1, 19.2). These compounding risks include deepening of existing inequities in risk distribution and resource access for overburdened communities (KMs 16.1, 20.1),[2] geopolitical instability and national security vulnerabilities (KM 17.2),[3] and the inability to achieve emissions reductions due to the lack of capacity and provisioning for the electrification of products and services (KMs 5.2, 13.4, 17.3). Climate change also has complex interactions with non-climate global shocks such as the COVID-19 pandemic (see Focus on COVID-19 and Climate Change). Current supply chain vulnerabilities show the need to adapt to avoid future interruptions (KMs 7.1, 11.2, 15.3, 20.2, 31.3).[4,5] Climate-related risks to supply chains threaten the livelihoods of suppliers, distributors, and laborers, as well as infrastructure (KMs 7.2, 21.2, 22.1). In 2021, builders paid more for materials due to West Coast wildfires and an active US housing market.[6] Extreme heat and flooding at ports and transportation hubs has impacted goods movement.[7] Overlooking these risks prolongs economic consequences to suppliers and customers, prompting fundamental shifts in global supply chains, consumption patterns, and competition over constrained natural resources (KMs 8.3, 10.1, 18.1, 19.3, 20.1, 30.1).[8]

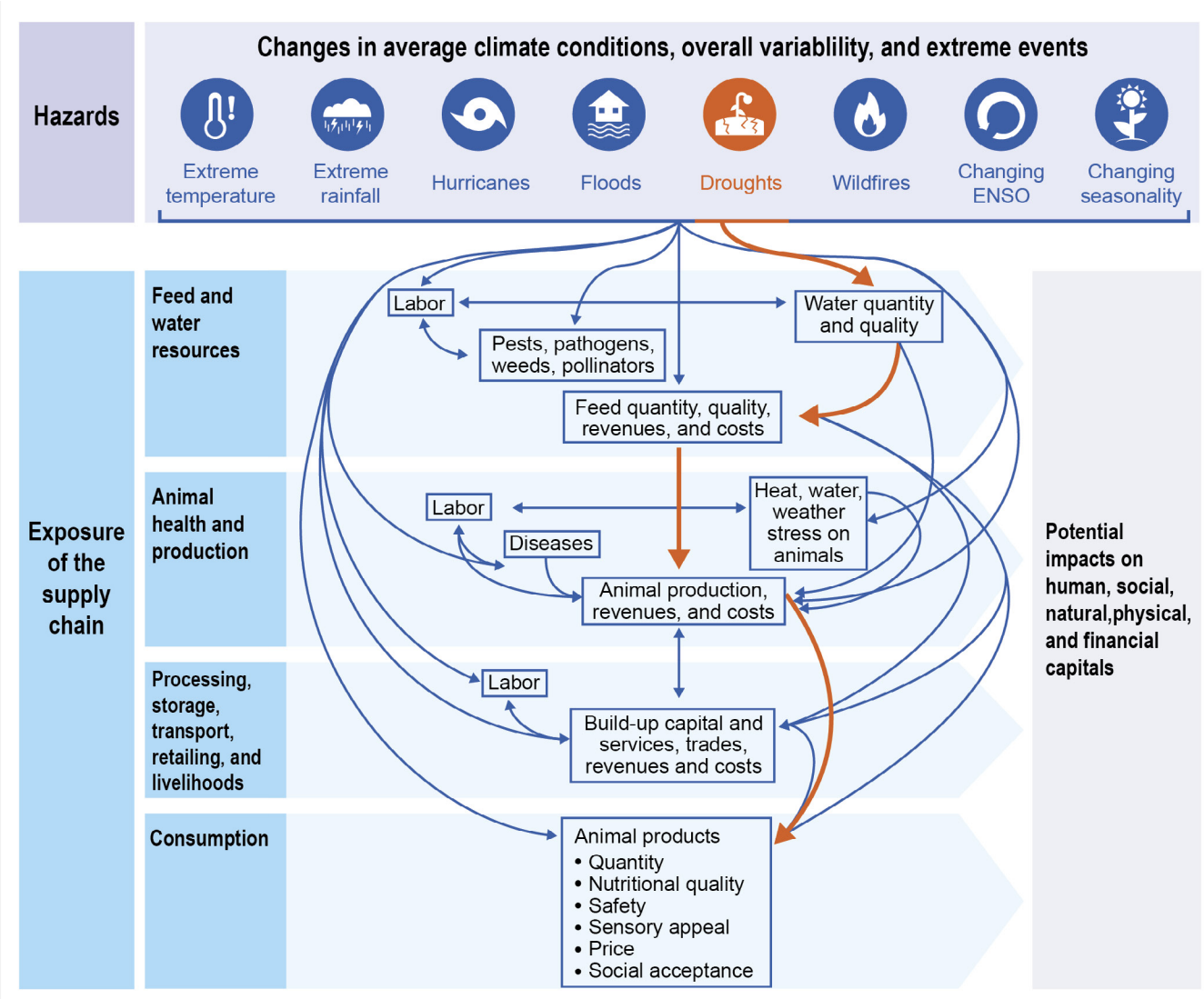
As an example, each stage in the food supply chain, including production, storage, processing, distribution, retail, and household food security, is vulnerable to climate change—from gradual changes in average climate conditions (e.g., precipitation and temperature) to increases in the frequency and intensity of extreme events (e.g., floods, drought, wildfire) and smoke migration (Figure F4.1; KMs 9.1, 10.3, 3.2, 14.2, 28.5, 29.3).[9] Sudden shocks to the food supply chain can have local to global impacts on food security, justice, and human migration patterns (KMs 11.2, 28.3, 29.3).[10,11] Extreme events in other countries raise domestic food prices and limit availability due to global supply chain interdependencies (KMs 6.1, 17.1, 9.1).

The transition to low-carbon energy sources to mitigate future climate change is accelerating demand for the upstream minerals, bulk electric supply goods (e.g., transformers, parts, chemicals), and materials for energy infrastructure and technologies.[12,13,14] Global competition, geopolitical tensions, and supply chain disruptions, along with a national lack of trained workers and inflation-related constraints on investment capital, are shifting materials sourcing (KMs 18.1, 21.5).[15] These disruptions will continue to hinder the global supply chains underpinning development and deployment of technologies for low-carbon and renewable energy generation and supply, as well as the related technologies for emissions mitigation, carbon capture, and electrification critical to achieving net-zero emissions (KM 32.1). Strategies are emerging to secure these critical energy development supplies. These include shifting to upstream sourcing from lower-risk countries near manufacturing sites, assisting countries to bolster mining and refining capacity, building redundant supply chains, and developing alternative materials or processes (Figure 17.2).[3] However, meeting the demand for these inputs may disproportionately harm overburdened and Indigenous communities, fueling inequality, political unrest, and economic loss in US-based investment and interests (KMs 5.2, 16.2, 18.2, 17.3).

Climate adaptation and emissions mitigation will require major transformations of supply chain transportation infrastructure and technologies (Chs. 31, 32).[16] The COVID-19 pandemic showed the sharp demand fluctuations, fragility, and chokepoints of an evolving, multimodal transportation system.[17] This system underlies the supply chain yet increases environmental injustices by siting warehouses and freight ways in overburdened communities (KMs 12.2, 13.4, 15.1, 29.2).[18] Adaptations in digitalization and related technologies (including e-commerce, electric-drive or automated vehicles, and related infrastructure), along with insufficiently localized supply chains, long-standing workforce challenges, and cybersecurity risks, all place demands on and pose risks to supply chain transportation systems. These challenges increase the importance of multisectoral and equity-centered planning and action for transportation (KMs 5.2, 13.2).

Integrated global supply chains will continue to be threatened by climate change and will in turn influence how the Nation responds to climate change. Markets often respond quickly if there are alternate materials or inputs available that are economically viable. Such shifts can present opportunities for disclosure of material risks, informed investment and improved livelihoods in local job creation, domestic economic activity, and innovation across sectors and technologies.[19,20] To protect the quality and security of life for all would require a rapid acceleration of supply chain adaptation measures that increase flexibility and ensure equitable access to goods and services.

Climate Change and Food Supply



Climate change poses challenges to the animal food products supply chain.

Figure F4.1. The figure shows potential climate change vulnerabilities of the livestock food supply chain, including impacts on feed and water resources; animal health and production; processing, storage, transport, retailing, and livelihoods; and human consumption. Blue lines indicate how climate change hazards can impact various sectors of the supply chain either directly or through cascading effects. Highlighted in orange is an example of the cascading effects of drought, where reduced water quantity decreases animal feed quantity, which in turn reduces animal production, resulting in increased food prices for consumers and an increased demand for deforestation-free agriculture and forest products. ENSO refers to El Niño–Southern Oscillation. Adapted from Godde et al. 2021[21] [CC BY 4.0].

Traceable Accounts

Description of Evidence Base and Research Gaps

Extensive evidence and recent lived experience during the ongoing pandemic confirm how supply chains are a core factor in the quality of life and national security of the United States.[5] Multiple examples from across this Assessment show that climate change burdens supply chains and challenges effective, efficient, and equitable provisioning of goods and services. These challenges play out differently depending on a supply chain's sourcing, distribution networks, and many complex factors that are beyond the scope of this discussion.[15] Supply chain climate vulnerabilities are distributed unevenly both globally and within the United States and are known but not well quantified. This uncertainty reflects disparities in the access to materials, technologies, and infrastructure (both physical and digital) that influence decision-making in supply chain management.

It is difficult to predict the expected changes of climate risks on supply chains, as well as human responses due to shocks and stressors. This uncertainty is due in part to the many complex factors that influence the size and composition of supply chains. The degree to which climate change will exacerbate challenges to existing supply chains also depends on the future frequency and intensity of extreme weather events. Finally, there is uncertainty in the choices that businesses and governments make in terms of policy to address risks, build resilience into supply chains, and ensure equitable distribution.[20]

Supply chains enable production of low-emitting energy technologies but are also sources of emissions themselves. Tracking emissions from activities across supply chains is of growing importance both to companies and to investors and disclosure organizations. Discussion of this topic is beyond the scope of this discussion.

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Fifth National Climate Assessment

Focus on Blue Carbon



Focus on Blue Carbon

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Focus on Blue Carbon

Blue carbon refers to carbon captured by marine and coastal ecosystems, such as mangroves, coastal wetlands, and seagrasses. Coastal ecosystems sequester carbon at a much faster rate than terrestrial ecosystems, and the carbon stored belowground can remain in place for decades to millennia if undisturbed by humans or extreme events. Conservation and restoration of coastal ecosystems can play a role in reducing carbon dioxide accumulations in the atmosphere by increasing sequestration of blue carbon.

Why So Blue, Carbon?

Blue carbon is the marine analog of green carbon, which refers to carbon captured by terrestrial (i.e., land-based) plants.[1] Marine ecosystems are aquatic environments with high salinity levels, including the open ocean, deep sea ocean, and coastal ecosystems. Marine and terrestrial plants capture and store carbon through photosynthesis and the accumulation of organic matter, such as roots, in the soil.[1,2] Blue carbon ecosystems (BCEs) are coastal ecosystems such as mangroves, wetlands, and seagrasses that store most of their carbon belowground in ocean sediments. Acre for acre, BCEs are estimated to store about twice as much carbon belowground than terrestrial vegetation (Figure F5.1).[3,4]

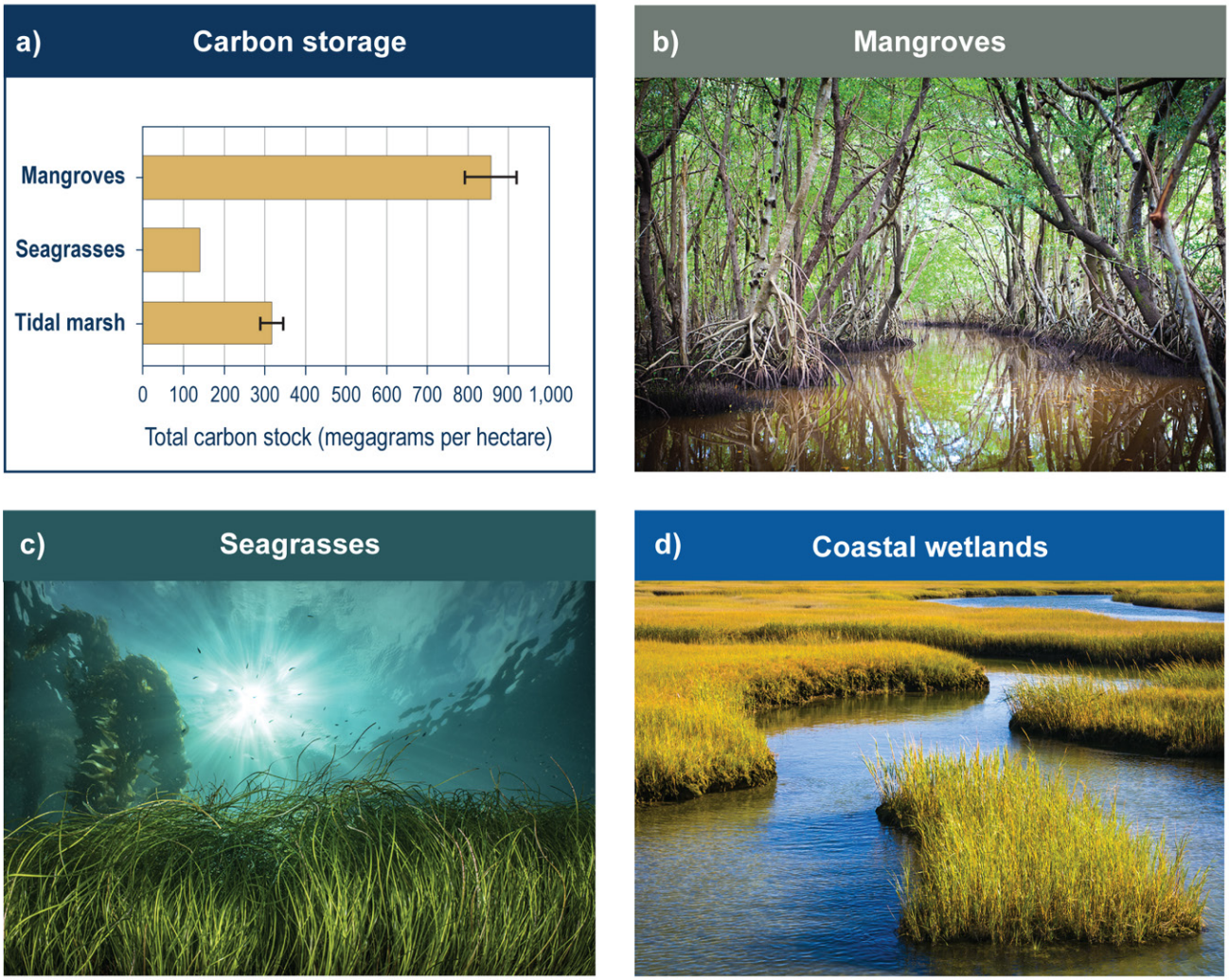
The Carbon Benefits

BCEs' ability to capture and store carbon has spawned numerous international efforts that support blue carbon as a natural climate mitigation option through enhanced stewardship, management, conservation, and restoration of these ecosystems and the ecosystem services and co-benefits they provide (KM 8.3).[2,3,5] This work includes creating and improving financing and policy mechanisms for coastal restoration that increases carbon sequestration,[6,7,8] as well as developing methods to better quantify carbon sequestration.[9,10,11]

The importance of estimating carbon emissions and sequestration in BCEs is recognized in international policies such as the Intergovernmental Panel on Climate Change (IPCC) guidelines for greenhouse gas inventories.[12] The United States has included coastal wetlands within its annual national inventory of greenhouse gas emissions and sinks,[13,14] and the government monitors sites across the US with the most blue carbon storage potential, such as the Florida Everglades, San Francisco Bay, and Chesapeake Bay. Globally, the US has one of the highest rates of BCE losses, largely due to hurricanes and coastal erosion.[15]

With conservation and restoration, BCEs could sequester enough carbon each year to offset about 3 percent of global emissions (based on 2019 and 2020 emissions).[3] Other coastal and marine ecosystems or species, such as kelp forests, freshwater wetlands, phytoplankton, and the deep sea may also capture carbon; however, the carbon sequestration potential of these ecosystems and species is likely lower than BCEs (Figure 8.19).[16,17]

Blue Carbon Ecosystem Sequestration Potential



Coastal blue carbon ecosystems play an important role in carbon sequestration but are vulnerable to climate change.

Figure F5.1. Blue carbon coastal ecosystems—mangroves (**b**), seagrasses (**c**), and coastal wetlands (**d**)—store more carbon belowground in soils and root systems (per hectare) than terrestrial vegetation, with mangroves storing the most carbon per hectare (**a**). They also provide other benefits such as reducing flood risk, supporting subsistence livelihoods, and providing recreational opportunities. However, blue carbon ecosystems are vulnerable to sea level rise, hurricanes, and other extreme events. In (a), black bars indicate the 95% confidence interval (which was unavailable for seagrasses). Figure credit: (a) Pathways Climate Institute. Photo credits: (b) YinYang, iStock/Getty Images Plus via Getty Images; (c) tswinner, iStock/Getty Images Plus via Getty Images; (d) Ken Wiedemann, iStock/Getty Images Plus via Getty Images.

Additional Benefits

BCEs are located at the interfaces among terrestrial, freshwater, and marine environments. They provide habitat for species, filter fresh water, recycle nutrients and other materials (KM 8.3), and help sustain human communities by providing other benefits, such as dissipating waves, reducing flood risk, and supporting coastal livelihoods, food security, cultural activities, and tourism (KMs 23.2, 30.4; Box 30.5).[18,19] Coastal seagrasses and wetlands provide nursery habitat for young crustaceans and fishes of economic and cultural value[20] and support the status and function of adjacent ecosystems. In addition, seagrasses may mitigate ocean acidification locally, thereby reducing some climate-driven stressors to shellfish and crustaceans.[21,22]

Effects of Climate Change on Blue Carbon

Sea level rise (SLR) and extreme events are the greatest climate change threats to BCEs.[23] In the past, many BCEs adapted to SLR through belowground root growth, sedimentation, and inland migration, which collectively increased the elevation of BCEs. As SLR accelerates, the ability of BCEs to continue to adapt is uncertain.[24,25] If BCEs cannot adapt to accelerating SLR, their geographical extent will decrease, and their species composition will change.[26] Currently, 43%–48% of wetlands along the Atlantic and Gulf Coasts are vulnerable to SLR, with northern wetlands limited by inland migration capacity and southern wetlands limited by local subsidence, which increases the relative rate of local sea level rise (KM 9.2).[27]

Growth of some plant species may increase in response to a warming climate and increased atmospheric carbon dioxide concentrations. This increased plant growth could locally offset accelerating SLR and allow some BCE species to continue to adapt. However, a 33-year coastal wetland experiment suggests that when SLR reaches a certain rate, plant growth will be hindered, thereby limiting these benefits.[28] This suggests that enhanced plant growth alone may not enable all coastal wetland species to adapt to accelerating SLR.

Human disturbance, SLR, and extreme events can erode and degrade BCEs, reducing carbon storage and potentially releasing previously stored carbon and methane.[29,30,31] If conservation efforts are not undertaken, this release of stored carbon could result in harmful climate change feedbacks.[32,33] For example, accelerating sea level rise would further degrade blue carbon ecosystems, reducing carbon sequestration and releasing stored carbon, which would further increase the rate of ecosystem degradation. Protecting and minimizing degradation of coastal areas to support carbon sequestration can have cascading ecological and societal benefits.[3]

Emerging Research

Although BCE conservation and restoration have wide-ranging benefits, uncertainties remain regarding carbon sequestration rates across different ecosystems and regions.[34] Research efforts are ongoing to improve methods, measurements, and modeling to fill knowledge gaps related to coastal carbon budgets.[35,36,37]

Seagrasses may mitigate local and/or regional ocean acidification rates by absorbing carbon dioxide and increasing the pH of seawater.[22] However, oceanic conditions are changing rapidly, and additional research is needed to assess this mitigation potential under high ocean acidification rates and warming ocean temperatures (KM 10.1).[38] The effect of ocean acidification on marine ecosystems is expected to vary depending on the combined influence of multiple climate drivers and other factors.[39]

The most effective means of enhancing BCEs and carbon sequestration are increasing local sediment supplies; enabling wetland expansion, including inland migration capacity; and restoring natural tidal conditions.[40] Mechanisms to support these enhancements are location-, ecosystem-, and stressor-dependent, and their success will be affected by past actions such as damming rivers, deforestation, building seawalls and other structures, and encroaching development.[41]

Traceable Accounts

Description of Evidence Base and Research Gaps

Although much is known about carbon cycling in coastal ecosystems, there are substantial challenges and uncertainties to quantifying carbon storage, carbon storage potential, and carbon sequestration rates across different ecosystems, vegetation types, and locations. Coastal systems are also stressed by natural coastal and climate variability (e.g., erosion, extreme storm events, sea level rise) and other historical and contemporary land uses that affect carbon cycling.[3,26] The extent to which these stressors may impact carbon storage or emissions is uncertain but is important to quantify for improved sequestration assessments.

Finding consistent and comparable data to compare belowground and aboveground carbon storage across coastal and terrestrial ecosystems is challenging. Cooley et al. (2022)[18] presented the most recent data compilation across several research efforts; however, these comparisons among ecosystems used different depths belowground for carbon stock measurements, and some measurements did not separate aboveground and belowground carbon storage or separate biomass carbon storage from soil carbon storage. Soil carbon storage, and the ratio of soil carbon to biomass storage, may indicate the potential of BCEs for carbon storage.

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Fifth National Climate Assessment: Appendix 1

Assessment Development Process



Appendix 1. Assessment Development Process

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A1.1. The US Global Change Research Program

Founded by Presidential Initiative in 1989 and codified by the Global Change Research Act of 1990,[1] the US Global Change Research Program (USGCRP) is charged with developing and coordinating "a comprehensive and integrated United States research program which will assist the Nation and the world to understand, assess, predict, and respond to human-induced and natural processes of global change."

USGCRP operates under the direction of the National Science and Technology Council as a confederation of 14 federal departments and agencies and is overseen by the White House Office of Science and Technology Policy (OSTP). The Subcommittee on Global Change Research (SGCR) oversees USGCRP's activities and coordinates interagency activities through the USGCRP National Coordination Office and informal interagency working groups. More information on USGCRP activities can be found at www.globalchange.gov and in the Decadal Strategic Plan.[2]

A1.2. Roles and Participants in NCA5

The Fifth National Climate Assessment (NCA5) followed a similar structure and governance model as the previous NCA, with roles and responsibilities described in Table A1.1.

Table A1.1. Descriptions of Roles for NCA5 Participants

Role	Description
Federal Steering Committee (FSC)	The FSC consisted of one representative from each USGCRP member agency. In consultation with the SGCR, the FSC was responsible for selecting CLAs, CLs, and REs; determining scope and content; and overseeing development and production of NCA5, including ensuring that the process adhered to principles of engagement and transparency.
Federal Coordinating Lead Author (CLA) and Agency Chapter Lead (ACL)	CLAs served as the federal coordinating lead for each chapter. ACLs provided additional agency input to chapter teams. Both CLAs and ACLs were responsible for coordination across chapters to ensure consistency and accuracy throughout the report and to ensure that chapters adhered to author guidance. CLAs were responsible for recommending CLs to the FSC. The FSC was responsible for reviewing and approving CLs.
Chapter Lead Author (CL)	CLs were responsible for the ultimate delivery of their chapter for approval and publication. These responsibilities included selecting a diverse and qualified author team and overseeing all aspects of development, assessment, writing, and editing of their chapter.
Chapter Author (CA)	CAs contributed writing, developed figures, responded to comments, and revised chapter drafts under the direction of the CLs. Each chapter's Key Messages represent the consensus of the CAs and CL.
Technical Contributor (TC)	TCs provided discrete, specific technical contributions on an as-needed basis, as identified by the CL. TCs did not participate in the consensus process of developing Key Messages.

Role	Description
Review Editor (RE)	REs, selected by the FSC from a public call for nominees, were responsible for ensuring that all substantive public and peer-review comments were appropriately addressed and documented by author teams.
Staff Point of Contact (POC)	USGCRP National Coordination Office staff filled the roles of POCs, providing administrative support, chapter coordination, and guidance throughout report development.
Technical Support Unit (TSU)	The NOAA TSU supported climate science data analysis; editing; figure development; data management and documentation; web design and development; and graphic design, layout, and other production activities.

A1.3. Creating the NCA5 Report

The NCA5 development process launched in February 2020 with the seating of the NCA5 Federal Steering Committee (FSC). The FSC decided to follow development, review, and publication processes similar to those used for NCA4, with some changes intended to increase the transparency, engagement, and usability of NCA5. Details on the NCA4 assessment development process were outlined in NCA4's Process Appendix[3] and are not repeated here. Additional process changes for NCA5 are described below.

Broadened Participation

More than 750 experts volunteered as chapter leads, authors, technical contributors, and review editors in NCA5 (Figure A1.1), a significant increase in participation compared to previous Assessments. In response to public comments calling for more diverse author teams and inclusion of a broader range of expertise, the number of all-federal author teams was reduced to three chapters. With few exceptions, contributors were limited to serving in a single role (Table A1.1) to ensure that as many people as possible could participate in NCA5.

Authors of NCA5



Hundreds of experts from all across the US came together to develop NCA5.

Figure A1.1. NCA5 was made possible by approximately 500 authors, 250 technical contributors, 41 review editors, 13 chapter coordinators, 14 Federal Steering Committee members, 18 peer reviewers, more than 40 staff members, thousands of participants in public engagement events, hundreds of public commenters and agency reviewers, and approximately 800 artists from every state and territory of the US. This picture is a subset of authors, coordinators, and review editors who attended the second all-authors meeting in Washington, DC, on April 4, 2023. Photo credit: Christopher Avery, USGCRP/ICF.

Chapter leads (CLs) were provided with multiple criteria to consider when selecting their author teams. All authors were required to have the scientific expertise needed to contribute meaningfully to the chapter. CLs were required to consider nominees submitted through a public call for author nominations but were not limited to selecting authors from those nominees. Additionally, CLs were required to build diverse teams by considering a range of disciplines (physical, social, biological sciences, Indigenous Knowledge, science communication, etc.), a broad array of experience (practitioner, academic, etc.), and diverse lived experiences and perspectives, including geographic location, career stage, professional organization type, race, ethnicity, gender, and past assessment experience. Regional chapters were strongly encouraged to include authors from each state within the region. Authors and contributors to NCA5 included experts from all 50 states, Puerto Rico, the US Virgin Islands, Guam, and Palau.

Increased Public Engagement Opportunities

Public engagement seeks to help authors understand the interests and concerns of NCA readers and ensures that the final report represents the priorities and needs of decision-makers across the country. In addition to taking public comment on the draft Assessment in the fall of 2022, NCA5 featured a new opportunity for public comment on the chapter's initial annotated outlines, or Zero Order Drafts.[4] A "how-to" video and step-by-step guide were developed to facilitate the public comment process. During this public comment period (January and February 2022), USGCRP also hosted 34 virtual public engagement workshops that were free and open to the public (Figure A1.2). During the workshops, authors spoke with members of the public about the draft chapter outlines and identified priority issues relevant to the chapter.

In some cases, workshop participants challenged authors to reconsider the key topics covered in the report or shifted authors' thinking about specific areas of emerging concern. In other cases, the workshops prompted authors to forge more connections across the report and with other chapter teams or identified where chapter teams had a gap in needed expertise.

NCA5 Zero Order Draft Public Engagement Workshops



Early public engagement helped inform the scope of NCA5.

Figure A1.2. The NCA5 Public Engagement Workshops attracted more than 7,000 registrations, with approximately 2,800 people participating via plenary discussions, breakout rooms, and interactive collaborative tools. The charts above show the self-identified organizational type (**left**) and region (**right**) of workshop registrants as the percentage of total registrants (not population weighted). For example, participants included more than 400 people who self-identified as being affiliated with a Tribe. Figure credit: USGCRP/ICF.

Updated Guidance to Better Incorporate Indigenous Knowledge

NCA5 leadership participated in three Tribal consultations and one Tribal listening session and took public input on the use of Indigenous Knowledge in federal decision-making.[5] Based on feedback received during a public comment process for the federal guidance,[6] the NCA guidance to authors on Information Quality was updated (see App. 2). Authors were also provided training on writing about Indigenous perspectives and using Indigenous Knowledge in author orientation and chapter leadership meetings.

Improved Diversity, Equity, Inclusion, Justice, and Accessibility

Beyond the steps listed above to ensure author diversity and widespread public engagement, NCA5 took several steps to improve the inclusive nature of the NCA development process, advance the conversation around equity and justice, and enhance accessibility of NCA5 products.

- For the first time, a code of conduct was instituted for all NCA participants to help ensure that all participants could engage in an inclusive, respectful, and safe environment.[7]
- Spanish translation was provided during the Caribbean public engagement workshop and of the draft Caribbean chapter released for public comment. For the first time, the entire Assessment report will be translated into Spanish.
- Throughout the report development process, USGCRP encouraged discussions around equity and justice topics. Authors were asked to consider the justice implications of climate change so as to make the report more broadly representative and inclusive of historically underrepresented communities.
- NCA5 represents the first time that the website for NCA is the report of record. As a result, this report was developed and designed to be delivered as a digital product. This website is designed to follow new standards of the US Web Design System[8] under the 21st Century Integrated Digital Experience Act of 2018.[9]
- NCA5 built on the success of NCA4 in its compliance with Section 508 of the Rehabilitation Act of 1973 to improve accessibility and usability by the broadest possible audience, including people with visual or physical limitations. For instance, guidance was provided to authors to avoid complex or nested tables and alternative text was developed for all images to support the use of screen readers. Graphics are also designed to be readable for users with color-perception challenges by using appropriate color schemes and visual presentations.

Strengthened Documentation Processes

Based on laws (e.g., the Foundations for Evidence-Based Policymaking Act, or Evidence Act of 2018;[10] see Appendix 2 for additional information) and transparency best practices that evolved since NCA4, processes for documenting multiple aspects of supporting materials were strengthened for NCA5. Authors were required to disclaim any intellectual property created in the process of producing this report to ensure that the report content could be released under the Creative Commons 1.0 Universal Public Domain Dedication (CC0 1.0). Additionally, NCA4's gold-standard process for metadata tracking and verification was improved, with software updates and a user manual to aid authors in their documentation process. Additional details on this process can be found in Appendix 2.

Creative Communications

Science communication support throughout the writing process was provided by the Technical Support Unit (TSU). Early author orientation and trainings emphasized TSU's data visualization and graphic design support for figure development, with the goal of including high-quality figures throughout NCA5 to convey important messages and supplement the text. The final report contains 388 figures.

USGCRP pursued several art–science collaborations throughout the NCA5 process. On October 11, 2022, USGCRP announced an open call for visual artwork. The call, which was open to youth and adults, invited works around the themes of NCA5 that depict climate change impacts and responses and that reflect the lived experience of people across the country. Five award winners and 92 finalists from the approximately 800 submissions received are featured in the Art × Climate Gallery and throughout the report.[11] Artwork that appears in chapters is denoted by a gray background and accompanied by the artist's statement. In addition, USGCRP collaborated with the National Endowment for the Arts and the Library of Congress to include the bespoke poem "Startlement," written for NCA5 by the 24th US Poet Laureate, Ada Limón.

Accessible Climate Data

An interactive online atlas (NCA5 Atlas) was developed to provide additional resources for climate impact and resilience planning, with a selection of climate variables curated for each US region. These variables were produced using the same methodology as the downscaled precipitation and temperature projections used throughout NCA5 (App. 3). The Atlas includes interactive maps, plain language descriptions, and links to subregional climate products such as the NOAA State Climate Summaries and the USGCRP Climate Indicators (App. 4). The NCA5 Atlas was created through a collaboration between NOAA and ESRI (Environmental Systems Research Institute Inc.) that complemented other agency-supported planning initiatives, including the Climate Explorer, the Interagency Sea Level Rise Scenario Tool, and the Climate Mapping for Resilience and Adaptation portal.

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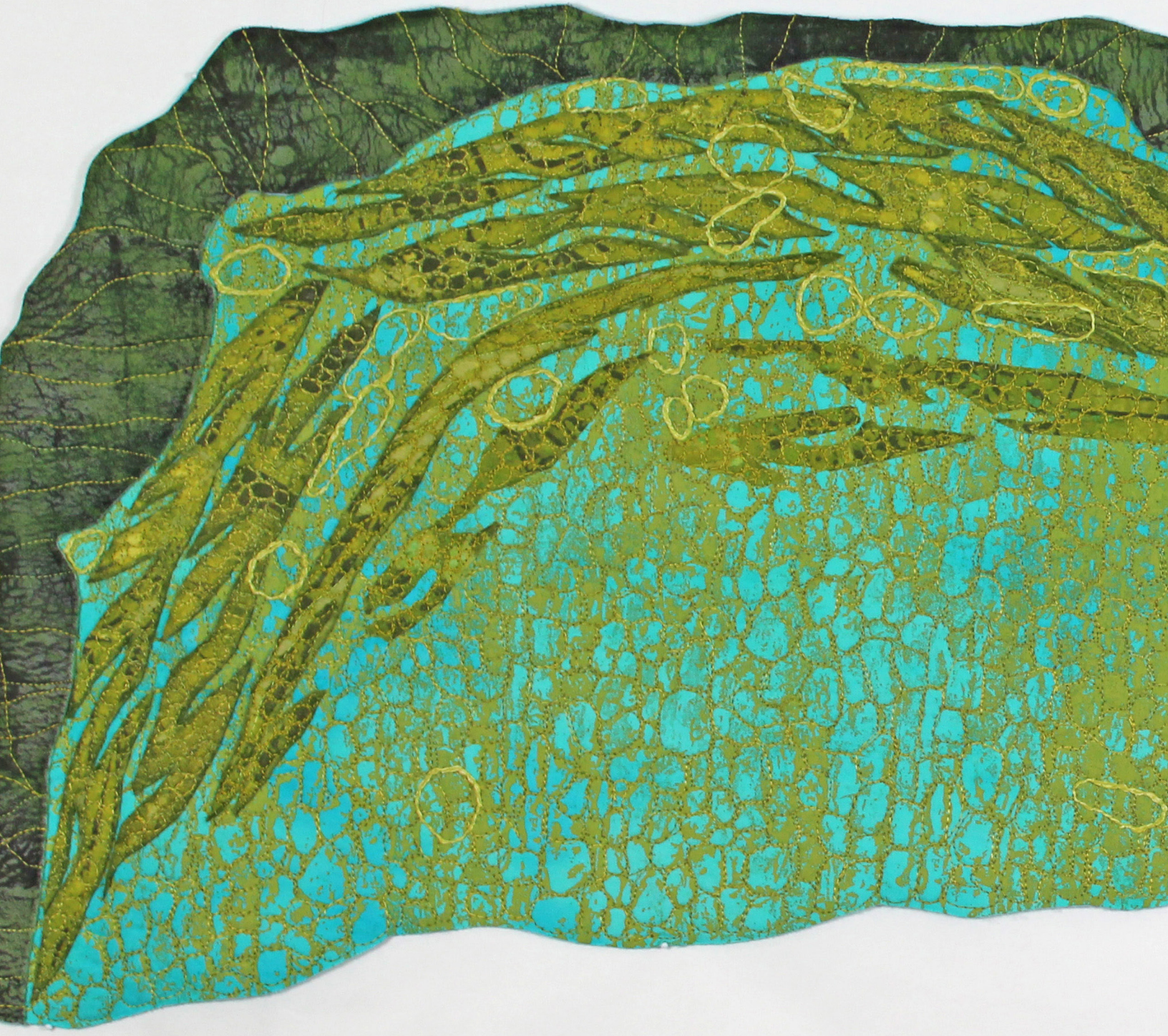
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Fifth National Climate Assessment: Appendix 2

Information Quality



Appendix 2. Information Quality

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A.2.1. Introduction

The National Climate Assessment (NCA) is required by law to meet the highest information quality standards set by the Federal Government. Specific information quality requirements are set out by the Information Quality Act (IQA),[1] the Office of Management and Budget (OMB) Final Information Quality Bulletin for Peer Review for highly influential scientific assessments (HISA),[2] and the Foundations for Evidence-Based Policymaking Act (EBPA, or Evidence Act 2018).[3] Because NOAA is the administrative agency for NCA5, its agency guidelines under these federal standards serve as the guiding principles for the Assessment. Information quality compliance is affirmed by the NCA Information Quality Officer, furnished by the administrative lead agency.

The **IQA** ensures that the Assessment data and information are of a sufficient quality by meeting standards of *objectivity*, *utility*, and *integrity*. This includes the requirement for information in the Assessment to demonstrate a capability of being reasonably *reproduced*. For analytic data, reproducibility means that independent analysis of the original or supporting data using identical methods would generate similar analytic results to an acceptable degree of precision.

The **OMB Final Information Quality Bulletin for Peer Review** establishes guidance to enhance the practice of peer review of government science documents in order to increase the quality and credibility of scientific information generated across the Federal Government. The bulletin sets the minimum peer-review requirements for documents with the HISA designation, including the National Climate Assessment.

The **Evidence Act** expands on prior open government policy initiatives and public access to agency data assets. It requires that all federal data assets and supporting information be open by default, distributed under an open license, and published as machine-readable—subject to legal exemptions for privacy sensitivities and/or intellectual property rights.

A2.2. Source Materials

Sources (or source materials) broadly include all information used in the Assessment. Authors must consider information quality when deciding whether to use a given source in a chapter. Information quality standards must be met any time a source is associated with the Assessment, including incorporating the source into the chapter, citing the source, or linking to the source.

Authors compiled information sources from peer-reviewed literature, other literature, Indigenous Knowledge, and other expert and local knowledge. Authors were provided with additional Federal guidance on use of Indigenous Knowledge.[4] A fifth type of information that may be used in the NCA is climate data processed and prepared for authors by NOAA's Technical Support Unit (TSU; see App. 3). Authors were advised to evaluate each source based on the following attributes:

- **Applicability and Utility**: The source is important, relevant, and useful for its intended audience (not only from the author's perspective but also from the public's).
- **Transparency and Traceability**: The source material, the methods supporting conclusions, and the evaluation of the source are documented and clear.
- **Objectivity**: The purpose, methods used to create the source material, presentation, substance, and interpretation of conclusions are clear, accurate, reliable, and unbiased.
- **Integrity and Security**: The source material will remain reasonably protected and intact over time, and both the information and the owners of the information are respected.
- **Reproducibility**: Procedures surrounding source materials are documented such that they can be reproduced, with checks for robustness on non-reproducible data.

While development of an NCA chapter often involves a comprehensive literature review, not every source evaluated in the report development process will be cited in the NCA chapters. An important responsibility of the authors is to determine which sources are most useful to include in the Assessment. References cited in the Assessment are those that are highly relevant and critical to the understanding of the intended users or audience of the Assessment.

To assist in source evaluation, authors were provided Information Quality Decision Pathways to determine whether a source met these standards and could be cited in the NCA. Additional source information came from previous Assessments and technical input reports; feedback from 34 public engagement workshops (see App. 1) and other engagement events; expert awareness of the literature from authors; chapter-specific submissions of technical resources and relevant literature to author teams; and a public request for scientific and technical inputs. Information submissions were requested via a Federal Register Notice published by NASA on behalf of the US Global Change Research Program in 2020.[5] This notice called for the public to submit "relevant scientific and/or technical research studies—including observed, modeled, and/or projected global change and climate science information, as well as societal drivers, vulnerability, impacts, and responses." The public call specifically encouraged submissions of regional information and information for cross-cutting or new topics since NCA4. This public call for information was open from October 15, 2020, through January 31, 2023.

The final report cites approximately 8,300 sources meeting the IQA requirements.

A2.3. Data and Metadata Standards

In addition to being evaluated on the attributes listed in the Source Materials section above, information based on data (including figures) must adhere to the standards of reproducibility and openness. To meet these requirements, NCA5 collected figure and data sources; dataset, analysis, and visualization methods; and hardware and software metadata (details about the underlying data and information), adhering to NOAA's implementation of ISO-19115 documentation standards.[6] All metadata is made openly accessible as a component of the final report and demonstrates NCA5 compliance with information quality standards.

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Fifth National Climate Assessment: Appendix 3

Scenarios and Datasets



Appendix 3. Scenarios and Datasets

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A3.1. Scenarios and Climate Model Output

Scenarios are descriptions of how conditions may develop over time based on clear and consistent assumptions about key drivers of change.[1] For example, scenarios can describe future emissions, population, energy, and land use to answer questions such as How much more greenhouse gases will humans emit? How will populations grow or move? How will we use land for agriculture, forestry, or cities?

Climate models use scenarios to describe the plausible evolution of human and natural factors that affect the future of Earth's climate system. Climate model output is neither a forecast nor prediction but is referred to as a projection. Climate projections are conditional: when or if we reach a particular outcome is dependent on both human choices and the complex ways in which the climate system responds to those choices. Scenarios and climate model projections allow us to explore how we answer questions about the future and the potential implications of choices made over time. These tools have evolved and improved over time, but they are limited by the current state of knowledge and the necessary simplifications models make in representing Earth's complex climate system.

The state of the science represented in the National Climate Assessment (NCA) is always evolving, often at different paces in different fields. No one set of models, scenarios, or climate projections was implemented across NCA5. Authors could assess and reference any climate scenarios that met legally required evidence quality standards (App. 2). These included, but were not limited to, the Representative Concentration Pathways (RCPs), which were used in Phase 5 of the Coupled Model Intercomparison Project (CMIP5), and a more recent set of scenarios that integrated Shared Socioeconomic Pathways (SSPs).[2,3,4] A set of SSP-RCP combinations was used in CMIP Phase 6 (CMIP6) international model experiments.[3,4,5] In NCA5, Chapter 3 provides a description of SSPs along with a graphic representation of scenario development (Figure 3.4), and the Guide to the Report provides a list of descriptive terms for the RCP and SSP scenarios that are commonly referenced in the report text (Table 3). For certain topics or impact studies, scenarios that preceded the RCPs may be relevant, such as those from the Special Report on Emissions Scenarios (SRES).[6] Similar to the RCPs and SSPs, the SRES scenarios include a set of consistent assumptions that translate into a range of carbon emissions and carbon dioxide concentrations; however, the SRES do not include a net-negative emissions scenario (Figure 33.19 in Walsh et al. 2014[7]). For a more in-depth discussion of emissions scenarios, RCPs, and SSPs, see Chapter 4 of Volume I of the *Fourth National Climate Assessment*.[8]

Overall, CMIP6 models show some specific improvements over CMIP5 in their representation of Earth system processes—mainly due to the fact that more models include biological and chemical interactions as well as higher resolution (Figure TS.2, Section TS.1.2.2 in Arias et al. 2021[9]).[10] Importantly, projections can vary based on the particular climate models and scenarios used, assumptions or parameters employed within those models and scenarios, and methods used to analyze or interpret model outputs. For instance, some CMIP6 models show a particularly large global temperature response to increasing atmospheric carbon dioxide concentrations—a response that is not considered to be realistic (KM 3.1; e.g., Meehl et al. 2020;[11] Nijsse et al. 2020[12]). Scientists can use different methods to account for potential model biases in the temperature response and other climate system changes.[13,14] When comparing projections across NCA5 or with another assessment, it is critical to understand how the methodologies underlying the findings may differ. Supporting information for NCA5 findings can be found in the chapter text, cited references, Traceable Accounts, or figure captions and metadata—all available via the report website.

Box A3.1. Projecting Climate Impacts Beyond 100 Years Into the Future

Climate change will not end in 2100. However, there is currently a limited number of climate studies with projections that extend past the year 2100. The lack of scenarios for emissions or land use that extend past 2100 constrains the NCA5 authors' ability to present or assess projections 100 years in the future as mandated by the Global Change Research Act of 1990.[15,16] One notable exception is the sea level rise (SLR) scenarios described in this appendix and in Chapter 9, which do extend past 2100 for the contiguous United States. To understand impacts at the century scale and beyond, authors could evaluate potential climate system changes based on applied laws of physics, Earth system dynamics, and extrapolation of climate system change indicators. Additionally, very high climate scenarios, such as RCP8.5 and SSP5-8.5, can be useful tools when considering a range of plausible greenhouse gas concentrations past 2100.[17,18]

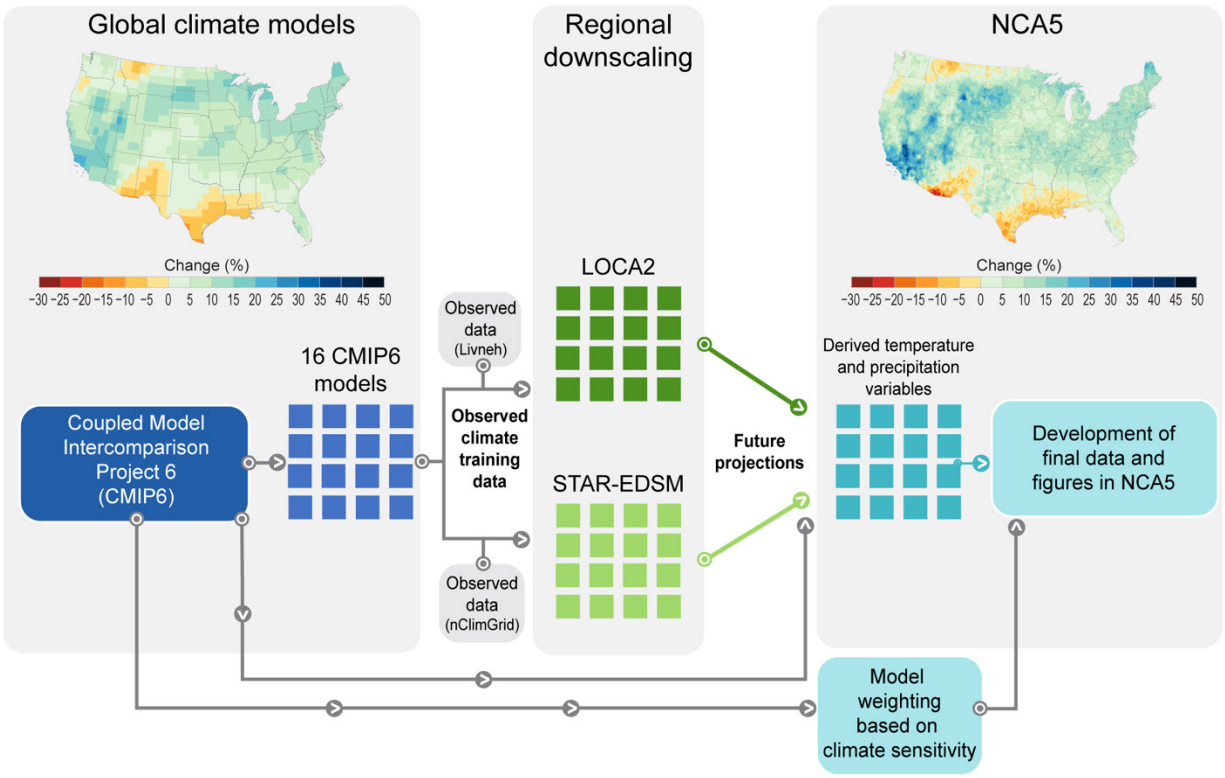
A3.2. Projected Climate Variables

The NOAA Technical Support Unit (TSU) provided authors with projected climate variable information from 43 CMIP6 models using a set of five SSP-RCP scenarios, which were described in a reference guide provided to authors to ensure consistent terminology throughout NCA5 (see Guide to the Report). Depending on author team requests and variable availability, in some circumstances the TSU selected a smaller number of CMIP6 models and scenarios from the larger ensemble (global climate models box in Figure A3.1).

To provide higher-resolution projections at national or subnational scales, 16 global CMIP6 models were downscaled using historically trained computer algorithms (statistical downscaling) and model weighting based on equilibrium climate sensitivity (Figure A3.1). Two datasets that employed different statistical downscaling methods were used to develop gridded temperature and precipitation datasets for NCA5: the Localized Constructed Analogs Version 2 (LOCA2)[19] and Seasonal Trends and Analysis of Residuals, Empirical-Statistical Downscaling Model (STAR-ESDM)[20,21] (regional downscaling box in Figure A3.1). A collection (ensemble) of models is often used to show an uncertainty range. LOCA2 and STAR-ESDM were applied to 16 CMIP6 models, and downscaled outputs were weighted based on CMIP6 climate sensitivity through Bayesian model averaging.[22,23,24,25] Projections of changes in average and extreme temperature and precipitation were made available to NCA5 authors for national and subnational scales spanning the entire 21st century (NCA5 box in Figure A3.1).

Development of NCA5 overlapped with CMIP6 data releases, limiting the availability of downscaled CMIP6 climate projections. While STAR-ESDM also provided downscaled data for selected individual weather stations, there remains an overall gap in climate projections for geographies outside the contiguous United States, including the regions covered by the Alaska, US Caribbean, and Hawai'i and the US-affiliated Pacific Islands chapters. Authors were also provided guidance on how to access regional datasets or dynamically downscaled data from the CMIP5 Coordinated Regional Climate Downscaling Experiment to include data for these regions where available.[26,27]

Downscaling Global Climate Model Data for NCA5



Global model data were downscaled and weighted to generate higher-resolution climate projections.

Figure A3.1. This flowchart shows the steps taken to downscale low-resolution global data from Phase 6 of the Coupled Model Intercomparison Project (CMIP6; **left side of the diagram**) to bias-adjusted high-resolution NCA5 products (**right side of the diagram**). Two downscaling algorithms (**center of the diagram**)—the Localized Constructed Analogs Version 2 (LOCA2) and Seasonal Trends and Analysis of Residuals, Empirical-Statistical Downscaling Model (STAR-ESDM)—were developed for each of the 16 selected global climate models (shown in dark blue) by training with two observational datasets (Livneh for LOCA2 and nClimGrid for STAR; shown in green). The resulting algorithms produce high-resolution bias-adjusted datasets of daily temperature and precipitation for the training dataset observational period. These model-specific algorithms are applied to global projections to produce high-resolution projections of temperature and precipitation in the United States for each model (shown in light blue). The individual model projections are averaged with model weights based on climate sensitivity to produce the final NCA5 datasets and graphics. LOCA2 and STAR provide gridded data for the 48 contiguous states. STAR additionally includes downscaled data for individual stations in Alaska, Hawai'i, and Puerto Rico. Figure credit: USGCRP/ICF, USGCRP, and North Carolina State University.

A3.3. Sea Level Rise

NCA5 authors were provided with sea level rise scenarios produced by an Interagency Task Force for the 2022 Sea Level Rise Technical Report.[28] The technical report uses five SLR scenarios covering the time period from 2020 to 2150, constructed using the sea level projections from the Intergovernmental Panel on Climate Change Sixth Assessment Report (IPCC AR6)[29] and defined by global mean SLR target values in 2100 as follows: Low (0.3 m [1 foot]), Intermediate-Low (0.5 m [1.5 feet]), Intermediate (1 m [3 feet]), Intermediate-High (1.5 m [5 feet]), and High (2 m [6.5 feet]). Specifically, the AR6 projections across all possible warming levels and emissions are filtered to find ones that describe pathways that meet these five target values of global mean sea level rise. Near-term SLR estimates are derived from an extrapolation of observed rates and acceleration through 2050.

These five SLR scenarios are related to, but distinct from, the CMIP6 temperature and precipitation projections described above in Sections A3.1 and A3.2. Describing these five scenarios reduces the complexity of sea level projections that are conditional on future emissions and difficult-to-quantify physical processes. This supports decision-making in a number of ways, including providing a risk-based framing and allowing planners to compare the performance of different management strategies over time under different SLR scenarios. Chapter 2 introduces these five scenarios; Chapter 9 uses these scenarios and the IPCC projections to provide details about sea level rise dynamics and regional sea level rise.

While it is not possible to directly assign probabilities to each of the scenarios, additional assumptions about the future (e.g., global warming level above preindustrial conditions; see the Guide to the Report) allow for the assignment of a probability of exceeding a particular sea level scenario in that assumed future (Table A3.1). Although generated using global mean SLR, these exceedance probabilities are applicable to the US due to the construction of the sea level projections. At 2100 and beyond, the primary driver of the upper end of the SLR scenarios is the potential for rapid ice sheet loss; to account for this possibility, the far-right column of Table A3.1 represents a future with very high emissions, high warming, and significant contributions to SLR from these ice loss processes.

Table A3.1. Sea Level Rise Exceedance Probabilities

The table shows the probabilities of exceeding the amounts of sea level rise (SLR) projected for the five scenarios (Low, Intermediate-Low, Intermediate, Intermediate-High, and High) provided in the 2022 Sea Level Rise Technical Report. Probabilities are shown for the end of the century (2100) for five global warming levels (calculated as global mean surface temperature increases above preindustrial levels for the period 2081–2100) as well as for a possible future with very high emissions and rapid ice sheet loss processes, which are currently understood with only *low confidence*. The probabilities are based on IPCC projections. Adapted from Sweet et al. 2022.[28]

Probability of exceeding the SLR scenario described below in 2100 at the global warming level described to the right	1.5°C (2.7°F)	2.0°C (3.6°F)	3.0°C (5.4°F)	4.0°C (7.2°F)	5.0°C (9°F)	*Low Confidence* ice sheet loss processes, very high emissions
Low (0.3 m)	92%	98%	>99%	>99%	>99%	>99%
Intermediate-Low (0.5 m)	37%	50%	82%	97%	>99%	96%
Intermediate (1.0 m)	<1%	2%	5%	10%	23%	49%
Intermediate-High (1.5 m)	<1%	<1%	<1%	1%	2%	20%
High (2.0 m)	<1%	<1%	<1%	<1%	<1%	8%

A3.4. Tools and Applications

In addition to projections, the TSU developed historical climate information for NCA5 authors. Historical analyses are based on NOAA's nClimGrid and GHCN-Daily datasets,[30] and access was provided via an interactive visualization tool. Historical and projected climate variables from the TSU analysis include average annual and seasonal temperature and precipitation, extreme maximum and minimum quantities, threshold exceedances, and derived variables such as mean summer soil moisture and minimum annual temperature. The full suite of historical and future climate data and metadata records developed for NCA5 will be made publicly available via the NCA5 Atlas and through the Global Change Information System. The NCA5 Indicators Appendix provides more detail on observed trends for commonly used climate metrics (App. 4).

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Fifth National Climate Assessment: Appendix 4

Indicators



Appendix 4. Indicators

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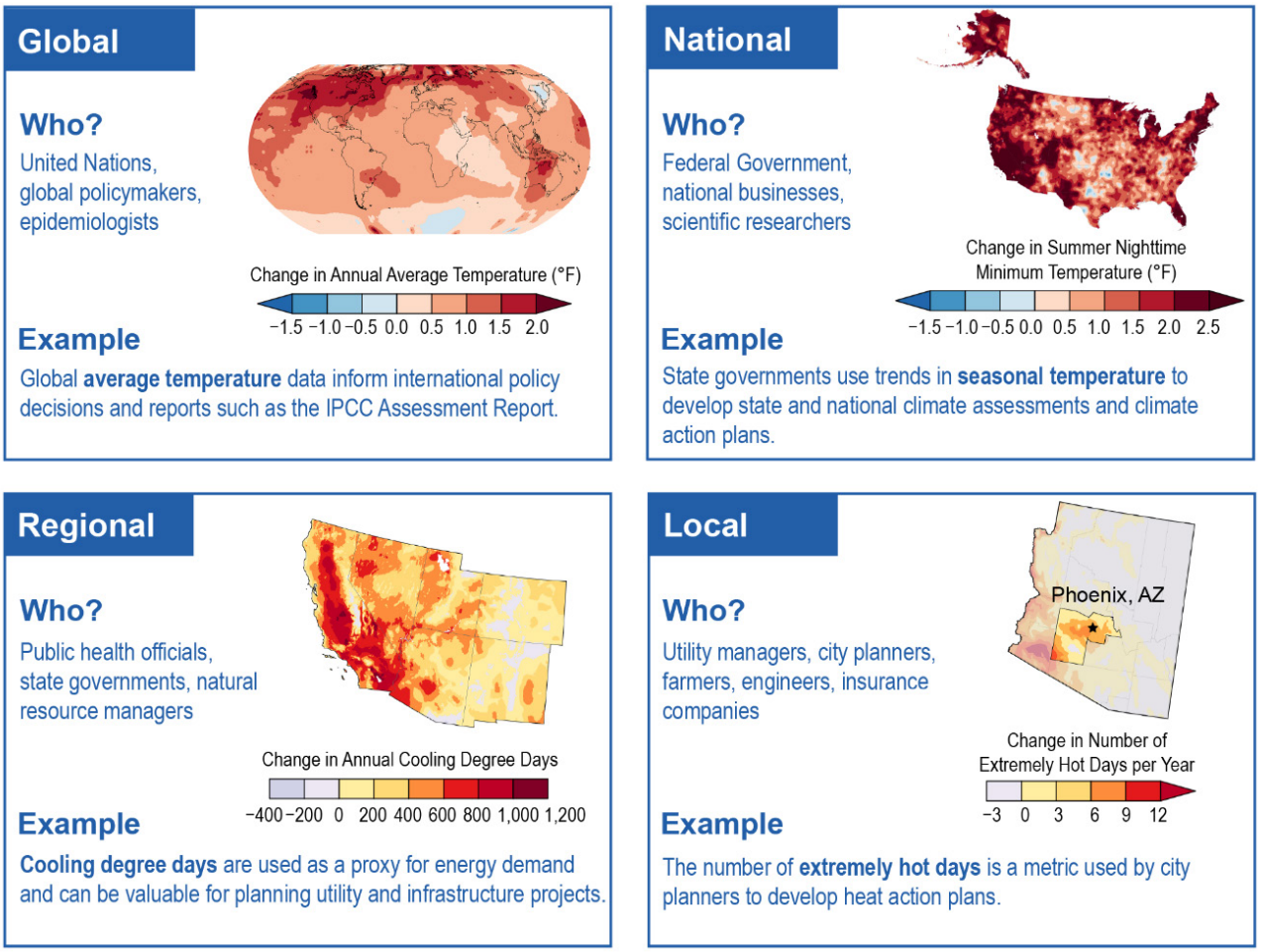
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A4.1. The Importance of Indicators

To evaluate the impacts of climate change, it is essential to first understand the many ways in which our climate is changing. Indicators characterize how environmental conditions are changing over time to help communicate climate impacts, risks, and vulnerabilities. Indicators provide foundational science in support of the US Global Change Research Program's (USGCRP) sustained assessment process, including the National Climate Assessment (NCA). In the NCA, indicators are defined as data (presented as charts or maps) based on historical observations and measurements that are used to track conditions, trends, and impacts related to our changing climate. Indicators show changes in physical, ecological, or societal systems and can represent data at varying scales, from global to local (Figure A4.1). Indicators are of most value when maintained and updated on a regular basis so that users and stakeholders can make informed decisions based on the most up-to-date information. Taken individually, each indicator depicts a specific change over time, while a broad set of indicators helps to show interconnections among the many components of global change and a warming world (Box A4.1).[1] While each indicator has an important relationship to climate,[2] it is beyond the scope of this appendix to explore these connections in detail. Attribution and causation related to a changing climate are discussed in other chapters throughout NCA5 (e.g., Chs., 2, 3, 15).

Changes in Temperature at Multiple Scales



Presenting indicators at different scales allows stakeholders to obtain information relevant to their needs.

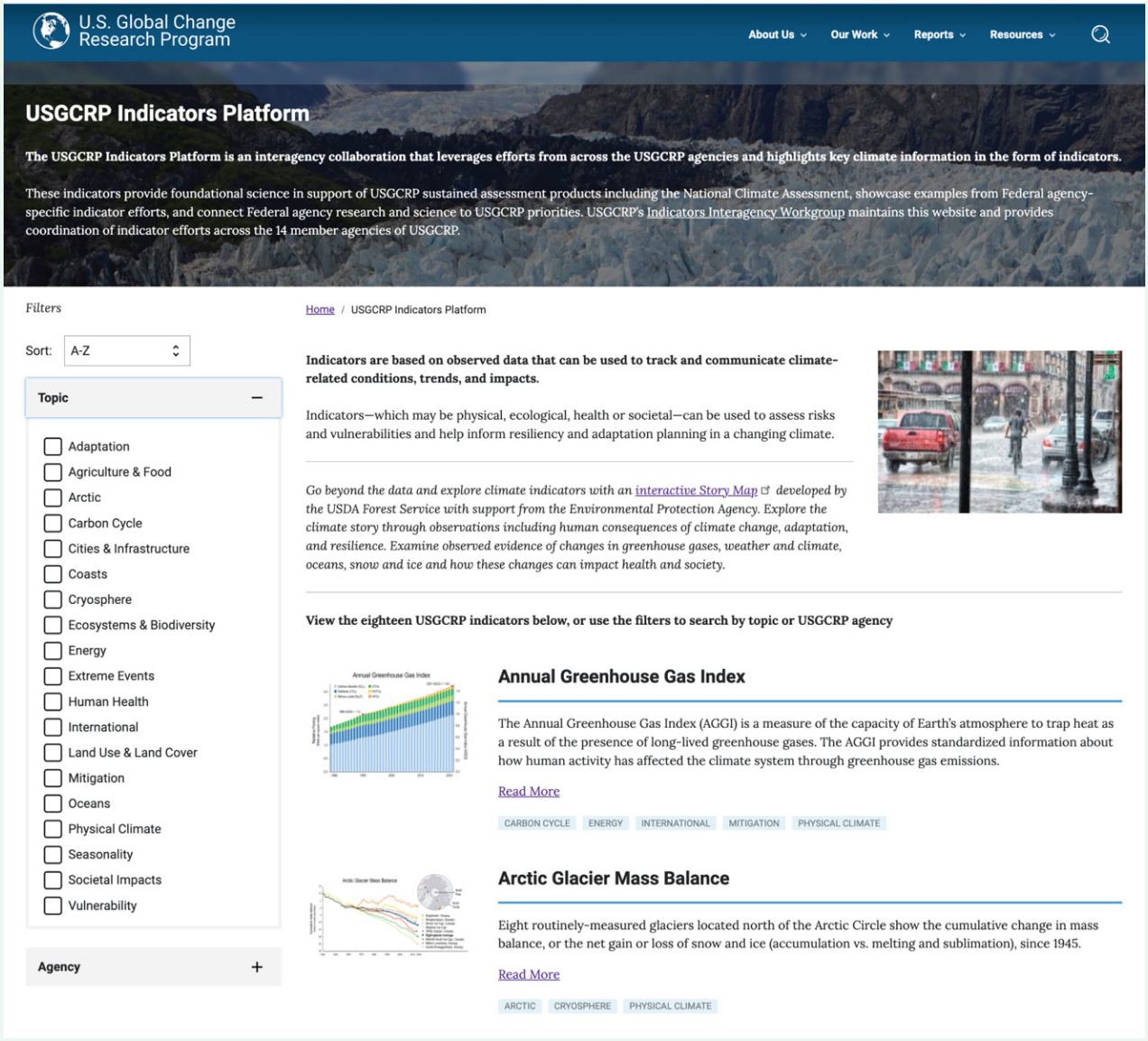
Figure A4.1. Many people use climate-related indicators for resource and management decisions, from small-scale farmers to global policymakers. Different indicators are relevant at different geographic scales, depending on who uses the information and for what purpose. In this figure, temperature indicators are shown at four scales, with each map depicting spatial patterns in the amount of observed change: (**top left**) global annual average temperature for the period 1993–2022, relative to 1901–1960; (**top right**) national (contiguous US and Alaska) summer nighttime minimum temperature for 1993–2022, relative to 1901–1960 (relative to 1926–1960 for Alaska; data are not available for the US Caribbean, Hawai'i, or the US-Affiliated Pacific Islands); (**bottom left**) regional (Southwest region) cooling degree days for 1993–2022, relative to 1951–1980; and (**bottom right**) local (Maricopa County, Arizona) number of days with maximum temperatures of 110°F or higher for 1993–2022, relative to 1951–1980. Data used for the regional and local indicators are available only from 1951 onwards. In general, increases in each metric have occurred since the start of their respective records, with important variations that are relevant to decision-makers at each scale (see Section A4.2 for additional explanation). Figure credit: North Carolina State University and NOAA NCEI.

Indicators are needed to support decision-making and describe and monitor impacts on people. Combined with other data, such as demographic and socioeconomic information (e.g., Figures A4.4, A4.14, 11.13), their utility is ever-growing, with many advancements being made in recent years (e.g., Di Napoli et al. 2022;[3] Kenney et al. 2020;[4] Walsh et al. 2020[5]). Indicators are being developed by USGCRP agencies (Box A4.1), their partners, academic institutions, and state, local, and Indigenous communities. The form, complexity, breadth, and design of indicators vary based on their intended uses, but effective indicators clearly convey information to advance understanding related to changes in key aspects of climate and the impacts on people and ecosystems. Measuring the health and societal effects of climate change is challenging because of the complex, often indirect relationships among climate drivers, environmental and social factors, and health outcomes.[6,7] Increasingly, physical, ecological, and socioeconomic data are being linked together to better track impacts on human systems, allowing communities to assess risks and make informed response and adaptation decisions. In the context of human health, identifying sets of indicators along exposure pathways can help track the related nature of exposures and the prevalence of health outcomes.[7,8] This holistic approach can provide insights into the extent to which changes in climate affect people and help identify opportunities for public health actions to reduce or prevent exposures and adverse health effects.

Box A4.1. Federal Indicator Resources

The US Global Change Research Program (USGCRP) coordinates efforts to highlight climate-relevant indicators from across federal agencies. The USGCRP Indicators Interagency Working Group guides this effort through advancing the research, development, and integration of indicators into USGCRP activities and products and highlights a subset of these on the USGCRP Indicators Platform (Figure A4.2).[9] Indicators hosted on the platform consist of peer-reviewed observational data and methods from federal entities and are routinely updated. They meet the standards set forth by the Information Quality Act regarding data quality, transparency, and traceability (App. 2).

USGCRP Indicators Platform



The USGCRP Indicators Platform leverages agency-supported science and data to understand how environmental, health, and societal conditions are changing.

Figure A4.2. Screenshot from the USGCRP Indicators Platform: https://www.globalchange.gov/indicators/. Figure credit: USGCRP 2023.[9]

Other federal climate-related indicators efforts include:

- CDC's National Environmental Public Health Tracking Climate Change Indicators[10]
- EPA's Climate Change Indicators in the United States[2]
- EPA's Climate Indicator Map Viewer[11]
- NASA's Vital Signs of the Planet[12]
- NOAA's National Marine Ecosystems Indicators[13]
- NOAA's State Climate Summaries[14]
- USDA's Climate Indicators for Agriculture[5]

Indicators appear in every NCA, with each report offering new ways to evaluate observed changes. This appendix marks the first time a section of the NCA has been established to present and discuss nationally relevant indicators. It highlights the important role of indicators and supports the NCA with scientific evidence, using a representative set of indicators relevant to multiple chapters. Observed changes relevant to each regional chapter can be represented with indicators, as shown in Table A4.1. Indicators in this appendix are grouped into six categories (Atmosphere; Ice, Snow and Water; Ocean and Coastal; Land and Ecosystems; Health; Adaptation and Mitigation), building on NCA4's Indicators of Change figure (Figure 1.2 in Jay et al. 2018[1]). Examples for each category were selected to cover a diverse range of regions, highlight both existing and newly developed indicators, and focus on topics relevant to urban and rural populations as well as the natural environment. These and many other indicators in NCA5 demonstrate that climate change is happening now (Table A4.1; KM 2.1; Figures 28.1, 30.5).

Table A4.1. Observed Regional Changes

This table shows observed changes pertinent to each NCA region, along with supporting evidence from associated NCA5 Key Messages and example indicators. The observed changes are only selected examples and do not necessarily convey which climate-related risks are most significant in each area. See the regional chapters for more detail on these observed changes and related climate impacts.

Region	Observed Change	Key Message	Example Indicator(s)
Northeast	Increasing frequency and intensity of precipitation	KM 21.2	Figure 2.8, Figure 21.1
	Increasing ocean temperatures	KM 21.2	Figure A4.11, Figure 21.4
	Rising sea levels	KM 21.2	Figure A4.10, Figure 2.5
Southeast	Increasing frequency, intensity, and duration of heatwaves	KM 22.2	
	Increasing wildfire risk	KM 22.2	Figure A4.14
	Rising sea levels	KM 21.4	Figure 2.5
US Caribbean	Increasing air temperatures	Ch. 23, Intro	Figure 1.5
	Increasing ocean temperatures	Ch. 23, Intro	Figure A4.11
	Increasing air pollution	KM 23.1	
Midwest	Increasingly variable precipitation	KM 24.1	Figure 2.4, Figure 2.8
	Lengthening growing season	KM 24.1	Figure 24.3
	Changing Great Lakes water quantity, quality, and temperature	KM 24.5	Figure 24.13
Northern Great Plains	Increasing winter temperatures	KM 25.1	Figure 2.4
	Increasing wildfire risk	KM 25.1	Figure A4.14
	Increasing frequency of spring flood events	KM 25.1	

Region	Observed Change	Key Message	Example Indicator(s)
Southern Great Plains	Increasing frequency and intensity of precipitation	Ch. 26, Intro	Figure 2.8, Figure 26.1
	Increasing ocean temperatures	KM 26.3	Figure A4.11
	Rising sea levels	KM 26.5	Figure 2.5
Northwest	Declining snowpack	Ch. 27, Intro	Figure A4.7
	Melting glaciers	Ch. 27, Intro	
	Rising sea levels	Ch. 27, Intro	Figure 2.5
Southwest	Declining flows in major rivers	KM 28.1	Figure 4.18, Figure 7.9
	Increasing wildfire risk	KM 28.5	Figure A4.14
	Increasing number of marine heatwaves	KM 28.2	Figure A4.11, Figure 28.4
Alaska	Thawing permafrost	Ch. 29, Intro	
	Increasing ocean temperatures	Ch. 29, Intro	Figure A4.11
	Declining sea ice	Ch. 29, Intro	Figure A4.6, Figure 2.3
Hawai‘i and the US-Affiliated Pacific Islands	Increasing drought frequency, severity, and duration	Ch. 30, Intro	
	Increasing tropical cyclone activity	KM 30.2	
	Rising sea levels	KM 30.3	Figure 2.5

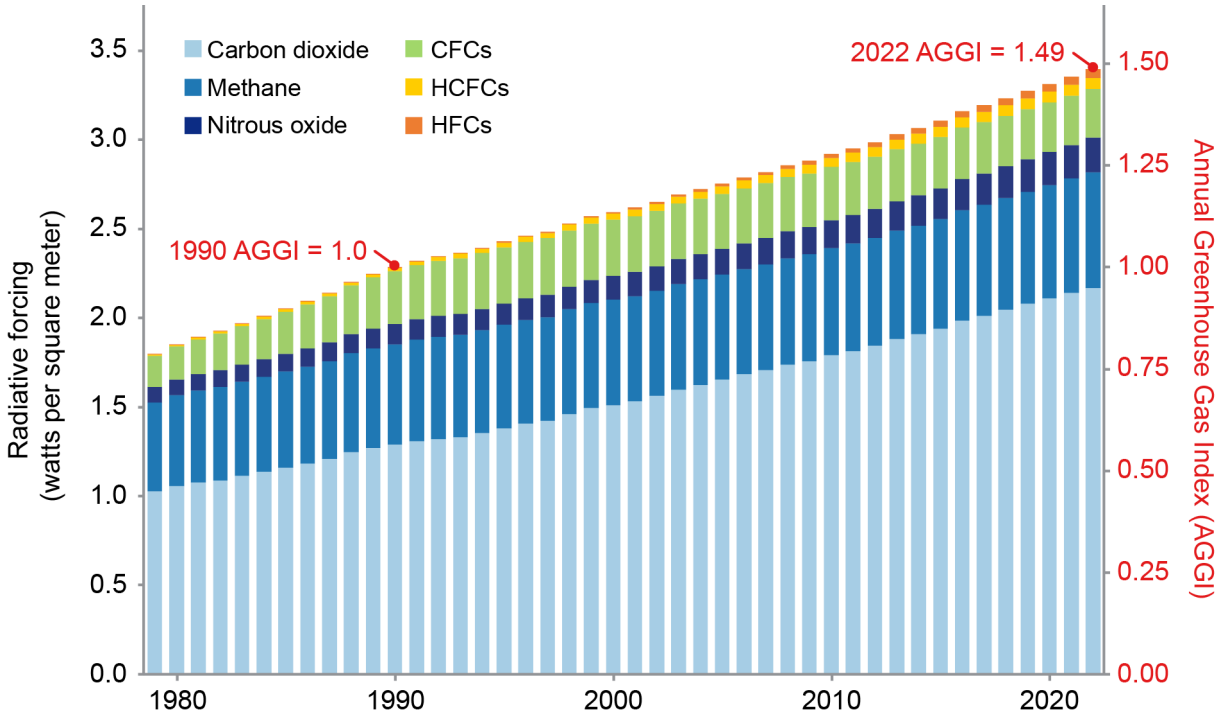
A4.2. Atmospheric Indicators

Both globally and across the US, temperatures are rising as a result of increasing greenhouse gases (GHGs) in our atmosphere (Figures 1.5, 2.4), primarily caused by human activities (Figures 2.1, 3.1; KMs 2.1, 3.1). Extreme events such as heatwaves, heavy downpours, and severe flooding are also increasing in frequency and intensity (KM 2.2; Figures 2.8, 21.1, A4.8). Atmospheric indicators are used to inform decision-making across a wide variety of scales (Figure A4.1) and often form the basis for assessing trends, impacts, and key risks[15] among all sectors.

Greenhouse Gases

Greenhouse gas emissions are the primary driver of climate change (KMs 2.1, 3.1), so tracking emissions is fundamental to understanding and responding to climate change. Figure 2.1 depicts the continual increase in carbon dioxide (CO_2) emissions by the greatest contributing countries and regions. The Annual Greenhouse Gas Index indicator (Figure A4.3) accounts for global emissions of CO_2 and the other major long-lived greenhouse gases from 1979 to 2022 and shows how the cumulative warming effects of these GHGs have been increasing over time.

Annual Greenhouse Gas Index



The warming effects of greenhouse gases are increasing over time.

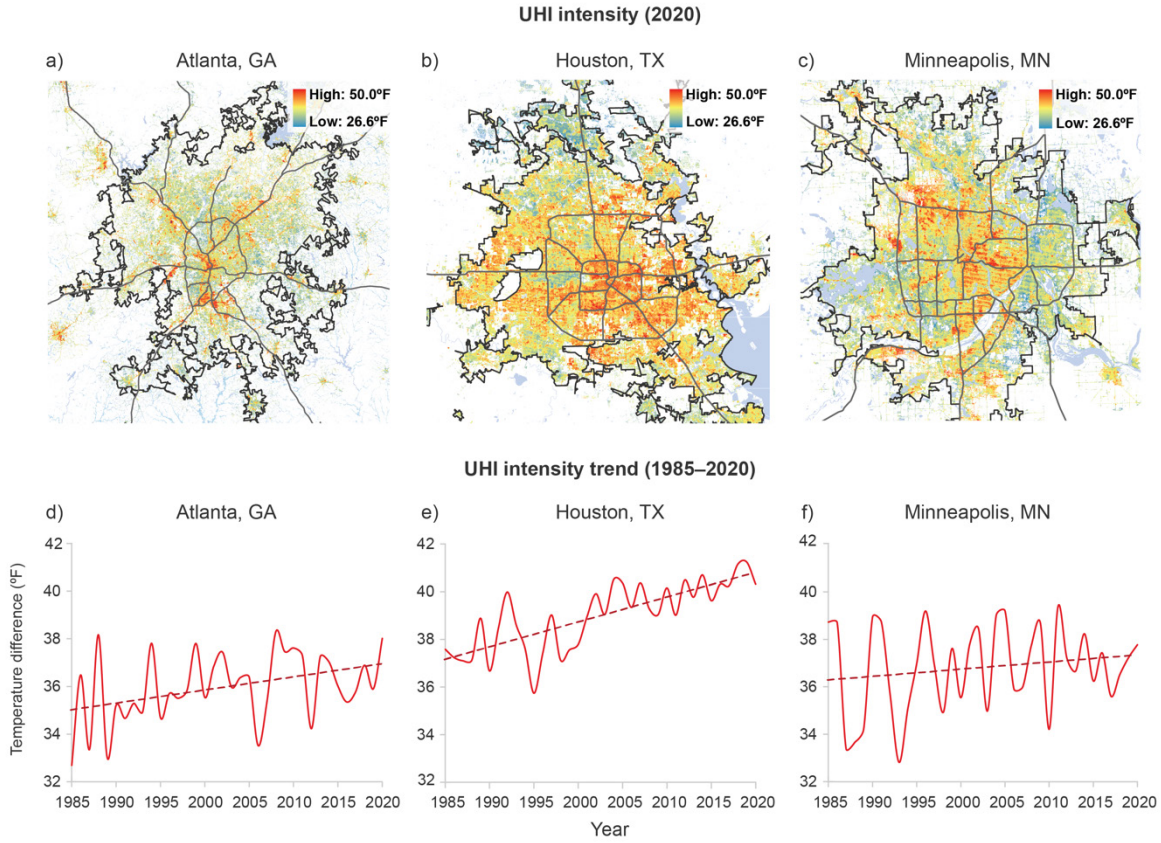
Figure A4.3. Radiative forcing (left vertical axis) is the change, either positive or negative, in the amount of energy from the sun that is trapped by Earth's atmosphere. Increases in the amount of radiative forcing will lead to warming. The Annual Greenhouse Gas Index (AGGI; right vertical axis) compares the total radiative forcing for each year from 1979 to 2022 to the year 1990 (represented by a red dot). The year 1990 was selected as the year for comparison because that is the year the Montreal Protocol[16] was signed, so its AGGI value is designated here as 1.0. The 2022 AGGI (also represented by a red dot) was 1.49, indicating that the average warming influence of long-lived greenhouse gases in the atmosphere has increased by a total of 49% since 1990. The increased radiative forcing leads to increasing temperatures, both in the oceans and over land. Indicators of these changes and impacts are found in this appendix and throughout the report. CFCs = chlorofluorocarbons, HFCs = hydrofluorocarbons, HCFCs = hydrochlorofluorocarbons. Adapted from USGCRP 2023.[17]

Temperature and Extreme Heat

Long-term observations show that warming due to climate change is unambiguous but is not occurring equally or in all areas (Figures A4.1, 2.4, 2.7). Figure A4.1 shows four different temperature indicators valuable to decision-makers at multiple scales. Globally, annual average temperatures have increased almost everywhere, with the greatest increases seen across North America and the Arctic (Figure A4.1, top left). On the national scale, nights have been warming faster than days (KM 2.2), with the greatest increases in summer nighttime minimum temperatures seen across large areas of Alaska, Florida, and the western and northeastern United States (Figure A4.1, top right). On the regional scale, cooling degree days (a proxy for energy demand used to cool buildings) have increased throughout the Southwest, with California experiencing the greatest changes (Figure A4.1, bottom left). And on a local level, the number of days per year with temperatures reaching 110°F or more have increased throughout Maricopa County, Arizona, with the Phoenix area experiencing notable increases in these extremely hot days (Figure A4.1, bottom right). Additionally, in the United States, the rate at which temperatures increase differs seasonally (Figure 2.4).[18] Changes in seasonal temperatures have led to shifts in the seasonality of certain events (Figure A4.13). In some areas, the combination of high humidity and high temperatures is contributing to the emergence of heat index values too severe for human tolerance (KM 2.3).[19,20] As temperatures increase, people's exposure to extreme heat becomes greater (KMs 3.12, 15.1).

These increasing temperatures directly and indirectly impact human health and societal outcomes (KM 2.2; Ch. 15). Populations directly exposed to more heatwaves experience increased heat-related illness and death.[21,22] Since the 1960s, the frequency of heatwaves and the duration of heatwave seasons have steadily increased in certain areas (KM 2.2).[23] Urban areas experience higher temperatures than surrounding landscapes because many structures such as roads and buildings absorb and radiate heat, exacerbating the effects of increasing temperatures (Figure A4.4; KM 12.1). Additionally, changes in land use in and around urban areas have contributed to temperature hotspots (Figure 6.3).

Urban Heat Island (UHI) Intensity



Urban heat island intensity is increasing in many US cities due to the combination of urbanization and rising temperatures.

Figure A4.4. Urban heat island (UHI) intensity is defined as the annual difference in average temperature between areas that are urban versus nonurban (within a 5 km, or approximately 3.1-mile, buffer zone of the city boundary). Indicators and maps of UHI intensity can help inform heat-mitigation strategies such as implementing urban vegetation cover.[24] Top row: Maps for the year 2020 are presented for (**a**) Atlanta, (**b**) Houston, and (**c**) Minneapolis, showing temperature differences used to determine UHI intensity for that year. Both hotspots and areas of lower temperatures are evident. Bottom row: Trends in average UHI intensity from 1985 to 2020 are presented for (**d**) Atlanta, (**e**) Houston, and (**f**) Minneapolis. Solid lines show observed data, while dashed lines represent the estimated trend for the period of record. Companion figures depicting the relationship between temperature and socioeconomic factors for these same cities can be seen in Figure 12.6. Figure credits: (a, c, d, f) adapted from Xian et al. 2022;[24] (b, e) USGS and NIEHS / Kelly Government Solutions.

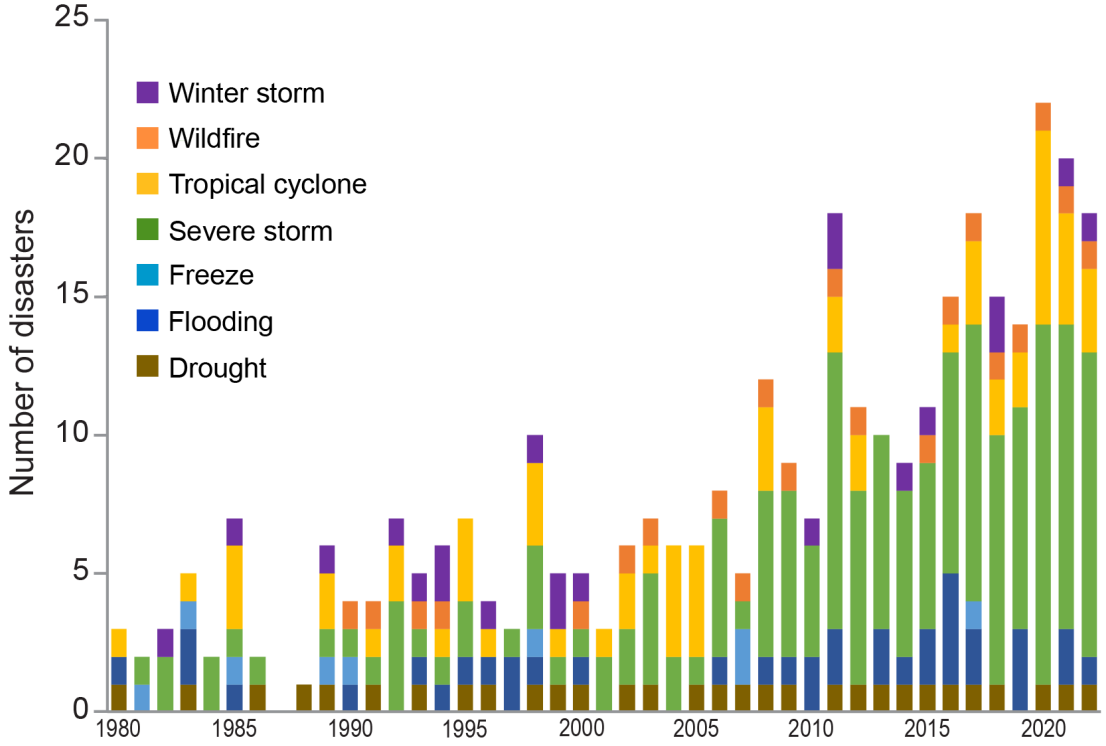
Precipitation

As temperatures rise, US precipitation patterns are changing, with long-term trends in average precipitation differing considerably by region and by season (Figure 2.4).[14] Indicators can show how changes in these patterns may affect different sectors. For example, too much or too little precipitation can impact both crop (KM 4.1) and hydropower (KM 5.1) production. Seasonal activities of sensitive plant and animal species may shift as precipitation amounts and timing change (Figure 8.11). Indicators can also be used to observe how heavy precipitation events are evolving in intensity (e.g., Figure 2.8), frequency (e.g., Kunkel et al. 2022[14]), and duration (e.g., Kunkel et al. 2020[25]). For example, evidence suggests that in recent years, extreme single-day precipitation events are increasing in the United States.[26] Heavy precipitation will become increasingly important to local engineering and community planning as the risk of flooding increases in a warmer world;[25] as a result, regional- and local-scale indicators are most valuable for informing adaptive actions to protect public health and safety.

Extreme Events

Climate change is increasing the frequency and severity of many extreme weather and climate events (Figure 1.7; KM 2.2), including heatwaves,[23] heavy precipitation (Figure 2.8; KMs 4.1, 21.1; KM 22.1), drought (Section A4.3), flooding (Section A4.3; KM 4.1), wildfire (Section A4.5; KM 7.1; Focus on Western Wildfires), and tropical cyclones (KM 2.2).[27] Other events, such as cold snaps, are becoming less frequent (KM 2.2). Extreme-event indicators allow communities to evaluate changes in risk, as major weather and climate disasters can threaten lives, damage property, and affect daily activities. One example is the number of disasters in the US each year that cause at least $1 billion in damages (Figures A4.5, 1.7, 2.6, 22.3). More frequent and compound extreme events (Focus on Compound Events) disproportionately impact already-overburdened groups (KM 18.2; Box 18.2), leaving communities with less time and fewer resources to respond to each disaster.

Billion-Dollar Disasters



The number of weather- and climate-related disasters exceeding $1 billion has substantially increased since 1980.

Figure A4.5. This indicator provides insight into the frequency of events exceeding $1 billion in damages (adjusted for inflation) from 1980 to 2022 across seven disaster types, each represented by its own color. The severe storm category includes events such as tornadoes, hail, and damaging winds but not tropical cyclones or winter storms. The only year with no billion-dollar events was 1987. Since then, the number of events each year has generally increased, with 2020 and 2021 having the two highest number of events on record. The number and cost of these disasters are due to several complex factors. Climate change is leading to increases in the frequency and intensity of extreme events, and, at the same time, there have been continual increases in the numbers of buildings, infrastructure, and people in climate-sensitive areas where these events may occur.[28] Economic factors can also play a role. For example, there is potential for property values to increase at rates higher than the Consumer Price Index, which can lead to higher damage assessments compared to previous years. An interactive version of this indicator, including the total annual cost and a breakdown by state and region, can be found at https://www.ncei.noaa.gov/access/billions/time-series/.[29] Adapted from USGCRP 2023.[30]

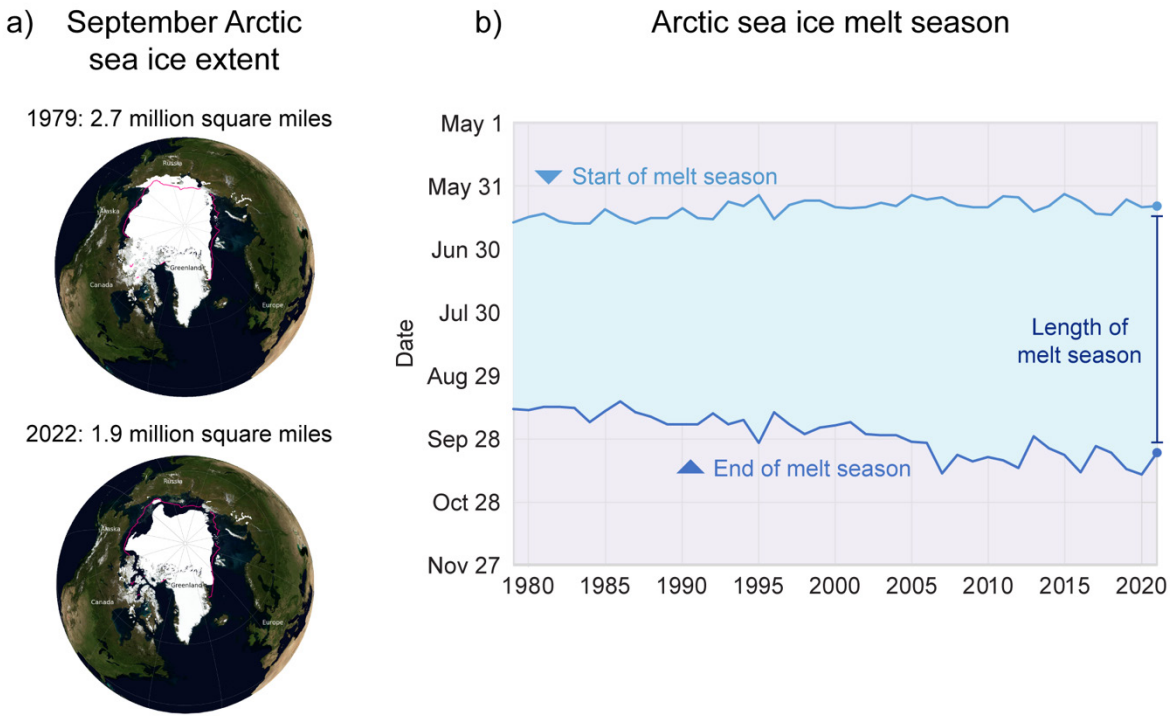
A4.3. Ice, Snow, and Water Indicators

Many parts of the US are experiencing intensified droughts or reduced snowpack, which are caused or exacerbated by rising temperatures (KMs 2.2, 4.1). These changes, combined with increasing water demand from growing populations, can reduce the reliability of water supplies,[31,32] and water-related indicators can help communities prepare for impacts. Also useful are indicators used to track changes in the cryosphere (the frozen parts of Earth's surface), as melting sea and land ice (e.g., ice sheets and glaciers) and thawing permafrost can contribute to sea level rise (KM 9.1; Figures 2.5, 9.1), affect water supply (KM 4.1), and have other negative impacts on humans and ecosystems (KM 8.2; Ch. 29).

Sea Ice

Changes in Arctic sea ice are some of the most visible and well-known indicators of a changing climate.[33,34,35] The steep decline of average Arctic sea ice extent in September, when the ice shrinks to its smallest area each year, is shown in Figure 2.3. Figure A4.6 illustrates how the total area of September sea ice has declined and how the overall length of the melt season is increasing over time. Melt location and timing is important, because as sea ice melts, it changes ocean and atmospheric circulation patterns, which can impact marine life and coastal economies (KM 10.1). Additionally, loss of sea ice is leading to increases in commercial shipping; exploration of oil, gas, and minerals; and geopolitical and global security issues (Ch. 17; KM 29.6).[36]

Changes in Arctic Sea Ice



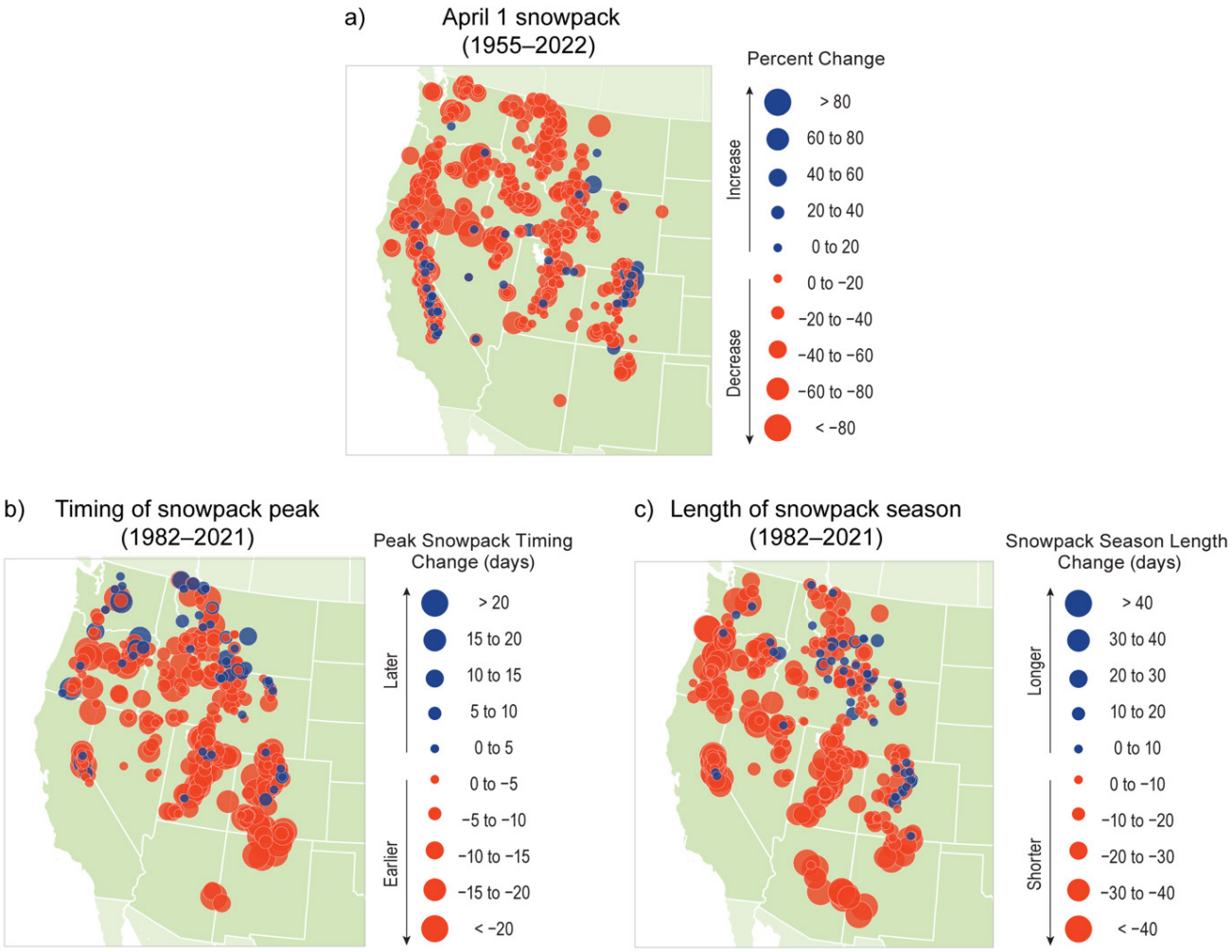
Arctic sea ice is shrinking as the melt season grows longer.

Figure A4.6. An increasingly later end to the melt season is the primary contributor to both the longer season and the declining ice extent. (**a**) This indicator compares the annual minimum sea ice extent—the smallest area of sea ice—measured in the Arctic in 1979 (the beginning of the record) and 2022 (the most recent year of observation). The pink line on each map represents the median ice edge for 1981 to 2010. (**b**) This indicator shows the annual length of the Arctic sea ice melt season from 1979 to 2021. The blue shaded area represents the amount of time between the date when ice begins to melt consistently (light blue line) and the date when it begins to refreeze (dark blue line). (a) Adapted from NSIDC 2023;[37] imagery from the Special Sensor Microwave Imager/Sounder (SSMIS) instrument, courtesy of NASA and NSIDC; (b) adapted from EPA 2023.[33]

Snowpack and Snow Cover

As US winters and springs warm, the amount and seasonality of snow is changing (KM 2.2). Higher temperatures cause snow to melt earlier, which affects timing and availability of water (KM 2.2).[38] A variety of indicators can be used to track changes in snowpack and snow cover (Figure A4.7). These indicators focus on the western US, where millions of people depend on the melting of mountain snowpack for drinking water, crop irrigation, and hydropower (Ch. 4; KM 28.1). Changes in snowpack and snow cover affect winter recreation, tourism, plants, and wildlife.[38]

Snowpack Changes in the West



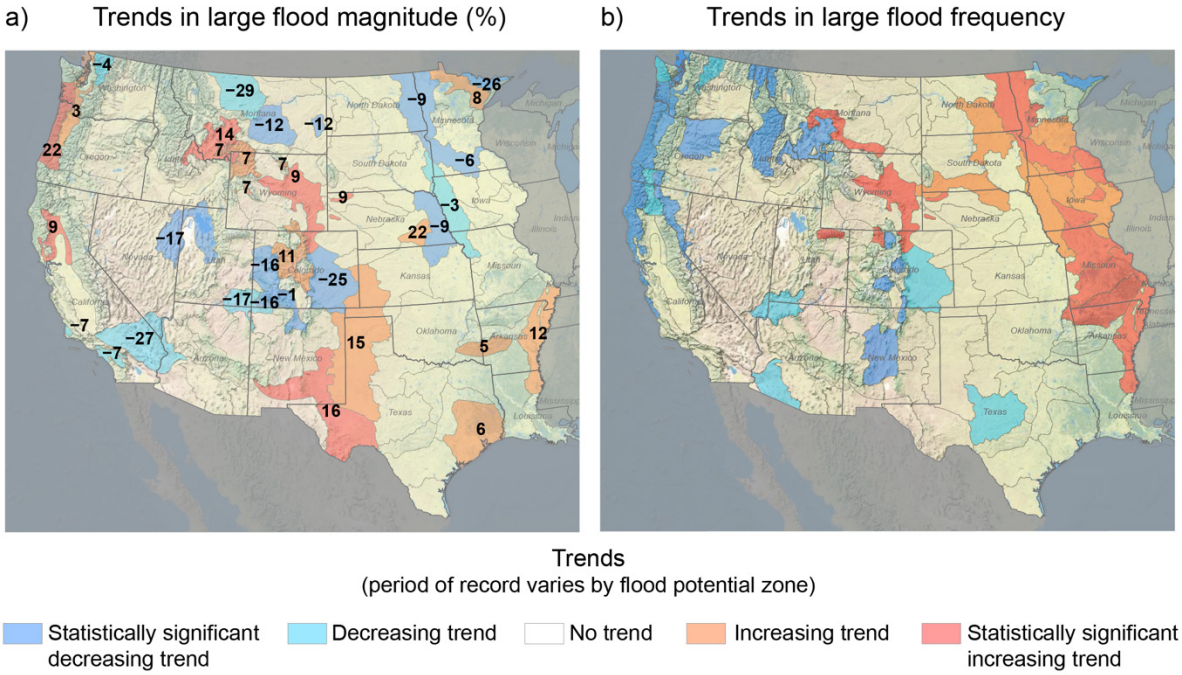
Western snowpack is declining, peak snowpack is occurring earlier, and the snowpack season is shortening in length.

Figure A4.7. The overall amount of snow has been declining across the western United States, as shown in three indicators: (**a**) trends in snowpack on April 1 (percent change) from 1955 to 2022 (red and blue circles represent a decrease and increase, respectively); (**b**) change in the annual date when snowpack reaches its maximum amount (days) from 1982 to 2021 (red and blue circles represent a shift to earlier and later timing, respectively); and (**c**) change in snowpack season length (days) from 1982 to 2021 (red and blue circles represent a shortening and lengthening of the snowpack season, respectively). Adapted from EPA 2023.[38]

Flooding

Indicators can be used to quantify trends in large floods, which is imperative for floodplain management and infrastructure design to maximize safety and resilience (KMs 4.2, 6.1, 12.4). For example, west of the Mississippi River, nearly 30% of monitored areas are experiencing increases in large flood frequency and/or magnitude (Figure A4.8). In contrast, other areas have recently experienced decreasing trends due to prevailing climate patterns such as the Southwest megadrought (KM 28.1).[39] Flood indicators are also used to track economic damage related to flooding (Figure 4.12) and monitor flood trends of individual streams.[40]

Flood Frequency and Magnitude West of the Mississippi River



Trends in flood magnitude and frequency vary widely across the western US.

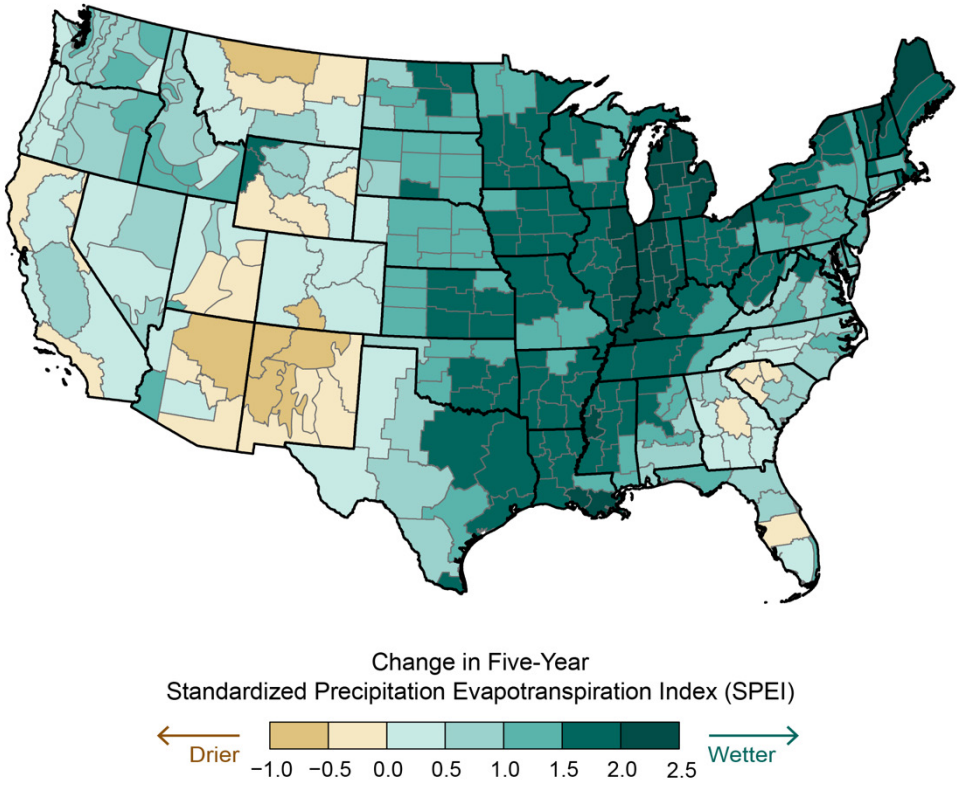
Figure A4.8. Flood magnitudes are increasing along the Oregon coastline, throughout large portions of the central Rockies and southern Great Plains, and in parts of the Gulf Coast, whereas flood frequencies are increasing across a large area east of the Rocky Mountain Front.[41] This indicator shows trends in (**a**) magnitude and (**b**) frequency of large floods in the western US within 117 flood potential zones. Shading in warm colors (reds) represents increasing trends, and shading in cool colors (blues) represents decreasing trends. Darker shades indicate where trends are statistically significant. (a) Percent change in annual flood magnitudes is indicated by black numbering. Trends in magnitudes vary by the available record length (most commonly from the early 1900s through 2020), while (b) trends in frequency are for 1945 to about 2020. Data are not yet available for the US Caribbean, Alaska, or Hawai'i and US-Affiliated Pacific Islands regions, as well as the contiguous US east of the Mississippi River. Additional information related to trends in large floods is provided in the Flood Potential Portal at https://floodpotential.erams.com/. Figure credit: USDA Forest Service.

Drought

The effects of drought can be far-reaching and long-lasting, posing risks to people and ecosystems and often contributing to other extreme events, such as drought-induced wildfire (KM 4.2; Focus on Western Wildfires). Several hydrologic measures exist for drought, and for certain applications, climate reanalyses can also be valuable in evaluating historical trends related to climate including drought metrics (e.g., Jasinski et al. 2019[42]). Some drought indicators consider water availability, measured by variables such as precipita-

tion (Figure 4.10), streamflow, groundwater and reservoir levels, or soil moisture (Figure 28.2). Other drought indicators take into account different climatic factors, such as temperature, potential evapotranspiration, and solar radiation (Figure 3.12). For example, the Standardized Precipitation Evapotranspiration Index (SPEI; Figure A4.9) measures the combination of precipitation and evapotranspiration to determine whether a certain area is experiencing extreme drought, extreme moisture, or conditions in between.[43] SPEI is a valuable indicator when considering how droughts might affect activities that depend on a balance between water supply and demand, particularly those related to agriculture and ecosystems.[44]

Change in Drought Conditions, 1900–2022



Long-term records show conditions are becoming drier in many portions of the West and wetter elsewhere, particularly the East.

Figure A4.9. Since the early 20th century, the eastern US has generally experienced wetter conditions, while portions of the West—especially the Southwest—have experienced drier conditions. This map shows the total change in drought conditions across the contiguous United States, based on the long-term average rate of change in the five-year Standardized Precipitation Evapotranspiration Index (SPEI) from 1900 to 2022. Data are displayed for small regions called climate divisions, as defined by NOAA.[45] Teal-shaded areas represent wetter conditions, and brown areas represent drier conditions. Data are not available for the US Caribbean, Alaska, or Hawai'i and US-Affiliated Pacific Islands regions. Adapted from EPA 2023.[44]

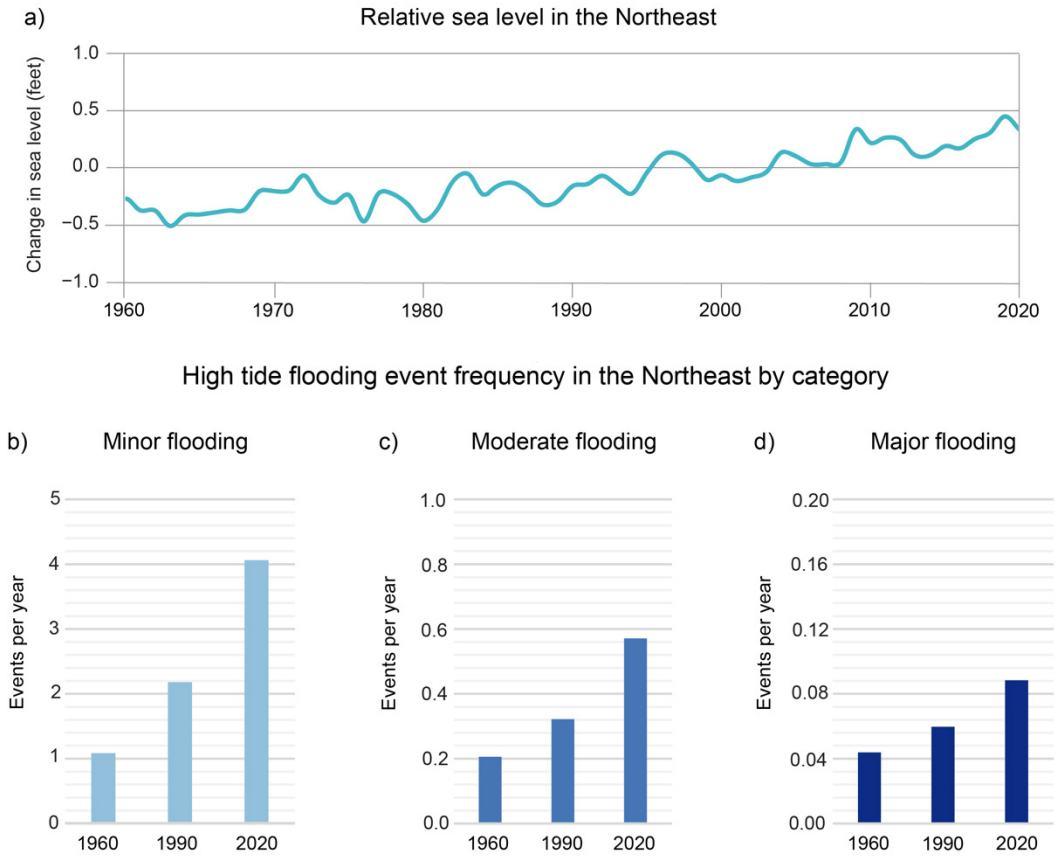
A4.4. Ocean and Coastal Indicators

Climate-driven changes to US oceans and coasts endanger marine ecosystems and coastal communities (Figures 10.1, 21.5) and threaten infrastructure and energy production (KMs 9.2, 10.1). Indicators can be used to track physical ocean conditions (e.g., sea surface temperatures, ocean acidification), ecological impacts (e.g., marine species shifts), and coastal impacts (e.g., high tide flooding). This information is used to evaluate risk, promote resilience, and increase the value of coastal and marine resources as ocean conditions change.

Sea Level Rise and Coastal Flooding

Global sea level is rising as warming ocean waters expand and glaciers and ice sheets melt. Along some US coastal areas, sea levels are rising faster than the global average, with the highest rates occurring along parts of the Atlantic coast and the Gulf of Mexico (Figures A4.10a, 2.5; KMs 21.2, 22.1, 26.1).[46] The increase in relative sea level is driving increases in physical and societal impacts such as high tide flooding (Figure A4.10b–d; KM 9.1).

Sea Level and Coastal Flooding in the Northeast



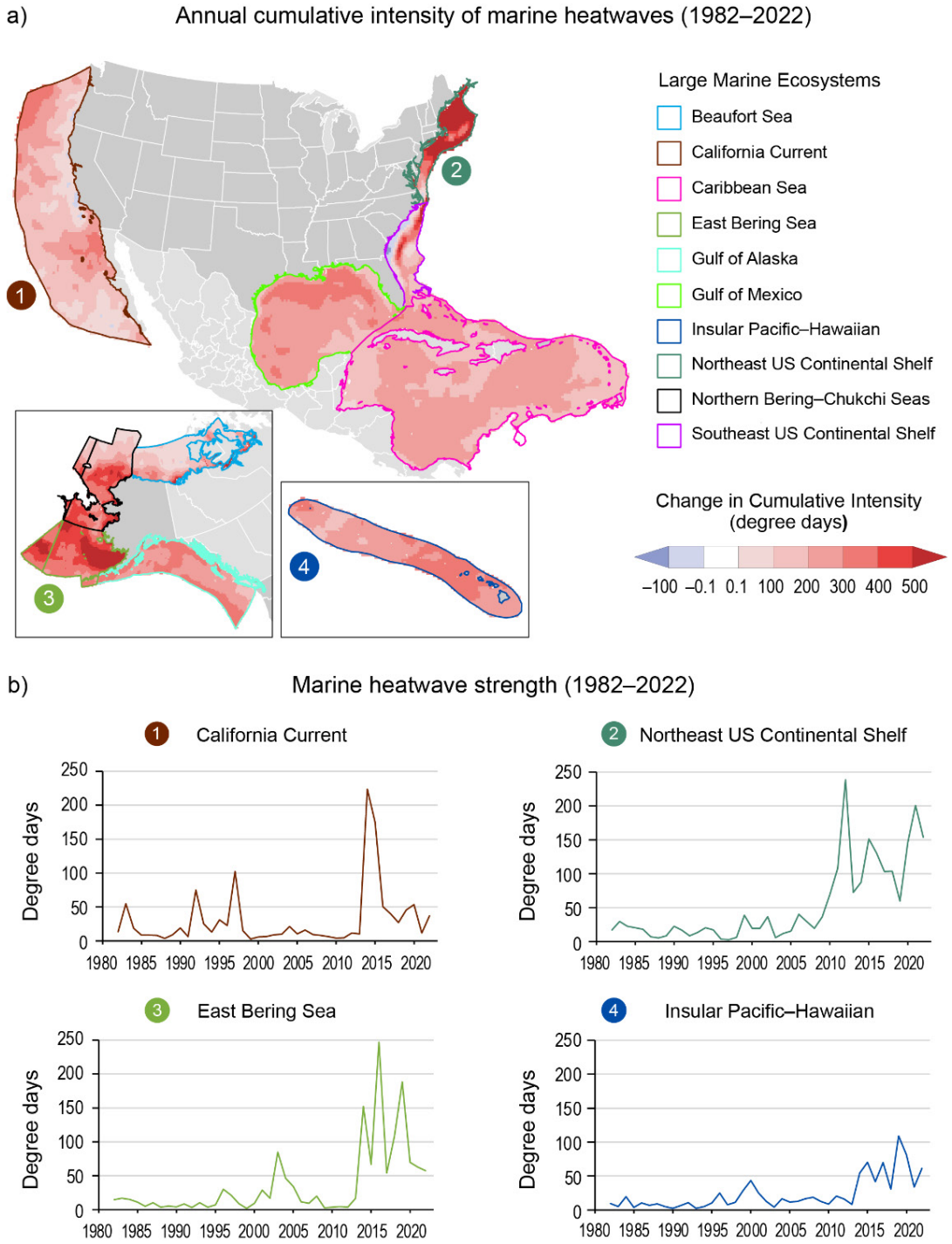
The combination of rising sea levels and the increased frequency of coastal flooding events exacerbates risk for coastal communities.

Figure A4.10. (**a**) The line chart shows the observed changes in relative sea level from 1960 to 2020 (compared to the 1991–2009 average), which is a combination of sea level changes and local uplift or subsidence of land, averaged along the Atlantic coast of the northeastern US. The bar graphs depict the frequency of (**b**) minor (disruptive), (**c**) moderate (damaging), and (**d**) major (destructive) high tide flooding events at 30-year intervals (1960, 1990, and 2020), also for the northeastern US (see Figure 9.3 for definitions of high tide flooding thresholds). The frequency of occurrence is expressed as the number of events per year, where a value of 0.1 is equivalent to a 10% annual chance of experiencing that type of flood event. See Chapter 9 for contiguous US data, including future projections. Figure credits: (a) adapted from Sweet et al. 2022;[47] (b, c, d) NOAA NCEI and NOAA.

Marine Heatwaves

Sea surface temperatures in oceans surrounding the US have risen steadily over time, as they have in most of the world's oceans (Figure 2.3).[48] Rising temperatures in these areas contribute to increases in marine heatwave frequency (KMs 10.1, 21.2), intensity (Figure A4.11), size, and duration.[49] These changes have detrimental impacts on surrounding ecosystems and economies, including shifts in the distributions of marine life (Figure A4.12; KMs 8.2, 10.1).

Marine Heatwaves



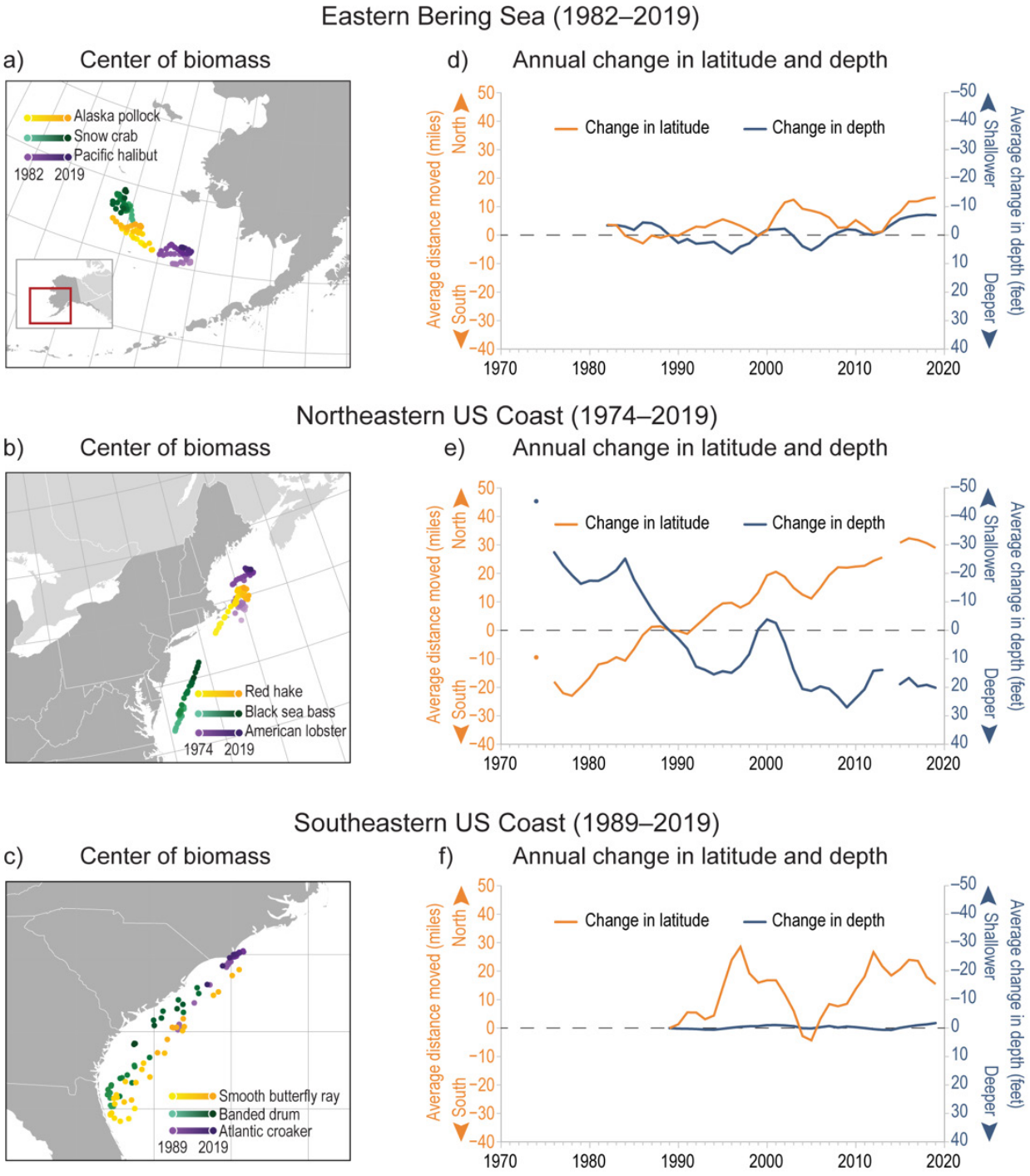
Extreme ocean temperatures are more common as ocean temperatures rise.

Figure A4.11. (**a**) The maps show the change in annual cumulative intensity of marine heatwaves (anomalously warm temperatures lasting five or more days) within large marine ecosystems surrounding the United States from 1982 to 2022. Cumulative intensity, or degree days, is determined by heatwave intensity multiplied by duration, compared to the 1982–2011 average. Areas with increases in cumulative intensity are shown in red, with darker colors indicating greater change. Areas in blue represent a decrease in cumulative intensity over time. (**b**) Charts show the heatwave strength in total degree days each year from 1982 to 2022 for select large marine ecosystems highlighted in the above maps. Figure credit: NOAA NCEI, University of Miami, DOE, and Eastern Research Group Inc.

Marine Species

Warming oceans have contributed to shifts in the geographic distribution of marine species (KM 10.1), which are extensively studied and tracked using indicators.[50] It is important to track climate-driven changes in the distribution, timing, and productivity of fishery-related species that can put marine fisheries and fishing communities at risk.[51] Many marine species are sensitive to environmental cues such as temperature ranges and track well with local climate velocities (the speed and direction at which species move in order to experience similar climate conditions).[52] However, several other factors can influence the abundance and geographic distribution of species, such as large-scale fishing practices, ocean currents, changes in habitats, and species' ability to adapt. Figure A4.12 depicts how multiple species adjacent to the Alaska, northeastern US, and southeastern US coasts have been shifting northward and, in some regions deeper, to cooler waters.

Marine Species Distribution



Marine species along US coasts are generally shifting northward to cooler waters.

Figure A4.12. (**left**) Maps show annual centers of biomass for three species in three regions: (**a**) the eastern Bering Sea (1982–2019) and the (**b**) northeastern (1974–2019) and (**c**) southeastern (1989–2019) US coasts. Species were chosen because they represent a variety of habitats and species types and are relatively abundant. Dots are shaded to show how species' locations have changed over time, with light shading representing earlier years and darker shading representing more recent years. (**right**) Charts show the annual change in latitude (orange lines; movement in miles) and depth (blue lines; change in feet) of several marine species in (**d**) the eastern Bering Sea (top; 64 species) and (**e**) the northeastern (middle; 53 species) and (**f**) southeastern (bottom; 63 species) US coasts, relative to 1989. Black dashed lines represent no overall change. Data were not available for 1975 or 2014 for the Northeast region. Adapted from EPA 2023.[50]

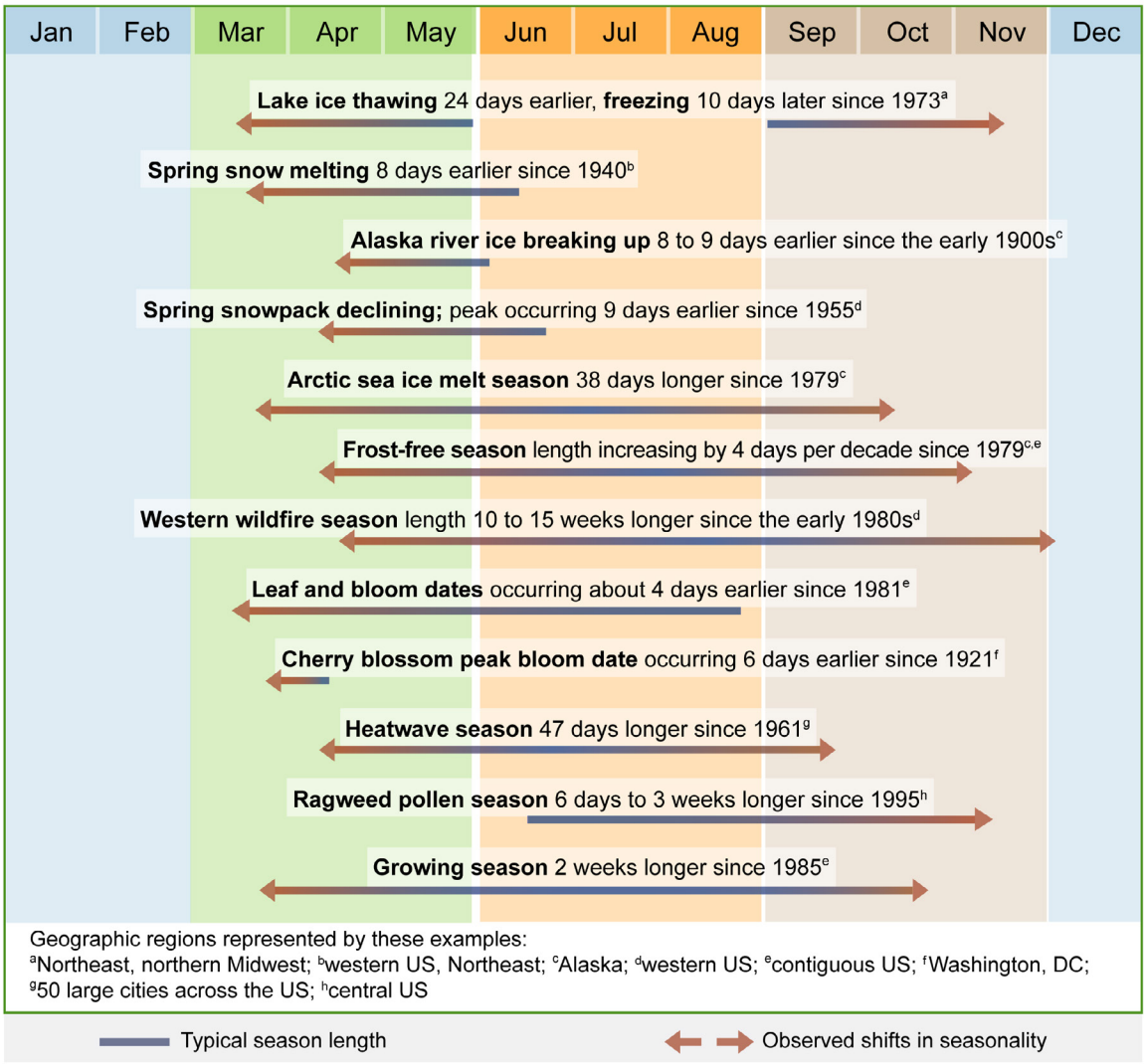
A4.5. Land and Ecosystems Indicators

Earth's land, food, and climate systems are inextricably intertwined (Figure 11.9). Climate and weather shape demand for and distribution of food, fish, and forest products. In turn, commodity production influences the climate via greenhouse gas exchange and land conservation or degradation. These feedbacks are driving the coupled climate–land system toward a host of outcomes for people and society, some undesirable.[53] Indicators can help land managers and policymakers identify optimal planning and solutions in the context of changing conditions.

Seasonal Change

Seasonality refers to recurring seasonal events or processes, such as the blooming of wildflowers in spring.[54] The timing, duration, and variability of many seasonal events are changing in response to changing temperature and moisture patterns (Chs. 2, 8; Figure 24.3). Indicators of seasonal change (Figure A4.13) are valuable for understanding relationships between climate and ecosystems and subsequent risks to environmental and social systems.[55] Knowledge of these changes is often generated by local and Indigenous populations, who have deep connections to local ecosystems because of their cultural and subsistence practices (Ch. 16).

Changes in Seasonality



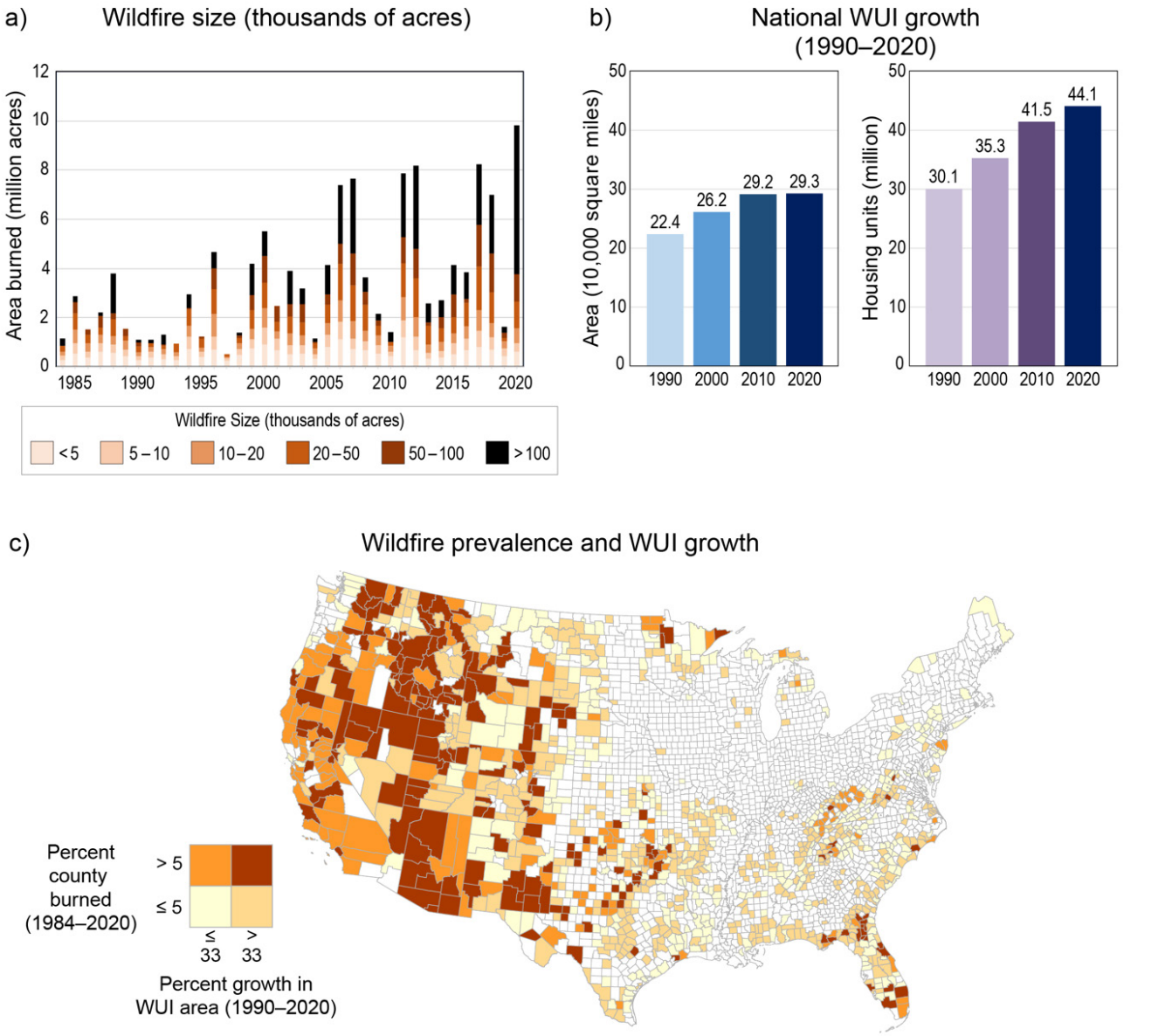
Observed evidence of changes in seasonality reflect a warming climate.

Figure A4.13. Many indicators show shifts in timing and duration of seasonal events or processes that are correlated with seasons. The length of the blue lines represents the approximate time of year when these events typically occur, and the direction of the arrows denotes earlier (←) and later (→) shifts in the season. Red line segments portray the observed change for illustrative purposes, whereas the actual observed values are provided as text above each line. Some of these indicators are limited to specific geographic regions. Adapted from EPA 2021.[54]

Wildland Fire and the Wildland–Urban Interface

Wildland fires affect carbon dynamics, ecosystems, biodiversity, and human health (Ch. 7; KMs 6.1, 14.2; Figures F2.1, 28.9). The wildland–urban interface (WUI) is the area where buildings and other developments meet or mix with undeveloped natural areas, including fire-prone vegetation. Over the past several decades, the WUI has grown rapidly,[56] expanding in both total area and number of homes. In addition, the annual average acreage burned by wildfires has increased since the mid-1980s.[57] Together, these changes have increased risks of loss of life and property damage in many areas across the United States (Figure A4.14). Other important wildfire-related indicators include greenhouse gas emissions resulting from wildfires and prescribed fires (Figure 7.2) and related socioeconomic indicators such as federal spending on wildfire suppression.[58]

Wildfires and Wildland–Urban Interface (WUI) Growth



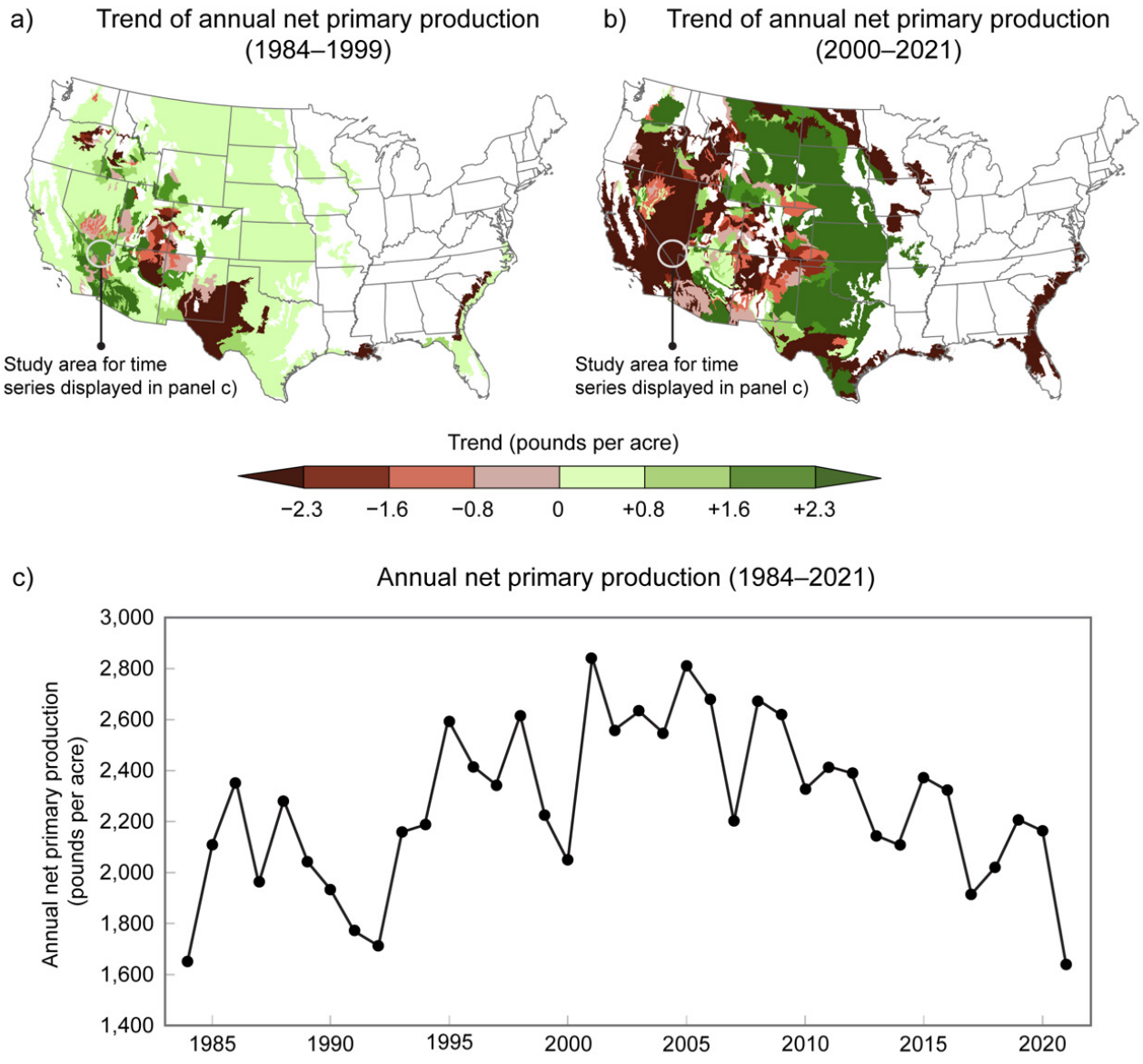
Area burned by wildfires is increasing and the wildland–urban interface is expanding in the contiguous US.

Figure A4.14. (**a**) The chart shows the number of acres burned between 1984 and 2020 for the contiguous US. The different shades within each bar indicate the proportional contribution of different fire size classes to the total for that year. (**b**) The two charts depict wildland–urban interface (WUI) growth in terms of area and number of housing units from 1990 to 2020 for the contiguous US. (**c**) The map portrays US counties where WUI growth and wildfires are most prevalent. Counties are categorized by their level of WUI growth between 1990 and 2020 and area burned between 1984 and 2020. Counties are not categorized where wildfires do not meet the minimum size requirements for Monitoring Trends in Burn Severity (MTBS) mapping[57] or where percent growth in WUI area is less than zero. WUI data are not available for the US Caribbean, Alaska, or Hawai'i and US-Affiliated Pacific Islands regions. In Alaska, wildfires burned over 34 million acres between 1984 and 2020; during this period, eight of the nine wildfire seasons when more than one million acres burned have occurred since 2000. Twenty-one wildfires in Hawai'i (more than 103,000 total acres) and four wildfires in Puerto Rico (about 6,300 total acres) were mapped between 1984 and 2020. MTBS wildfire data are not available for other parts of the US Caribbean and US-Affiliated Pacific Islands regions (wildfire data from another source for the US-Affiliated Pacific Islands region is presented in Figure 30.13). Figure credits: (a, c) USDA Forest Service; (b) adapted from Radeloff et al. 2018.[56]

Agriculture and Food Systems

The climate–agriculture–food system is complex (Figure 11.9). Agricultural production and natural resources face challenges from increasing climate variability and change. Optimized management and policy decisions require an integrated indicator system that communicates climate-driven production impacts; trends in the social-ecological systems underpinning agriculture (e.g., heat-related mortality of workers; Figure 11.1); crop insurance payments (KM 11.2);[5] how management performs in relation to desired social-ecological conditions;[59] degree of adaptation (KM 11.1); and the relationships among climate change, consumption, and production.[60] Currently, the most developed agriculture-related indicators are production-oriented (Ch. 11), such as range or crop yield, crop pathogens, animal heat stress, migration of plant hardiness zones (Figure 11.3), timing of budbreak in fruit trees, and ratios of outputs to inputs (total factor productivity).[5] The productivity of rangeland vegetation provides many valued ecosystem services,[61] but it has severely declined in some areas of the US in recent decades (Figure A4.15),[62] with a strong correlation to regional-scale climate change exposure.[63]

Rangeland Production



Rangeland vegetation production has severely declined in some areas and increased in others.

Figure A4.15. Rangeland annual net primary production (ANPP) measures the annual production of rangeland vegetation, which provides key ecosystem services supporting soil, air, and water quality and billions of dollars in commerce. This figure illustrates ANPP in pounds per acre on rangelands by ecological subsection (see Cleland et al. 2007[64]) during the periods (**a**) 1984–1999 and (**b**) 2000–2021. Positive values indicate areas where ANPP has increased over time, and negative values show where it has decreased. Areas in white are not classified as rangeland ecosystems. (**c**) The time series shows annual values of ANPP from 1984 to 2021 for a select location in the Mojave Desert (indicated by the circle on the maps). ANPP increased in this area over the first half of the time period but has since seen a steady decline. Data are not available for the US Caribbean, Alaska, or Hawai'i and US-Affiliated Pacific Islands regions. Adapted with permission from Reeves et al. 2021[62] [CC BY-NC-ND 4.0].

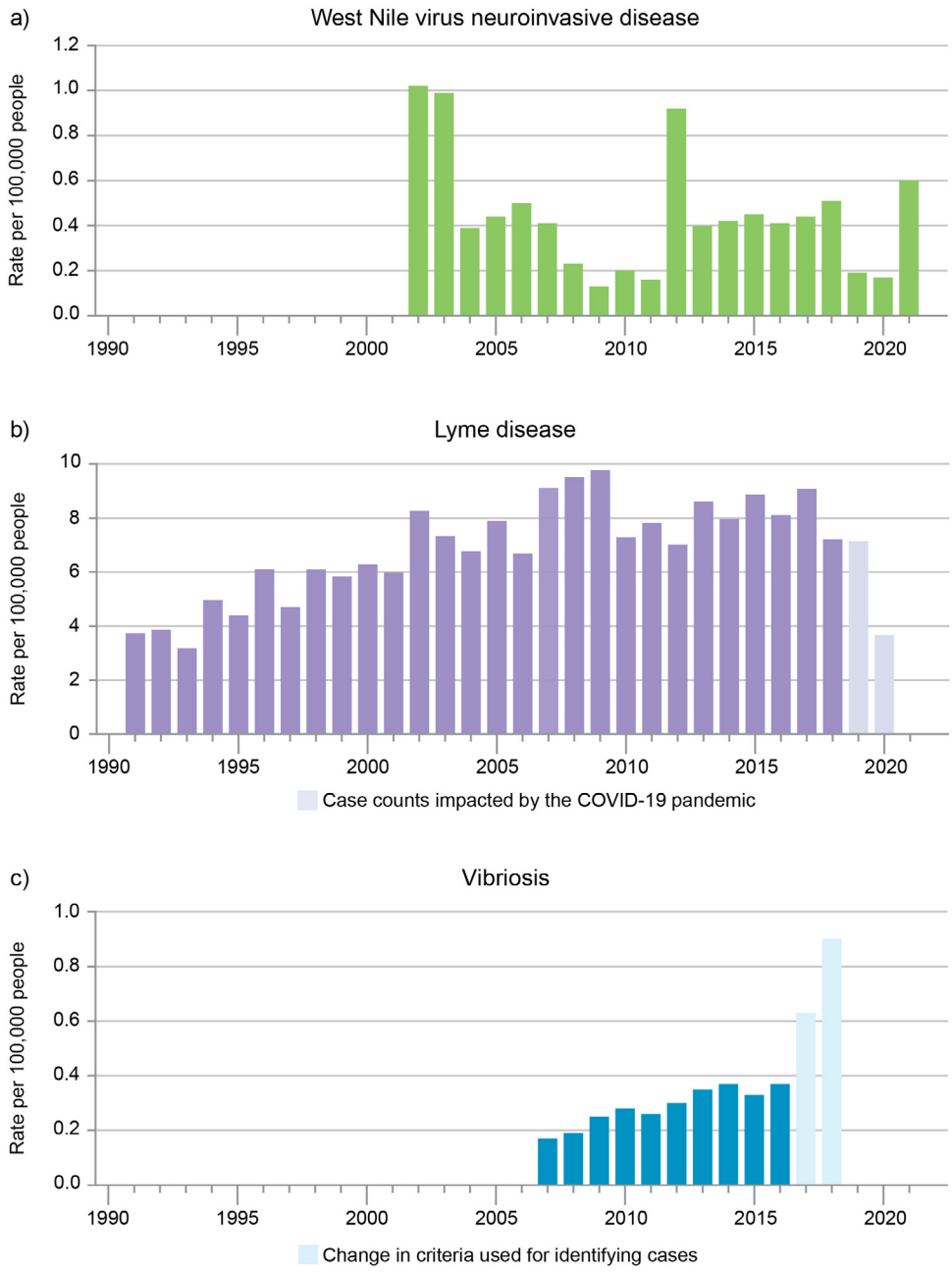
A4.6. Health Indicators

Climate change increases risks and impacts to human health and well-being by exacerbating existing health threats and creating new challenges based on multiple factors and pathways. A variety of health outcomes are affected by climate change, including mental health challenges as well as physical health issues such as cardiorespiratory conditions from poor air quality, injuries and mortality from extreme weather events, and malnutrition from changing climate and environmental factors.[15]

It is important that health indicators include more than just measures of health outcomes to understand how climate impacts and exposures influence health burdens. A broader approach is helpful because of the complex, often indirect relationships among climate drivers, environmental and social factors, and health outcomes, and because of challenges with collecting and reporting health data including lag times in availability. Some widely utilized health indicators include heat-related illnesses and deaths,[21,22,65] described in part in NCA4, which also details the impacts of a changing climate on vector-, water-, and foodborne diseases but without quantitative context.[66] To build upon this body of knowledge and to highlight robust examples of infectious disease metrics with 1) strong science supporting the linkages among climate, environment, and human risk factors; 2) national coverage; and 3) ample temporal extent, this appendix presents indicators for three nationally notifiable infectious diseases routinely reported to the CDC (Figure A4.16).

Changes in temperature, precipitation patterns, and extreme events can alter the seasonality, distribution, and prevalence of vector-, water-, and foodborne diseases (KM 15.1).[7] West Nile virus (WNV) neuroinvasive disease and Lyme disease are impacted by climate change through complex shifts in land use, vector ecology, and human behavior (Chs. 8, 15). Vibriosis, linked to warming marine and coastal waters, is an illness contracted through exposure to *Vibrio* bacterial species from contaminated seafood or from open skin wounds exposed to contaminated water.[7]

Infectious Diseases Impacted by Climate Change



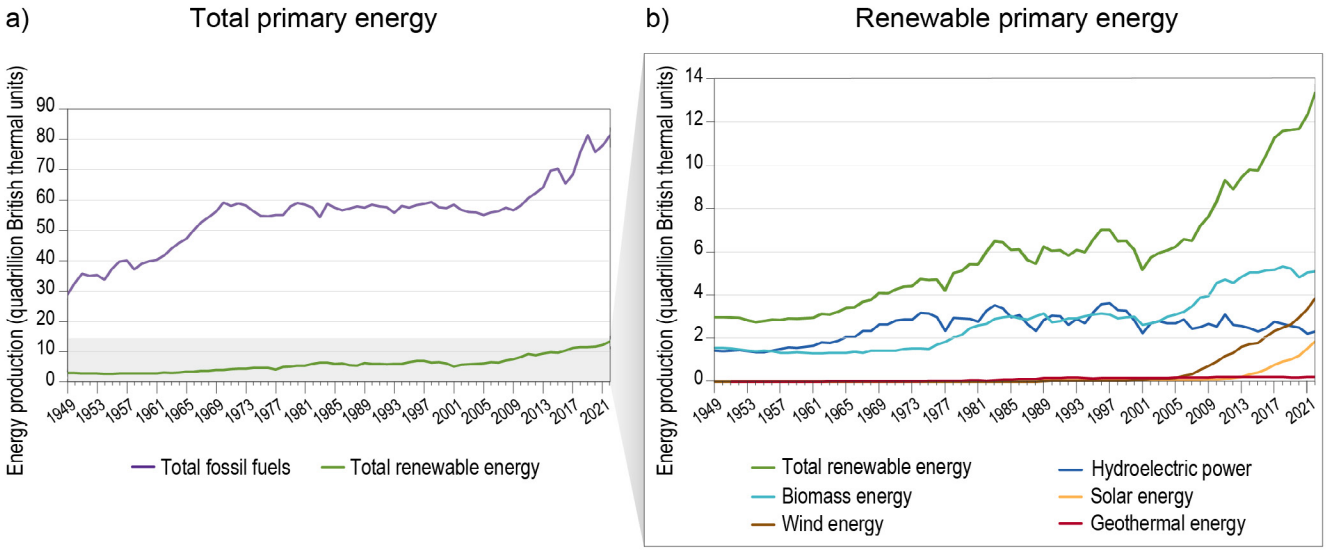
Climate, environmental, and social factors influence infectious disease rates.

Figure A4.16. Indicators of diseases widely recognized as being affected by climate change can provide a general gauge of the disease burden and help guide resources and public health actions. Incidence rates of (**a**) West Nile virus (WNV) neuroinvasive disease, (**b**) Lyme disease, and (**c**) vibriosis are presented for the years 2002–2021, 1991–2020, and 2007–2018, respectively. For WNV neuroinvasive disease, the pattern of incidence rates is variable, ranging from 1 per 100,000 people in 2002, when it became a nationally notifiable condition, to 0.6 per 100,000 people in 2021. Lyme disease incidence rates have trended upward from 4 cases per 100,000 people in 1991 to 7 cases per 100,000 in 2018. Similarly, trends in vibriosis have risen since 2007. Confirmed and probable cases are collected by state and local health departments and reported to the National Notifiable Diseases Surveillance System or the COVIS (Cholera and Other *Vibrio* Illness Surveillance) system. Annual counts and rates for each state are compiled by the CDC. Surveillance data for Lyme disease in 2019 and 2020 were markedly affected by the COVID-19 pandemic (light purple bars). Case definitions are occasionally revised, but because the vibriosis case definition changed significantly in 2017, trends before (dark blue bars) and after (light blue bars) are not comparable. (a) Adapted from EPA 2023;[67] (b) adapted from EPA 2023;[68] (c) adapted from Sheahan et al. 2022.[69]

A4.7. Adaptation and Mitigation Indicators

Adaptation to promote climate resilience of populations, ecosystems, and infrastructure as well as mitigation to reduce emissions are critical, particularly for protecting human well-being and the environment (Chs. 31, 32). Indicators of adaptation and mitigation are important tools that help track and assess progress[70,71,72], as well as evaluate adaptation decisions and improve resilience (KM 31.5). This can be done, for example, by aggregating the number of documented adaptation activities by state over a certain time period (Figures 1.3, 31.1, 32.20). Although valuable for decision-making and evaluating effectiveness, indicators of resilience, adaptation responses, and adaptive capacity remain relatively limited.[72,73,74] Figure A4.17 is an example of a mitigation indicator showing how US energy production from renewables has increased in recent years (KM 32.1; Figures 26.6, 32.3).

Energy Production by Source



US energy production from renewables is increasing.

Figure A4.17. The figure shows annual time series of US energy production for (**a**) total primary energy (which includes both fossil fuels and renewable energy) and (**b**) categories of renewable energy (biomass, wind, hydroelectric, solar, and geothermal) for 1949–2022. US energy production from renewable sources (dark green line) has increased since the 1960s, reaching a record high in 2022, primarily due to increases in wind (brown line) and biomass (light blue line) energy. Energy production from fossil fuels (purple line) also increased during this same time period, although with increased use of cleaner fossil fuels (KM 5.3). Adapted from EIA 2023.[75]

Climate change disproportionately impacts certain communities and populations (Ch. 20). Social, environmental, and economic factors[76,77,78] contribute to disparities experienced by groups at greater risk of climate change stressors (KM 15.2). Indices that combine multiple variables have been developed to capture complex issues affecting communities that are overburdened (e.g., Figures 15.5, 22.12). Furthermore, indicators that couple human and social dimensions with climate data (e.g., Figures 11.13, 12.6, 22.18) are necessary to better assess who is at highest risk from impacts and to prioritize and evaluate response decisions.

A4.8. Knowledge Gaps and New Approaches

It is vital to recognize data specific to Indigenous communities to adequately address the disproportionate impacts of climate change (Ch. 16).[79] Indicators drawing from Indigenous Knowledge (KM 16.3)[80] and focusing on the concept of cultural keystone indicator species[81] may better represent the perspectives of Indigenous Peoples affected by climate change than the indicators featured in this appendix.

Indicators are used to evaluate community response and preparedness,[82] as well as the capacity for socio-ecological systems to build resilience.[83] However, it is difficult to incorporate consistent indicators of resilience and adaptation (e.g., Brooks 2014;[84] Keenan and Maxwell 2021[85]). Distilling best practices at the community scale remains a challenge.[86] The emerging understanding of compound events and their impacts (Ch. 18) will likely inform new indicator development. Confidence in attributing outcomes to climate change varies among physical climate indicators, especially for societal and ecosystem indicators (e.g., IPCC 2022[15]).

Data sharing and transparency standards arising from the Information Quality Act (IQA; App. 2), are well established for geophysical information and are reliably compiled in several recurring volumes,[2,9,87] whereas biological and health information is typically built on local and less-federated data. For health, limitations in sharing data, due to privacy concerns or cost, hinder the creation of nationally consistent indicators.[8] Advances in applying IQA standards to nonphysical data will increase the availability and credibility of this information.

Newer observing systems and sensors and community-led ("citizen") science bring additional data options. In recent years, broader public participation in data collection and curation has played an increasingly important role in contributing to existing or potential indicators. Such efforts include improvements in documenting physical climate variables at finer scales,[88] capturing the impacts on or responses of ecosystems, and recording climate-related influences on human health.[89]

While indicators provide valuable information on past changes, it is important that they be well positioned to provide information on how these changes may continue in the future, to assist with planning, adaptation, and strategic policy decisions. For example, national surveillance systems, such as the National Notifiable Diseases Surveillance System,[90] could integrate indicators into existing data collection and analysis processes to advance interpretation of observed data, trends, and impacts. New indicators that track how compound events are changing over time would potentially help communities become more climate resilient (see Focus on Compound Events).

Looking ahead, indicator systems that reflect the coupled nature of climate systems and management systems will be needed for optimal planning and policymaking. This will require integration across disciplines, stakeholder groups, government agencies, and nations.[91]

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Fifth National Climate Assessment: Appendix 5

Glossary of Terms



Appendix 5. Glossary of Terms

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About the Glossary of Terms

Authors of the Fifth National Climate Assessment (NCA5) were encouraged to briefly define important terms within their chapters. Some terms, however, require more detailed or nuanced definitions. This Glossary was developed to help readers understand key terms and ensure consistency of usage across the report.

Most of the definitions presented here have been adapted from authoritative sources, including other US Global Change Research Program (USGCRP) reports, Intergovernmental Panel on Climate Change (IPCC) assessments, and academic and scientific societies and organizations (e.g., American Meteorological Society). These external sources are indicated with citations. Where definitions have been developed from multiple sources, the Fifth National Climate Assessment[1] is cited.

Where a term is used in a chapter in a manner that is inconsistent with the glossary definition, the intended definition is provided within the chapter text.

Terms and subterms (e.g., "Flash drought" as a subterm of "Drought") are bolded, and references to other terms defined in the glossary are underlined and hyperlinked. Related terms of particular importance are noted and linked at the end of the definition.

Note on Glossary Development Process

Terms selected for inclusion in the Glossary of Terms are those that are used in multiple chapters of the Assessment and required a definition that went beyond what would be provided in a simple dictionary definition.

The editorial team followed a prioritized selection process for definitions. The team sought existing definitions from the following sources: the *Second State of the Carbon Cycle Report* (SOCCR2, 2018[2]); the *Climate Science Special Report* (Volume I of the Fourth National Climate Assessment [NCA4]; CSSR, 2017[3]); *Impacts, Risks, and Adaptation in the United States* (Volume II of NCA4; USGCRP, 2018[4]); *Impacts of Climate change on Human Health in the United States: A Scientific Assessment* (USGCRP, 2016[5]); and the Contributions of Working Groups I, II, and III to the IPCC Sixth Assessment Report (IPCC WGI, 2021[6] IPCC WGII, 2022[7] and IPCC WGIII, 2022[8]). If these sources did not offer adequate definitions, the editorial team searched for definitions from scientific and academic society glossaries, reports, and websites (e.g., American Meteorological Society, American Psychological Association, World Health Organization) and federal and state agency reports and websites. In the rare cases for which adequate definitions were not available from these sources, the editorial team collaborated with USGCRP leadership to develop definitions based on the text of the Assessment (or of NCA4) or the underlying Assessment literature.

As the editorial team examined sources, draft definitions were selected if they fit the proper context in which the term was used in the Assessment and were relatively succinct and understandable while also providing enough information for the reader to understand how the term was used. The team removed any policy-prescriptive terminology, assessment descriptions, or specific language referring to scenarios during editing, unless required to define the term.

The draft glossary was reviewed by Assessment author teams to ensure that all necessary terms were included and that the definitions were technically and scientifically accurate. The editorial team conducted an initial review for new term inclusion, as well as a science, technical, and stylistic edit of definitions, and these decisions were reviewed by the Assessment Director.

Finally, the Glossary of Terms was reviewed by the Federal Steering Committee prior to final copyediting and formatting.

Glossary

Note: Underlined text indicates a term that is defined in the glossary.

Term	Definition
Acidification, ocean	The process by which the pH measurement of ocean water moves toward more acidic levels due to the absorption of carbon dioxide, which interacts with ocean water to form carbonic acid, thereby lowering the pH. Increased acidity reduces the ability of plankton and shelled animals to form and maintain carbonate-containing body parts such as shells.[3]
Adaptation	**Climate adaptation:** In human systems, the process of adjustment to actual or expected climate and its effects to moderate harm or exploit beneficial opportunities. In natural systems, the process of adjustment to actual climate and its effects. Human intervention may facilitate adjustment to expected climate and its effects.[7] Related terms: Adaptive capacity, Maladaptation, Climate Resilience. **Equitable adaptation:** Adaptation that intentionally incorporates recognitional, procedural, and distributional principles of equity in design, planning, and execution.[1,9] **Incremental adaptation:** Adaptation that maintains the essence and integrity of a system or process at a given scale. In some cases, incremental adaptation can accrue to result in transformative adaptation. Incremental adaptations to change in climate are understood as extensions of actions and behaviors already known to reduce the losses or enhance the benefits of natural variations in extreme weather/climate events.[7] **Transformative adaptation:** Adaptation that changes the fundamental attributes of a social–ecological system, often involving persistent, novel, and significant changes to institutions, behaviors, values, and/or technology in anticipation of climate change and its impacts.[1,8,10,11]
Adaptive capacity	The ability of systems, institutions, humans, and other organisms to adjust to potential damage, to take advantage of opportunities, or to respond to consequences.[7]
Adaptive management	A process of iteratively planning, implementing, and modifying strategies for managing resources in the face of uncertainty and change. Adaptive management involves adjusting management approaches in response to observations of their effect on, and changes in, the system brought on by resulting feedback effects and other variables.[7]
Aeroallergens	Various airborne substances, such as pollen or spores, that can cause an allergic response.[5]
Aerosols (atmospheric)	A suspension of airborne solid or liquid particles, with typical particle size in the range of a few nanometers to several tens of micrometers. Aerosols have both natural and human-caused sources. Overall, they tend to produce cooling by scattering incoming radiation and by affecting cloud cover, although some aerosols can cause warming directly by absorbing radiation and indirectly through their interactions with clouds.[2,6] Related term: Particulate matter.
Afforestation	The process of establishing trees on land that has lacked forest cover for a very long time or land that has never been forested.[2] Related terms: Deforestation, Reforestation.
Agricultural intensification	The process of increasing the use of capital, labor, and inputs (e.g., fertilizers, pesticides, machinery) relative to land area to increase agriculture productivity.[12]
Agrivoltaics	The use of land for both agriculture and solar photovoltaic energy generation. Agrivoltaics is also sometimes referred to as agrisolar, dual-use solar, or low-impact solar. Solar grazing is a variation where livestock graze in and around solar panels.[13]

Term	Definition
Agroecology	The science and practice of applying ecological concepts, principles, and knowledge to the study, design, and management of sustainable agricultural ecosystems. It includes the roles of human beings as a central organism by way of social and economic processes in farming systems. Agroecology examines the roles and interactions among all relevant biophysical, technical, and socioeconomic components of farming systems and their surrounding landscapes.[12] For NCA5, agroecology considers farming practices and management approaches that are developed through a systems science lens, taking into account local conditions and history. Agroecology might include subsistence and organic farming but might also include prudent use of resources through technological interventions (Ch. 11).[1]
Agroforestry	Collective name for land-use systems and technologies where woody perennials (trees, shrubs, palms, bamboos, etc.) are deliberately used on the same land-management units as agricultural crops and/or animals in some form of spatial arrangement or temporal sequence. In agroforestry systems, there are both ecological and economic interactions between the different components. Agroforestry can also be defined as a dynamic, ecologically based, natural resource management system that, through the integration of trees on farms and in the agricultural landscape, diversifies and sustains production to increase social, economic, and environmental benefits for land users.[7]
Air pollution	Degradation of air quality with negative effects on human health or the natural or built environment due to the introduction, by natural processes or human activity, into the atmosphere of substances that have a direct (primary pollutants) or indirect (secondary pollutants) harmful effect.[6] Related terms: Ozone, Particulate matter, Carbon monoxide, Volatile organic compounds.
Albedo	The fraction of solar radiation reflected by a surface or object, often expressed as a percentage. Snow-covered surfaces have a high albedo (highly reflective). Soil albedos range from high to low, and vegetation-covered surfaces and the ocean have a low albedo (low reflectivity). Earth's planetary albedo varies mainly through changes in cloudiness, snow, ice, leaf area, and land cover.[2]
Altimetry	A technique for measuring the height of Earth's surface with respect to the center of Earth's mass within a defined terrestrial reference frame.[3]
Anthropogenic	Caused or influenced by humans; human-induced.[2]
Anthropogenic emissions	Emissions of greenhouse gases (GHGs), precursors of GHGs, and aerosols caused by human activities. These activities include the burning of fossil fuels, deforestation, land-use and land-cover change, livestock production, fertilization, waste management, and industrial processes.[8] [This definition is in reference to human-caused emissions that drive changes in radiative forcing; for information on other emissions, see Air pollution.] Related terms: Air pollution, Emissions.
Aquaculture	The production of aquatic organisms under controlled conditions throughout part or all their life cycle.[14] Related term: Mariculture.
Aquifer	A layer of saturated geologic materials that could yield water to springs or wells.[15]
Aridification	Aridification is a transition of the climate and hydrology of a region toward drier conditions.[16]
Assisted migration (ecological)	Human-assisted movement of populations or species to a new location within the historical range, expansion of their historical range, or migration beyond locations accessible by natural dispersal to mitigate potential impacts of climate change.[17]

Term	Definition
Atlantic meridional overturning circulation (AMOC)	The main current system in the South and North Atlantic Oceans. AMOC transports warm upper-ocean water northward and cold deep-ocean water southward, as part of the global ocean circulation system.[3] Changes in the strength of AMOC can affect other components of the climate system.[6]
Atmospheric river (AR)	A long, narrow, and transient corridor of strong horizontal water vapor transport that is typically associated with a low-level jet stream ahead of the cold front of an extratropical cyclone. The water vapor in ARs is supplied by tropical and/or extratropical moisture sources. ARs frequently lead to heavy precipitation where they are forced upward, for example, by mountains or by ascent in a warm conveyor belt. Horizontal water vapor transport in the midlatitudes occurs primarily in ARs and is focused in the lower troposphere.[3]
Attribution	The process of evaluating the relative contributions of multiple causal factors to a change or event with an assessment of confidence.[8]
Biochar	Relatively stable, carbon-rich material produced by heating biomass in an oxygen-limited environment. Biochar is distinguished from charcoal by its application: biochar is used as a soil amendment with the intention to improve soil functions and to reduce greenhouse gas emissions from biomass that would otherwise decompose rapidly.[8]
Biodiversity	The variety of life, including the number of plant and animal species, other life forms, genetic types, habitats, and biomes in an ecosystem.[2]
Bioenergy	A form of renewable energy produced from plant and animal biomass.[2]
Biofuel	Fuel produced from plant or animal matter.[2]
Biogeochemical cycles	Fluxes or flows of chemical elements between Earth's different carbon reservoirs, such as from living to nonliving, from atmosphere to land or ocean, from plants to dead organic matter in soils, and from decomposition of organic matter into carbon-containing gases.[2]
Biomass	The mass of living organisms or the material derived from organisms.[2]
Biosphere	Parts of Earth's surface in which living organisms reside.[2]
Black carbon	Black carbon is a solid form of mostly pure carbon that absorbs solar radiation (light) at all wavelengths. Black carbon is the most effective form of particulate matter, by mass, at absorbing solar energy and is produced by incomplete combustion of carbon-based fuels.[18]
Bleaching, coral	Loss of coral pigmentation through the loss of intracellular symbiotic algae (known as zooxanthellae) and/or loss of their pigments.[6]
Blocking (atmospheric)	Associated with persistent, slow-moving high-pressure systems that obstruct the prevailing westerly winds in the middle and high latitudes and the normal eastward progress of extratropical transient storm systems. It is an important component of intra-seasonal climate variability in the extratropics and can cause long-lived weather conditions such as cold spells in winter and heatwaves in summer.[3]
Blue carbon	Carbon captured and stored by marine and coastal ecosystems such as mangroves, coastal wetlands, and seagrasses (Focus on Blue Carbon).[1]
Boreal (zone)	A biogeographical zone or region characterized by a northern type of fauna or flora. The zone has a definite winter with snow and a short, generally hot summer. It includes a large part of North America between the Arctic zone and about 40°N, extending to 35°N into the interior.[15]

Term	Definition
Built environment	The human-made or modified landscapes, structures, and infrastructure facilities that provide spaces for people to live, work, and recreate (Ch. 12).[1,19]
Buyout	A type of property acquisition program in which an entity, usually a government, purchases properties in high-risk areas with an intent to remove structures and create open space.[20]
Carbon capture and storage (CCS)	The process of capturing carbon dioxide and injecting it into geological formations underground or in the deep ocean for long-term storage.[2] Related term: Carbon sequestration.
Carbon cycle	The series of processes by which carbon compounds flow among reservoirs in the environment, such as the incorporation of carbon dioxide into living tissue by photosynthesis and its return to the atmosphere through respiration, the decay of dead organisms, and the burning of fossil fuels. In the carbon cycle, carbon flow or output from one reservoir transfers carbon to other reservoir(s).[2]
Carbon dioxide (CO_2)	A naturally occurring gas, as well as a by-product of burning fossil fuels from fossil carbon deposits, burning biomass, land-use changes, and industrial processes (e.g., cement production). CO_2 is the principal anthropogenic greenhouse gas that affects Earth's radiative balance. As the reference gas against which the radiative forcing of other greenhouse gases are measured, it has a global warming potential of 1.[2] Related terms: Global warming potential, carbon dioxide equivalent.
Carbon dioxide equivalent (CO_2-eq)	The amount of carbon dioxide emissions that would produce the same effect as another greenhouse gas (e.g., methane, nitrous oxide) on the radiative balance of Earth's climate system over a specified time horizon. CO_2-eq emissions are commonly used to compare emissions of different greenhouse gases but should not be taken to imply that these emissions have an equivalent effect across all measures of climate change.[2,8] Related terms: Carbon dioxide, Global warming potential.
Carbon dioxide removal (CDR)	A set of techniques that aim to remove and/or sequester carbon dioxide (CO_2) directly from the atmosphere by either increasing natural carbon sinks or using chemical engineering to remove the CO_2.[3]
Carbon flux	The direction and rate of transfer, or flows, of carbon between pools of carbon.[2] Related terms: Carbon cycle, Carbon sink, Carbon source.
Carbon intensity / Emissions intensity	A measure of the greenhouse gas or carbon dioxide emissions or removals per unit of activity or other defined variable, such as GDP, output energy use, or transport. For example, emissions intensity of energy generation sources is defined as the amount of greenhouse gases emitted per unit of energy produced (Ch. 30).[1,8]
Carbon monoxide (CO)	A colorless, odorless, poisonous gas produced by incomplete combustion. CO is oxidized to carbon dioxide and plays a part in local and regional air quality.[5,15]
Carbon sequestration	The storage of carbon through natural, deliberate, or technological processes in which carbon dioxide is diverted from emissions sources or removed from the atmosphere and stored biologically in the ocean and terrestrial environments (e.g., vegetation, soils, and sediment), underground, or in geological formations.[2]
Carbon sink	Any process, activity, or mechanism that removes carbon from the atmosphere. A carbon sink may also refer to a physical location, defined area, or geological or biological element of Earth's system (e.g., the ocean, a country, biomass) that stores acquired carbon from the atmosphere for a specified period of time.[1,2,3] Related terms: Carbon cycle, Carbon flux, Carbon source.

Term	Definition
Carbon source	Any process, activity, or mechanism that releases carbon into the atmosphere. A carbon source may also refer to a physical location, defined area, or geological or biological element (e.g., the ocean, a country, biomass) from which carbon is released to the atmosphere, either through natural or technological processes.[1,2,3] Related terms: Carbon cycle, Carbon flux, Carbon sink.
Cascading impact	Cascading impacts from extreme climate and weather occur when an extreme hazard (or cascading hazards) generates a sequence of secondary events (i.e., cascading events) in natural and human systems that result in physical, natural, social, or economic disruption (i.e., cascading effects), whereby the resulting impact is significantly larger than the initial impact. Cascading impacts are complex and multidimensional and are associated more with the magnitude of vulnerability than with the magnitude of the hazard.[7] Related term: Compound event.
Climate	Climate, in a narrow sense, is usually defined as the average weather or, more rigorously, as the statistical description in terms of the average and variability of defining factors over a period of time ranging from months to thousands or millions of years. The classical period for averaging these variables is 30 years, as defined by the World Meteorological Organization. The relevant quantities are most often surface variables such as temperature, precipitation, and wind. Climate, in a wider sense, is the state, including a statistical description, of the climate system.[2] Related term: Weather.
Climate change	Changes in average weather conditions that persist over multiple decades or longer. Climate change encompasses both increases and decreases in temperature, as well as shifts in precipitation, changes in frequency and location of severe weather events, and changes to other features of the climate system.[2] Related term: Global warming.
Climate feedback	An interaction in which a perturbation in one climate quantity causes a change in a second, and the change in the second quantity ultimately leads to an additional change in the first. A negative feedback is one in which the initial perturbation is weakened by the changes it causes; a positive feedback is one in which the initial perturbation is enhanced. The initial perturbation can either be externally forced or arise as part of internal variability.[6]
Climate model	A numerical representation of the climate system based on the physical, chemical, and biological properties of its components, their interactions, and feedback processes and accounting for some of its known properties. The climate system can be represented by models of varying complexity; that is, for any one component or combination of components, a spectrum or hierarchy of models can be identified, differing in such aspects as the number of spatial dimensions; the extent to which physical, chemical, or biological processes are explicitly represented; or the level at which empirical parameterizations are involved. Climate models are applied as a research tool to study and simulate long-term climate projections (decadal or longer) and operationally used to create shorter climate predictions (seasonal, annual, interannual).[1,2] Related term: Earth system model.
Climate projection	The simulated response of the climate system to a scenario of future emissions or concentrations of greenhouse gases and aerosols, generally derived using climate models. Climate projections depend on the emissions, concentration, or radiative forcing scenario used, which, in turn, is based on assumptions concerning, for example, future socioeconomic and technological developments that may or may not be realized.[2] Related terms: Climate, Climate model.
Climate sensitivity	The change in the surface temperature in response to a change in the atmospheric carbon dioxide concentration or other radiative forcing.[8]
Climate services	Climate services are scientifically based usable information and products that assist in decision-making and actions relevant to climate change risks, impacts, and responses. Climate services include appropriate engagement from users and providers, have effective access mechanisms, and respond to user needs.[1,6,21]

Term	Definition
Climate-smart agriculture (CSA)	An agricultural approach that helps guide actions needed to transform and reorient agricultural systems to effectively support development and ensure food security in a changing climate. CSA addresses three main objectives: sustainably increasing agricultural productivity and incomes, adapting and building resilience to climate change, and reducing and/or removing greenhouse gas emissions where possible.[7]
Climate variability	Deviations of climate variables from a given average state, including the occurrence of extremes, at all spatial and temporal scales beyond that of individual weather events. Variability may be intrinsic, due to fluctuations of processes internal to the climate system (i.e., internal variability), or extrinsic, due to variations in natural or anthropogenic external forcing (i.e., forced variability).[8] Related term: Natural variability, climate.
Coastal zone	The area extending from the ocean inland across the region directly influenced by marine processes.[22] Related term: Exclusive economic zone.
Co-benefits	The positive effects that a policy or measure aimed at one objective might have on other objectives, irrespective of the net effect on overall social welfare. Co-benefits are often subject to uncertainty and depend on local circumstances and implementation practices, among other factors. Co-benefits are also referred to as ancillary benefits.[2]
Colonialism	A form of domination in which at least one society exerts power to exploit one or more other societies in order to gain some set of goods it perceives as valuable to the fulfillment of its economic, social, and cultural development.[1,23] **Settler Colonialism:** A type of domination in which a colonizing society seeks to obtain valuable goods by permanently inhabiting the territories that one or more other societies (e.g., Indigenous Peoples) already inhabit. Many settler colonial processes involve attempts by the colonizing society to erase the presence and history of the Indigenous Peoples.[1,23]
Community health	Community health encompasses approaches to promote health, well-being, and equity at the population level by addressing social, behavioral, environmental, economic, medical, and spiritual determinants of health.[24] Related terms: Health system / Healthcare system, Well-being.
Community science / Citizen science	Also known as participatory science, a participation by the public in advancing scientific knowledge by formulating research questions, collecting data, and interpreting results.[25]
Compound event	An event that consists of two or more extreme events occurring simultaneously or successively, combinations of extreme events with underlying conditions that amplify the impact of the events, or combinations of events that are not themselves extremes but lead to an extreme event or impact when combined. The contributing events can be of similar or different types.[3]
Contaminant	Any physical, chemical, biological, or radiological substance or matter found in any medium where it does not belong, particularly at concentrations that may pose a threat to human health or the environment.[5]
Continental shelf	The submerged margins of the continental plates, operationally defined as regions with water depths shallower than 656 feet (200 m).[2]

Term	Definition
Coproduction (of knowledge)	The integration of different knowledge systems and methodologies to systematically understand phenomena, systems, and processes.[26]
Coupled Model Intercomparison Project (CMIP)	A climate modeling activity from the World Climate Research Programme, which coordinates and archives climate model simulations based on shared model inputs by modeling groups from around the world. The CMIP Phase 3 (CMIP3) multimodel dataset includes projections using Intergovernmental Panel on Climate Change Special Report on Emissions Scenarios (SRES). The CMIP Phase 5 (CMIP5) dataset includes projections using the Representative Concentration Pathways (RCPs). The CMIP Phase 6 (CMIP6) involves a suite of common model experiments as well as an ensemble of CMIP-endorsed Model Intercomparison Projects (MIPs).[8] Related terms: Representative Concentrated Pathways, Shared Socioeconomic Pathways.
Cryosphere	All regions on and beneath the surface of the Earth and ocean where water is in solid form, including sea ice, lake ice, river ice, snow cover, glaciers, ice sheets, and frozen ground (e.g., permafrost).[2]
Cultural burning	The purposeful use of fire by a cultural group (e.g., family unit, Tribe, clan/moiety, society) for a variety of purposes and outcomes. Also called Indigenous prescribed burning.[27] Related terms: Prescribed fire, Wildfire.
Debris flow	Fast-moving landslides that generally occur during periods of intense rainfall or rapid snowmelt and usually start on hillsides or mountains. They can travel at speeds up to and exceeding 35 mph and can carry large items such as boulders, trees, and cars. Areas recently burned by a high-severity wildfire are especially susceptible to debris flows, including the areas downslope and outside of the burned area.[28] Related term: Landslide.
Decarbonization	Human actions to reduce carbon dioxide emissions from human activities.[7]
Deforestation	The process of removing or clearing trees from forested land with lasting conversion of that land to non-forest.[2] Related terms: Afforestation, Reforestation.
Degree days, cooling (CDD) / Degree days, heating (HDD)	A measure of the departure of the average daily temperature from a given standard: one degree day for each degree of departure above or below the standard for one day. Degree days can be accumulated over a "season" such that the total can be used as an index of the effect of past temperature on some quantity, such as plant growth, fuel consumption, or power output. CDDs are used to estimate energy requirements when the average daily temperature is higher than a given standard, while HDDs are used when the average daily temperature is lower than the standard. For example, if a standard/threshold of 65°F is used and a location has an average daily temperature of 75°F, then there were 10 CDDs for that day.[15,29]
Deoxygenation (aquatic)	See Hypoxia.
Detection (climate)	Detection (of change) is the process of demonstrating that climate or a system affected by climate has changed in some defined statistical sense, without providing a reason for that change. An identified change is detected in observations if its likelihood of occurrence by chance due to internal variability alone is determined to be small, for example, less than 10%.[6]
Disadvantaged community	See Overburdened community.

Term	Definition
Disaster risk management	Processes for designing, implementing, and evaluating strategies, policies, and measures to improve the understanding of current and future disaster risk, foster disaster risk reduction and transfer, and promote continuous improvement in disaster preparedness, prevention and protection, and response and recovery practices, with the explicit purpose of increasing human security, well-being, quality of life, and sustainable development.[7]
Discount rate (economics)	Discounting is a mathematical operation that uses a discount rate to make monetary (or other) amounts received or expended at different times (years) comparable across time. If the discount rate is positive, future values are given less weight than those today. The choice of discount rate(s) is debated as it is a judgment based on hidden and/or explicit values.[7]
Discrimination	The differential treatment of an individual or group of people on the basis of, for example, their race, color, national origin, religion, sex (including pregnancy and gender identity), age, marital and parental status, disability, sexual orientation, or genetic information.[30]
Dissolved oxygen	A measure of how much oxygen is dissolved in the water. Dissolved oxygen in surface water is used by all forms of aquatic life; therefore, this constituent typically is measured to assess the "health" of lakes and streams.[31] Related term: Hypoxia.
Disturbance regime (ecological)	The temporal and spatial characteristics of a disturbance agent and the impact of that agent on the landscape. More specifically, the cumulative effects of multiple disturbance events over space and time.[32]
Domoic acid (poisoning)	A harmful algal bloom toxin, domoic acid is a potent neurotoxin naturally produced by several species of the algal diatom genus *Pseudo-nitzschia*. Domoic acid usually transfers to higher-trophic-level animals via filter feeding bivalves or fish, exposing many vertebrate species including marine mammals, birds, and even humans. The clinical signs of acute domoic acid toxicity, well defined as amnesic shellfish poisoning, results in severe illness and sometimes death.[33]
Downscaling	A method that derives local- to regional-scale information from larger-scale models or data analyses. Two main methods exist: dynamical downscaling and empirical/statistical downscaling. The dynamical method uses the output of regional climate models, global models with variable spatial resolution, or high-resolution global models. The empirical/statistical methods are based on observations and develop statistical relationships that link the large-scale atmospheric variables with local/regional climate variables. In all cases, the quality of the driving model remains an important limitation on quality of the downscaled information. The two methods can be combined, for example, applying empirical/statistical downscaling to the output of a regional climate model consisting of a dynamical downscaling of a global climate model.[6] Related term: Climate model.

Term	Definition
Drought	An exceptional period of water shortage for existing ecosystems and the human population (due to low rainfall, high temperature and/or wind).[34] **Agricultural drought:** A period with abnormal soil moisture deficit that impinges on crop production, which results from a combined shortage of precipitation and excess evapotranspiration, generally during the growing season.[6,34,35] **Ecological drought:** Depending on the affected biome, an episodic deficit in water availability that drives ecosystems beyond thresholds of vulnerability, impacts ecosystem services, and triggers feedbacks in natural and/or human systems.[34] **Flash drought:** The rapid onset or intensification of drought. It is set in motion by lower-than-normal rates of precipitation, usually accompanied by abnormally high temperatures, winds, and incoming solar radiation.[6,34] **Hydrological drought:** A period with large runoff and water deficits in rivers, lakes, and reservoirs.[6,34] **Megadrought:** A very lengthy and pervasive drought, lasting much longer than normal, usually a decade or more.[6,34] **Meteorological drought:** A period with an abnormal precipitation deficit.[6,34]
Earth system	Earth functions as a system of interdependent parts. These parts include the physical, chemical, and biological processes that all interact to shape our planet and the organisms on it.[36] Related term: Earth system model.
Earth system model (ESM)	A coupled atmosphere–ocean general circulation model in which a representation of the carbon cycle is included, allowing for interactive calculation of atmospheric carbon dioxide or compatible emissions. Additional components (e.g., atmospheric chemistry, ice sheets, dynamic vegetation, nitrogen cycle, and urban or crop models) may be included.[6] Related term: Climate model.
Eco-anxiety	Also known as climate anxiety, a chronic fear of environmental doom.[37]
Ecosystem	A functional unit consisting of living organisms, their nonliving environment, and the interactions within and between them. The components included in a given ecosystem and its spatial boundaries depend on the purpose for which the ecosystem is defined. In some cases, ecosystem boundaries are relatively sharp, while in others they are diffuse, and they can change over time. Ecosystems are nested within other ecosystems, and their scale can range from very small to the entire biosphere. In the current era, most ecosystems either contain people as key organisms, or they are influenced by the effects of human activities in their environment.[2] Related term: Ecosystem services.
Ecosystem-based adaptation	The use of ecosystem management activities to increase the resilience and reduce the vulnerability of people and ecosystems to climate change.[7] Related term: Adaptation, climate.
Ecosystem services	Ecological processes or functions that have monetary or nonmonetary value to individuals or society at large. These are frequently classified as supporting services such as productivity or biodiversity maintenance, provisioning services such as food or fiber, regulating services such as climate regulation or carbon sequestration, and cultural services such as tourism or spiritual and aesthetic appreciation.[7] Related term: Ecosystem.

Term	Definition
El Niño–Southern Oscillation (ENSO)	A natural interaction between surface air pressure and surface water temperature in the tropical Pacific Ocean. ENSO has two phases: the warm oceanic phase, El Niño, accompanies high surface air pressure in the western Pacific, while the cold phase, La Niña, accompanies low surface air pressure in the western Pacific. Each phase generally lasts 6 to 18 months. ENSO events occur irregularly, about every 3 to 7 years. The extremes of this climate oscillation cause extreme events (such as floods and droughts) in many regions of the world.[2]
Emissions	The release of climate-altering gases and aerosols into the atmosphere from human and natural sources.[5] [This definition is in reference to greenhouse gas emissions. For information on other emissions, see Air pollution.] Related terms: Air pollution, Anthropogenic emissions.
Emissions scenarios	Quantitative illustrations of how the release of different amounts of climate-altering gases and aerosols into the atmosphere from human and natural sources will produce different future climate conditions. Scenarios are developed using a wide range of assumptions about population growth, economic and technological development, and other factors.[5] Related term: Scenario.
Endemic (disease)	The constant or usual presence of a disease or infectious agent within a geographic area or population.[5]
Energy end use	Energy used for services such as transportation, cooking, indoor thermal comfort, refrigeration, and illumination.[2]
Energy supply	The processes for extracting energy resources and converting them into more desirable and suitable forms of secondary energy and for delivering energy to places where demand exists.[2]
Energy systems	Comprises all components related to the production, conversion, delivery, and use of energy.[7]
Ensemble (modeling)	A collection of comparable datasets that reflect variations within the bounds of one or more sources of uncertainty and that, when averaged, can provide a more robust estimate of underlying model behavior. Ensemble techniques are used by the observational, reanalysis, and modeling communities.[6]
Environmental injustice	Environmental actions, behaviors, laws, and policies that have not been fair, that have limited meaningful involvement in environmental decision-making, or have unjustly allocated the risks and benefits of environmental action across communities, most often based on race, color, national origin, income, and gender identity, among others.[1,38] Related terms: Environmental justice, Justice, Just transition.
Epidemiology	The study of the distribution and determinants of health conditions, states, or events in specified populations.[5]

Term	Definition
Equity	**Climate equity:** The principle of being fair and impartial and a basis for understanding how the impacts and responses to climate change, including costs and benefits, are distributed in and by society in more or less equal ways. Often aligned with ideas of equality, fairness, and justice and applied with respect to equity in the responsibility for, and distribution of, climate impacts and policies across society, generations, and gender, and in the sense of who participates and controls the processes of decision-making.[7] **Health equity:** The attainment of the highest level of health for all people, where everyone has a fair and just opportunity to attain their optimal health regardless of race, ethnicity, disability, sexual orientation, gender identity, socioeconomic status, geography, preferred language, or other factors that affect access to care and health outcomes.[39] **Social equity:** The consistent and systematic fair, just, and impartial treatment of all individuals—including individuals who belong to underserved communities and communities of color, people who belong to communities that may face discrimination, and people who live in rural areas—who have been systematically denied a full opportunity to participate in aspects of economic, social, and civic life.[40]
Evaporative demand	Evaporative demand quantifies the potential loss of water from the surface as driven by atmospheric factors including temperature, wind speed, humidity, and cloud cover. Periods of high evaporative demand are connected to droughts and increased fire danger.[41]
Evapotranspiration	The combined processes through which water is transferred to the atmosphere from open water and ice surfaces, bare soil, and vegetation that make up the Earth's surface.[8] Related term: Transpiration.
Exclusive economic zone	An area of the ocean, generally extending 200 nautical miles (230 miles) beyond a nation's territorial sea, within which a coastal nation has jurisdiction over both living and nonliving resources.[42]
Exposure	The presence of people; livelihoods; species or ecosystems; environmental functions, services, and resources; infrastructure; or economic, social, or cultural assets in places and settings that could be adversely affected by climate change.[8] Related terms: Hazard, Risk.
Extratropical cyclone	A large-scale (on the order of 600+ miles) storm in the middle or high latitudes having low central pressure and fronts with strong horizontal gradients in temperature and humidity. A major cause of extreme wind speeds and heavy precipitation, especially in wintertime.[3]
Extreme events	A weather event that is rare at a particular place and time of year, including, for example, heatwaves, cold waves, heavy rains, periods of drought and flooding, and severe storms. Definitions of "rare" vary, but an extreme weather event would normally be as rare as or rarer than the 10% or 90% probability density function estimated from observations. By definition, the characteristics of what is called extreme weather may vary from place to place in an absolute sense.[2]
Extreme heat	Temperatures that are much hotter and/or humid than average. Because some places are hotter than others, this depends on what is considered average for a particular location at that time of year.[43] Related term: Heatwave.
Extreme precipitation	An extreme/heavy precipitation event is an event that is of very high magnitude with a very rare occurrence at a particular place. Types of extreme precipitation may vary depending on duration (hourly, daily, or multiday [e.g., 5 days]), although all of them qualitatively represent high magnitude.[6]

Term	Definition
Federally Recognized Tribes	An American Indian or Alaska Native tribal entity that is recognized as having a government-to-government relationship with the United States—with the responsibilities, powers, limitations, and obligations attached to that designation—and is eligible for funding and services from the Bureau of Indian Affairs.[44]
Fenceline community	Communities located adjacent to hazardous industrial facilities, which are disproportionately BIPOC (Black, Indigenous, and People of Color) and low-wealth communities (Ch. 15).[1] Related terms: Frontline community, Overburdened community, Vulnerable community.
Flood	The overflowing of the normal confines of a stream or other water body or the accumulation of water over areas that are not normally submerged.[6] **Flash flood:** A flood caused by heavy or excessive rainfall in a short period of time, generally less than six hours. Flash floods can occur within minutes or a few hours of excessive rainfall. They can also occur even if no rain has fallen, for instance, after a levee or dam has failed or after a sudden release of water by a debris or ice jam.[45] **High tide flooding:** Occurs when sea level rise combines with local factors to push water levels above the normal high tide mark. Changes in prevailing winds, shifts in ocean currents, and strong tidal forces (which occur during full or new moons) can all cause high tide flooding, inundating streets and other infrastructure even on sunny days.[46]
Food security	When all people at all times have both physical and economic access to enough food for an active, healthy life.[2,47] Related terms: Food sovereignty, Subsistence.
Food sovereignty	The ability for nations, Tribes, and communities to feed their own people on their own terms.[48] Related term: Subsistence.
Foodborne illness	Illness or disease caused by foods or drinks contaminated with biological or chemical toxins or pathogens, including disease-causing microbes or toxic chemicals.[5]
Forcing	A change or impact to a factor that affects Earth's climate.[2] Related term: Radiative forcing.
Fossil fuels	Carbon-based fuels from fossil hydrocarbon deposits, including coal, oil, and natural gas.[6]
Fractionated (land ownership)	As a result of the General Allotment Act of 1887, reservation land was divided up and allotted to individual Tribal members. After the death of the original allottee owner, title ownership was divided up among the heirs. As the land passed through each generation, the number of owners grew exponentially, resulting in the highly fractionated ownership of much Tribal land today.[49]
Fragmentation (habitat, land)	Occurs when a large, fairly continuous tract of vegetation is converted to other land cover or vegetation types such that only scattered fragments of the original type remain.[50] Related term: Land cover.
Frontline community	A community that includes people who are both highly exposed to climate risks (because of the places they live and the projected changes expected to occur in those places) and have fewer resources, capacity, social or economic safety nets, or political power to respond to those risks. Frontline communities are those that experience the "first and worst" consequences of climate change. These are often, but not limited to, communities of color and low-income communities.[1,9] Related terms: Overburdened community, Vulnerable community.

Term	Definition
Glacier	A perennial mass of ice, and possibly firn and snow, originating on the land surface by accumulation and compaction of snow and showing evidence of past or present flow. A glacier typically gains mass by accumulation of snow and loses mass by ablation. Land ice masses of continental size are referred to as ice sheets.[6] Related term: Ice sheet.
Global climate model (GCM)	See Climate model.
Global mean sea level (GMSL)	The average of relative sea level or of sea surface height across the ocean.[3]
Global warming	The increase in global surface temperature relative to a baseline reference period, averaging over a period sufficient to remove interannual variations (e.g., 20 or 30 years). A common choice for the baseline is 1850–1900 (the earliest period of reliable observations with sufficient geographic coverage), with more modern baselines used depending on the application.[6]
Global warming potential (GWP)	An index measuring the radiative forcing following an emission of a unit mass of a given substance, accumulated over a chosen time horizon, relative to that of the reference substance, carbon dioxide. The GWP thus represents the combined effect of the differing times these substances remain in the atmosphere and their effectiveness in causing radiative forcing.[6] Related term: Carbon dioxide equivalent.
Governance	The processes and structures that steer society and the multiplicity of actors who are involved. Institutional arrangements of governance comprise the sets of rules, norms, and shared practices that underlie decision-making.[2]
Green infrastructure	The strategically planned, interconnected set of natural and constructed ecological systems, green spaces, and other landscape features that can provide functions and services, including air and water purification, temperature management, floodwater management, and coastal defense, often with benefits for people and biodiversity. Green infrastructure includes planted and remnant native vegetation, soils, wetlands, parks, and green open spaces, as well as building and street-level design interventions that incorporate vegetation.[8] Related term: Nature-based solutions.
Greenhouse gas (GHG)	Gaseous constituents of the atmosphere, both natural and anthropogenic, that absorb and emit radiation at specific wavelengths within the spectrum of radiation emitted by Earth's surface, by the atmosphere itself, and by clouds. This property causes the greenhouse effect. Water vapor, carbon dioxide, nitrous oxide, methane, and ozone are the primary GHGs in Earth's atmosphere. Other GHGs include sulfur hexafluoride, hydrofluorocarbons, chlorofluorocarbons, and perfluorocarbons; several of these are also ozone-depleting (and are regulated under the Montreal Protocol).[6] Related term: Anthropogenic emissions.
Greenhouse gas mitigation	See Climate mitigation.
Groundwater recharge	The process by which external water is added to the zone of saturation of an aquifer, either directly into a geologic formation that traps the water or indirectly by way of another formation.[7] Related term: Aquifer.
Growing degree days	A heat index that relates the development of plants, insects, and disease organisms to environmental air temperature. Growing degree days are calculated by subtracting a base temperature from the daily average temperature, and growing degree day values less than zero are set to zero. The reference temperature (base temperature) below which development either slows or stops is species dependent. For example, the base temperature for cool-season plants (canning pea, spring wheat, etc.) is 40°F (5°C); for warm-season plants (sweet corn, green beans, etc.), 50°F (10°C); and for very-warm-season plants (cotton, okra, etc.), 60°F (15°C).[15]

Term	Definition
Harden (infrastructure)	Hardening infrastructure means making infrastructure more resilient in the face of extreme events (such as hurricanes, tornadoes, and earthquakes) and other disasters, both natural and human-made.[1,51] Related terms: Built environment, Infrastructure.
Hardiness zones (plants, agriculture)	10°F geographic bands based on the annual lowest winter temperature in a particular location, averaged over a period of years. They serve as a standard by which gardeners and growers can determine which plants are most likely to thrive at a location.[52,53]
Harmful algal bloom (HAB)	A sudden, rapid growth of algae in lakes, estuaries, and ocean waters caused by various factors including warmer surface waters, increased nutrient levels, or increased light levels. Some HABs may be toxic or harmful to humans and ecosystems.[2]
Hazard	The potential occurrence of a natural or human-induced physical event or trend that may cause loss of life, injury, or other health impacts, as well as damage and loss to property, infrastructure, livelihoods, service provision, ecosystems, and environmental resources.[7] Related terms: Impact, Risk.
Health system / Healthcare system	All organizations, people, and actions whose primary intent is to promote, restore, or maintain health. This may include infrastructure or systems of medical care services such as hospitals, clinics, home care, long-term care facilities, assisted living, physicians, health plans, and other community services.[1,54,55]
Heatwave	A period of abnormally hot weather, often defined with reference to a relative temperature threshold, lasting from two days to months. Heatwaves and warm spells have various and, in some cases, overlapping definitions.[7] Related term: Marine heatwave.
Homelessness	See Unhoused and Unsheltered.
Hydrocarbon	A compound composed of hydrogen and carbon (e.g., petroleum products and fossil fuels).[2]
Hypoxia (aquatic)	Deficiency of oxygen in water bodies, defined as oxygen concentrations less than 2 milligrams per liter. Hypoxia can be a symptom of eutrophication (nutrient overloading). Deoxygenation (the process of removing oxygen) leads to hypoxia and the expansion of oxygen minimum zones.[2] Related term: Dissolved oxygen.
Ice sheet	An ice body originating on land that covers an area of continental size, generally defined as covering >19,000 square miles (>50,000 km^2) and that has formed over thousands of years through accumulation and compaction of snow.[6] Related term: Glacier.
Impact (climate)	The consequences of realized risks on natural and human systems, where risks result from the interactions of climate-related hazards (including extreme weather/climate events), exposure, and vulnerability. Impacts generally refer to effects on lives, livelihoods, health, and well-being; ecosystems and species; economic, social, and cultural assets; services (including ecosystem services); and infrastructure.[7] Related terms: Adaptation, Exposure, Hazard, Vulnerability, Risk.
Indicator, climate	An observation or calculation that allows scientists, analysts, decision-makers, and others to track environmental trends, understand key factors that influence the environment, and identify effects on ecosystems and society.[2]

Term	Definition
Indigenous communities / Indigenous Peoples	Unless otherwise noted, this term is used in NCA5 to refer to culturally and politically self-determining groups whose right to self-determination in North America, Hawai'i, the US-Affiliated Pacific Islands, Puerto Rico, and the US Virgin Islands began before the establishment of the United States.[1]
Indigenous Knowledges	Bodies of dynamic and experiential knowledges gained over time by Indigenous Peoples, often associated with a specific place. Indigenous Knowledge includes observations, oral and written knowledge, innovations, practices, rituals, and beliefs; some Indigenous Knowledge is considered sacred and secret to a group or individuals. Indigenous Knowledge is inherently heterogeneous due to the cultural and geographic contexts from which it is derived. Also known as Native Science, Traditional Knowledges, Traditional Ecological Knowledges, or Indigenous Ways of Knowing.[1]
Industrial era	The multicentury period from the onset of large-scale industrial activity around 1750 to the present day. The reference period c. 1850–1900 is used to approximate preindustrial global average surface temperature.[6] Related term: Industrial Revolution.
Industrial Revolution	A period of rapid industrial growth with far-reaching social and economic consequences, beginning in Britain during the second half of the 18th century and spreading to Europe and later to other countries, including the United States. The invention of the steam engine was an important trigger of this development. The Industrial Revolution marks the beginning of a strong increase in the use of fossil fuels, initially coal, and hence emissions of carbon dioxide.[6] Related terms: Industrial era.
Inequity	An unfair or unjust difference in the distribution, allocation, management, or use of a resource, benefit, or burden between groups of people.[1,56,57] Related terms: Equity, Injustice, Justice.
Infrastructure	The physical structures, services, and institutions (i.e., roads, electric utilities, legal systems) needed by a community, organization, or country.[5] Related terms: Green infrastructure, Built environment.
Injustice	Occurs when some benefit to which a person is entitled is denied without good reason or when some burden is imposed unduly.[58] Related terms: Equity, Inequity, Justice.
Integrated assessment model (IAM)	Models that integrate knowledge from two or more domains into a single framework. They are one of the main tools for undertaking integrated assessments. One class of IAM used in respect to climate change mitigation may include representations of multiple sectors of the economy, such as energy, land use, and land-use change; interactions between sectors; the economy as a whole; associated greenhouse gas emissions and sinks; and reduced representations of the climate system. This class of model is used to assess linkages between economic, social and technological development, and the evolution of the climate system. Another class of IAM additionally includes representations of the costs associated with climate change impacts but includes less detailed representations of economic systems. These can be used to assess impacts and mitigation in a cost–benefit framework and have been used to estimate the social cost of carbon.[6,8]
Internal (climate) variability	See Climate variability.
Inundation (hydrology)	The total water level that occurs on normally dry ground as a result of flooding. Along the coast, there are a few common sources of inundation, including abnormally high tides, storm surge, persistent onshore winds, and waves. In rivers and tidal estuaries, runoff from excessive rainfall can provide another source of inundation.[59]
Invasive species	A species that is not native to a specific location or nearby, lacks natural controls, and tends to rapidly increase in abundance, displacing native species. Invasive species may also damage the human economy or human health.[7]

Term	Definition
Irreversible (climate changes)	Changes in components of the climate system that either cannot be reversed or can only be reversed on timescales much longer than the timescale of interest.[3]
Just transition	A set of principles, processes and practices that aim to ensure that no people, workers, places, sectors, countries, or regions are left behind in the transition from a high-carbon to a low-carbon economy. It stresses the need for targeted and proactive measures from governments, agencies, and authorities to ensure that any negative social, environmental, or economic impacts of economy-wide transitions are minimized, while benefits are maximized for those disproportionately affected. Key principles of just transitions include respect and dignity for vulnerable groups, fairness in energy access and use, social dialogue and democratic consultation with relevant stakeholders, the creation of decent jobs, social protection, and rights at work. Just transitions could include fairness in energy, land use, and climate planning and decision-making processes; economic diversification based on low-carbon investments; realistic training/retraining programs that lead to decent work; gender-specific policies that promote equitable outcomes; the fostering of international cooperation and coordinated multilateral actions; and the eradication of poverty. Lastly, just transitions may embody the redressing of past harms and perceived injustices.[8] Related term: Climate justice.
Justice	The moral or legal principles of fairness and equity in the way people are treated, often based on the ethics and values of society.[7] Related term: Equity. **Climate justice:** Justice that links development and human rights to achieve a human-centered approach to addressing climate change, safeguarding the rights of the most vulnerable people, and sharing the burdens and benefits of climate change and its impacts equitably and fairly.[7] Related term: Just transition. **Distributional justice:** Allocating resources and opportunities, including access to information, so that no single group or set of individuals receives disproportionate benefits or burdens (Chs. 1, 20).[1] **Environmental justice:** The just treatment and meaningful involvement of all people regardless of income, race, color, national origin, Tribal affiliation, or disability with respect to the development, implementation, and enforcement of environmental decision-making, laws, regulations, policies, and other related activities.[1,2,60] Related term: Environmental injustice. **Procedural justice:** Ensuring that the people interested in and affected by outcomes of decision-making processes are fairly and meaningfully engaged and included (Chs. 1, 20).[1] **Recognitional justice:** Acknowledging that certain people have borne disparate burdens related to current and historical social injustices and thus may have different needs (Chs. 1, 20).[1] **Social justice:** Just or fair relations within society that seek to address the distribution of wealth, access to resources, opportunity, and support according to principles of justice and fairness.[7]
La Niña	See El Niño–Southern Oscillation.
Land cover	The physical characteristics of the land surface such as crops, trees, or concrete.[2] Related term: Land use.
Land use	Describes the human use of land. It represents the economic and cultural activities (e.g., agricultural, residential, industrial, mining, and recreational uses) that are practiced at a given place. Land use differs from land cover in that some uses are not always physically obvious.[61] Related term: Land cover.
Landslide	The movement of a mass of rock, debris, or earth down a slope.[62] Related term: Debris flow.

Term	Definition
Leakage	Can refer to leakage of methane or other gases during drilling and storage and during transfers through pipelines. Leakage also can refer to the situation in which a carbon sequestration activity (e.g., tree planting or avoided deforestation) on one piece of land inadvertently, directly, or indirectly triggers an activity that in whole or in part counteracts the carbon effects of the initial activity.[2]
Maladaptation (climate)	Occurs when actions are taken that may lead to increased risk of adverse climate-related outcomes, including via increased greenhouse gas emissions, increased or shifted vulnerability to climate change, more inequitable outcomes, or diminished welfare, now or in the future. Most often, maladaptation is an unintended consequence.[7]
Managed retreat	See Planned relocation.
Marginalized population / Marginalized community	Community excluded from mainstream social, economic, educational, and/or cultural life. Examples of marginalized populations include, but are not limited to, groups excluded due to race, gender identity, sexual orientation, age, physical ability, language, and/or immigration status.[1,63] Related terms: Overburdened community, Underrepresented community.
Mariculture	Generally, aquaculture is the production of aquatic organisms under controlled conditions throughout part or all their life cycle. Mariculture (short for marine aquaculture) refers specifically to the culturing of oceanic species (as opposed to freshwater species).[14,64] Related term: Aquaculture.
Marine heatwave	A period during which water temperature is abnormally warm for the time of the year relative to historical temperatures, with that extreme warmth persisting for days to months. The phenomenon can manifest in any place in the ocean and at scales of up to thousands of kilometers.[8]
Meteorological	Referring to the atmosphere and its phenomena, particularly weather and weather forecasting.[5]
Methane (CH_4)	A greenhouse gas that is the major component of natural gas and is associated with all hydrocarbon fuels. Significant anthropogenic emissions of CH_4 also occur as a result of animal husbandry and paddy rice production. CH_4 is also produced naturally where organic matter decays under anaerobic conditions, such as in wetlands.[8]
Microgrid	A group of interconnected energy-consuming devices and equipment (e.g., homes, businesses, or industrial facilities) and distributed energy resources within clearly defined electrical boundaries that act as a single controllable entity with respect to the utility grid. These microgrids generally operate while connected to the utility grid but can disconnect from the conventional utility grid and operate autonomously to meet anticipated or potential utility outages. A microgrid typically consists of a smart distribution network limited to a well-defined boundary, a load management system, distributed energy resources, and storage solutions. Distributed energy resources generate power in the form of solar panels, wind turbines, engine generators, or other power generation sources.[65]
Migration (human)	Movement of a person or a group of persons either across an international border or within a nation. It is a population movement encompassing any kind of movement of people, whatever its length, composition, and causes; it includes migration of refugees, displaced persons, economic migrants, and persons moving for other purposes, including family reunification.[7]

Term	Definition
Mitigation	**Climate mitigation:** Measures to reduce the amount and rate of future climate change by reducing emissions of heat-trapping gases or removing carbon dioxide from the atmosphere.[2] **Hazard mitigation:** Any sustained action taken to reduce or eliminate the long-term risk to human life and property from hazards.[66]
Monsoon	A shift in winds that often causes a very rainy season or a very dry season. Although monsoons are usually associated with parts of Asia, they can happen in many tropical and subtropical regions—including several locations in the United States.[67] **North American Monsoon:** A regional-scale atmospheric circulation system with increases in summer precipitation over northwestern Mexico and the southwestern United States. The monsoonal characteristics of the region include a pronounced annual maximum of precipitation in boreal summer (June–July–August) accompanied by a surface low-pressure system and an upper-level anticyclone, although seasonal reversal of the surface winds is primarily limited to the northern Gulf of California.[6]
Morbidity	A disease or condition that reduces health and quality of life.[5]
Natural variability (climate)	Climatic fluctuations that occur without any human influence; that is, internal variability combined with the response to external natural factors such as volcanic eruptions, changes in solar activity, and, on longer timescales, orbital effects and plate tectonics.[6] Related term: Climate variability.
Nature-based solutions (NBSs)	Actions to protect, sustainably manage, and restore natural or modified ecosystems that address societal challenges effectively and adaptively, simultaneously providing human well-being and biodiversity benefits.[8] Related term: Green infrastructure.
Negative feedbacks	See Climate feedback.
Net-zero CO_2 emissions	Condition in which anthropogenic carbon dioxide (CO_2) emissions are balanced by anthropogenic CO_2 removals over a specified period.[6]
Net-zero greenhouse gas emissions	Condition in which metric-weighted anthropogenic greenhouse gas (GHG) emissions are balanced by metric-weighted anthropogenic GHG removals over a specified period. The quantification of net-zero GHG emissions depends on the GHG emissions metric chosen to compare emissions and removals of different gases, as well as the time horizon chosen for that metric.[6]
Nitrous oxide (N_2O)	The main anthropogenic source of N_2O, a greenhouse gas, is agriculture (soil and animal manure management), but important contributions also come from sewage treatment, fossil fuel combustion, and chemical industrial processes. N_2O is also produced naturally from a wide variety of biological sources in soil and water, particularly microbial action in wet tropical forests.[6]
North Atlantic Oscillation (NAO)	The leading mode of large-scale atmospheric variability in the North Atlantic basin characterized by alternating (see-saw) variations in sea level pressure or geopotential height between the Azores High in the subtropics and the Icelandic Low in the mid- to high latitudes, with some northward extension deep into the Arctic.[8]
Nutrients (ecological)	Chemicals such as nitrogen and phosphorous that plants and animals need to live and grow. At high concentrations, particularly in water, nutrients can become pollutants.[2,5] Related term: Harmful algal bloom.

Term	Definition
Overburdened community	Population or geographic location in the United States that experiences disproportionate environmental and climatic harms and risks. This disproportionality can be a result of greater vulnerability to environmental hazards, lack of opportunity for public participation, or other factors. Increased vulnerability may be attributable to an accumulation of negative or lack of positive environmental, health, economic, or social conditions within these populations or places. The term describes situations where multiple factors, including both environmental and socioeconomic stressors, may act cumulatively to affect health and the environment and contribute to persistent environmental health disparities.[9,68] Related terms: Marginalized community, Underrepresented community, Underserved community.
Ozone (O_3)	The triatomic form of oxygen and a gaseous atmospheric constituent. In the troposphere, O_3 is created both naturally and by photochemical reactions involving gases resulting from human activities. Tropospheric O_3 acts as a greenhouse gas. O_3 in the upper atmosphere protects Earth from harmful levels of ultraviolet radiation from the sun. In near-surface air, O_3 is an air pollutant with harmful effects on human health.[2,6]
Pacific Decadal Oscillation (PDO)	A long-term ocean fluctuation of the Pacific Ocean. The PDO waxes and wanes approximately every 20 to 30 years. From ocean surface topography data, together with other ocean and atmospheric data, scientists can determine whether we are in a "cool" phase or a "warm" phase. The cool phase is characterized by a cool wedge of lower-than-normal sea surface heights and ocean temperatures in the eastern equatorial Pacific and a warm horseshoe pattern of higher-than-normal sea surface heights connecting the north, west and southern Pacific. In the warm, or "positive," phase, the west Pacific Ocean becomes cool, and the wedge in the east warms.[69]
Paleoclimate	Climate during periods prior to the development of measuring instruments, including historic and geologic time, for which only proxy climate records are available.[6]
Paris Agreement	An international climate agreement adopted in 2015 with the central aim to hold global temperature rise in this century to well below 2°C above preindustrial levels and to pursue efforts to limit the temperature increase even further to 1.5°C. Under this agreement, all parties agreed to put forward emissions-reduction targets and to strengthen those efforts in the years ahead, as the agreement is assessed every five years. Each country's proposed mitigation target (the "intended nationally determined contribution") becomes an official "nationally determined contribution" when the country ratifies the agreement. Parties also agreed to adaptation efforts and finance mechanisms to support low greenhouse gas emissions and climate-resilient development.[3,70]
Particulate matter (e.g., $PM_{2.5}$ and PM_{10})	A term for atmospheric aerosols often used when discussing surface air quality. Of greatest concern for health are particles of aerodynamic diameter less than or equal to 10 micrometers, usually designated as PM_{10}, and less than or equal to 2.5 micrometers, usually designated as $PM_{2.5}$.[8] Related term: Aerosols.
Pathogen	Microorganisms (e.g., bacteria) or viruses that cause disease.[2]
Peatlands	Peatlands are wetland ecosystems where soils are dominated by peat. In peatlands, net primary production exceeds organic matter decomposition as a result of waterlogged conditions, which leads to the accumulation of peat.[7] Related term: Soil organic matter.
Permafrost	Ground (soil or rock and included ice and organic material) that remains at or below 32°F (0°C) for at least two consecutive years.[7]
pH	A dimensionless measure of the acidity of water (or any solution) given by its concentration of hydrogen ions (H+). pH is measured on a logarithmic scale where pH = −log10(H+), where the concentration of hydrogen ions is measured in units of moles per liter. Thus, a pH decrease of 1 unit corresponds to a 10-fold increase in the concentration of H+, or acidity; a decrease of units corresponds to alkalinity; and 7 is a neutral reference point.[2]

Term	Definition
Phenology	The pattern of seasonal life-cycle events in plants and animals, such as timing of blooming, hibernation, and migration.[2]
Photosynthesis	The process by which green plants, algae, and other organisms use sunlight to synthesize energy from carbon dioxide and water. Photosynthesis in plants generally involves the green pigment chlorophyll, consumes carbon dioxide and water, and generates oxygen as a by-product.[2]
Photovoltaic (PV; solar)	A system that converts sunlight directly into electricity using cells made of silicon or other conductive materials. When sunlight hits the cells, a chemical reaction occurs, resulting in the release of electricity.[71] Related term: Renewable energy.
Phytoplankton	Microscopic algae or other microorganisms that live in saltwater and freshwater environments.[2]
Planned relocation	In human systems, a form of mobility in response to direct climate impacts and/or indirect economic costs of estimated and projected climate impacts. Planned relocation, also referred to as managed retreat, is typically initiated, supervised, and/or implemented by public, private, and civic stakeholders and involves small communities and individual assets but may also involve large populations.[1,8]
Positive feedbacks	See Climate feedback.
Post-traumatic stress disorder (PTSD)	A mental health problem that can occur after war, assault, accident, natural disaster, or other trauma.[5] Related term: Trauma.
Potential evapotranspiration (PET)	The potential rate of water loss from wet soils and from plant surfaces, without any limits imposed by the water supply.[6] Related term: Evapotranspiration.
Precursor emissions (biogeochemistry)	As it refers to climate change, emissions of atmospheric compounds that are not greenhouse gases (GHGs) or aerosols but that have an effect on GHG or aerosol concentrations by taking part in physical or chemical processes regulating their production or destruction rates.[6] Related term: Air pollution.
Premature death	Death that occurs earlier than a specified age, often the average life expectancy at birth.[5]
Prescribed fire	The controlled application of fire by a team of fire experts under specified weather conditions to meet management objectives. Sometimes called a controlled burn or prescribed burn.[72,73] Related terms: Cultural burning, Wildfire.
Primary productivity	The synthesis of organic compounds by plants and microbes, on land or in the ocean, primarily by photosynthesis using light and carbon dioxide as sources of energy and carbon, respectively. It can also occur through chemosynthesis, using chemical energy, for example, in deep sea vents.[6]
Proxy (data)	Indirect measurement of climate aspects. Examples of proxy data are biological or physical records from ice cores, tree rings, and soil boreholes.[2]

Term	Definition
Radiative forcing	The change in the net (downward minus upward) radiative flux (expressed in watts per square meter) at the tropopause or at the top of atmosphere due to a change in an external driver of climate change, such as a change in the concentration of carbon dioxide or in the output of the sun. Sometimes, internal drivers are still treated as forcings even though they result from the alteration in climate, for example, aerosol or greenhouse gas changes in paleoclimates. The traditional radiative forcing is computed with all tropospheric properties held fixed at their unperturbed values and after allowing for stratospheric temperatures, if perturbed, to readjust to radiative-dynamical equilibrium. Radiative forcing is instantaneous if no change in stratospheric temperature is accounted for. The radiative forcing once rapid adjustments are accounted for is the effective radiative forcing.[3]
Redlining	A practice in which lenders avoid providing services to individuals living in communities of color because of the race or national origin of the people who live in those communities. Redlining is now prohibited by the Fair Housing Act and the Equal Credit Opportunity Act.[74]
Reforestation	The process of establishing a new forest by planting or seeding trees in an area where trees have previously been removed.[2] Related terms: Afforestation, Deforestation.
Relative humidity	The ratio of actual water vapor pressure to that at saturation with respect to liquid water or ice at the same temperature.[6]
Relative sea level	The height of the sea surface, measured with respect to the height of the land at a particular location. Relative sea level changes in response to both changes in the height of the sea surface and changes in the height of the underlying land.[3,75]
Remote sensing	The process of detecting and monitoring the physical characteristics of an area by measuring its reflected and emitted radiation at a distance (typically from satellite or aircraft).[76]
Remotely sensed data	Data obtained via remote sensing.
Renewable energy	Any form of energy that is replenished by natural processes at a rate that equals or exceeds its rate of use.[8]
Representative Concentration Pathways (RCPs)	Scenarios that include time series of emissions and concentrations of the full suite of greenhouse gases and aerosols and chemically active gases, as well as land use and land cover. The word "representative" signifies that each RCP provides only one of many possible scenarios that would lead to the specific radiative forcing characteristics. The term "pathway" emphasizes that not only the long-term concentration levels are of interest but also the trajectory taken over time to reach that outcome. RCPs usually refer to the portion of the concentration pathway extending up to 2100, for which integrated assessment models produced corresponding emissions scenarios. Extended concentration pathways describe extensions of the RCPs from 2100 to 2300 that were calculated using simple rules generated by stakeholder consultations and do not represent fully consistent scenarios.[6] Related terms: Radiative forcing, Scenario.

Term	Definition
Resilience	The ability to prepare for threats and hazards, adapt to changing conditions, and withstand and recover rapidly from adverse conditions and disruptions.[1] **Climate resilience:** The capacity of interconnected social, economic, and ecological systems to cope with a climate change event, trend, or disturbance, responding or reorganizing in ways that maintain their essential function, identity, and structure. Climate resilience is a subset of resilience against climate-induced or climate-related impacts.[1,7] Related terms: Hazard, Risk, Vulnerability. **Community resilience:** The ability of communities to withstand and recover and learn from past cumulative or compounding disasters to strengthen future response and recovery efforts. This can include, but is not limited to, physical and psychological health of the population, social and economic equity and well-being of the community, effective risk communication, integration of organizations (governmental and nongovernmental) in planning, response, and recovery.[77] **Ecological resilience:** The capacity of natural systems subject to instability to absorb disturbances without shifting to a fundamentally different ecosystem domain.[1,78,79]
Respiration (biogeochemistry)	Metabolic pathways that break down complex molecules to release chemically stored energy for maintenance, growth, and reproduction, resulting in the release of waste products such as carbon dioxide, nitrous oxide, or methane.[2]
Riparian	Riparian zones, or areas, are lands that occur along the edges of rivers, streams, lakes, and other water bodies. Examples include streambanks, riverbanks, and floodplains.[80]
Risk	Threats to life, health, and safety, the environment, economic well-being, and other things of value. Risks are evaluated in terms of how likely they are to occur (probability) and the damages that would result if they did happen (consequences).[2,5] **Transition risk:** A risk associated with uncertain impacts, including financial and economic, that could result from a transition to a net-zero emissions economy.[81] Related term: Net-zero CO_2 emissions
Risk assessment	Studies that estimate the likelihood of specific sets of events occurring and their potential positive or negative consequences.[5]
Risk perception	The psychological and emotional factors that affect people's behavior and beliefs about potential negative hazards or consequences.[5]
Riverine	Includes all wetlands and deepwater habitats contained within a channel—except for wetlands dominated by trees, shrubs, persistent emergents, emergent mosses, or lichens, or habitats with water containing ocean-derived salts of 0.5 parts per trillion or greater.[82]
Runoff	The flow of water over the surface or through the subsurface, which typically originates from the part of liquid precipitation and/or snow/ice melt that does not evaporate, transpire, or refreeze and returns to water bodies.[7]
Saltwater intrusion	Displacement of fresh surface water or groundwater by the advance of salt water due to its greater density. This usually occurs in coastal and estuarine areas due to decreasing land-based influence (e.g., from reduced runoff or groundwater recharge or from excessive water withdrawals from aquifers) or increasing marine influence (e.g., relative sea level rise).[7]

Term	Definition
Scenario	A plausible description of how the future may develop based on a coherent and internally consistent set of assumptions about key driving forces (e.g., rate of technological change, prices) and relationships. Note that scenarios are neither predictions nor forecasts but are used to provide a view of the implications of developments and actions.[6] Related terms: Representative Concentration Pathways, Shared Socioeconomic Pathways.
Sea level change	See Sea level rise.
Sea level rise	Increase to the height of sea level, both globally and locally (relative sea level change) due to a change in ocean volume as a result of a change in the mass of water in the ocean (e.g., due to melt of glaciers and ice sheets), changes in ocean volume as a result of changes in ocean water density (e.g., expansion under warmer conditions), changes in the shape of the ocean basins, and changes in Earth's gravitational and rotational fields, as well as local subsidence or uplift of the land. Sea level change refers to sea level rise or sea level fall.[7]
Sexual and gender minority (SGM)	SGM populations include, but are not limited to, individuals who identify as lesbian, gay, bisexual, asexual, transgender, Two-Spirit, queer, and/or intersex (i.e., LGBTQI+). It is an umbrella term that refers to all people who are minorities based on their sexual orientation, gender identity and/or expression, and/or sex characteristics. LGBTQI+ people are SGM: lesbian, gay, and bisexual people are minorities based on their sexual orientation; transgender people are minorities based on their gender identity and/or expression; and intersex people are minorities based on their sex characteristics.[83,84]
Shared Socioeconomic Pathways (SSPs)	A basis for emissions and socioeconomic scenarios, an SSP is one of a collection of pathways that describe alternative futures of socioeconomic development in the absence of climate policy intervention. The combination of SSP-based socioeconomic scenarios and Representative Concentration Pathway–based climate projections can provide a useful integrative frame for climate impact and policy analysis.[3] Related term: Scenario.
Sink	Any process, activity, or mechanism that removes a greenhouse gas, an aerosol, or a precursor of a greenhouse gas from the atmosphere.[8] Related terms: Carbon sequestration, Carbon sink.
Snow water equivalent (SWE)	The depth of liquid water that would result if a mass of snow melted completely.[3] Related term: Snowpack.
Snowpack	Snow that accumulates over winter and slowly melts to release water in spring and summer.[2] Related term: Snow water equivalent.
Social determinants of health	The conditions in the environments where people are born, live, learn, work, play, worship, and age that affect a wide range of health, functioning, and quality-of-life outcomes and risks. Social determinants of health can be grouped into five domains: economic stability, education access and quality, healthcare access and quality, neighborhood and built environment, and social and community context.[85]
Socioeconomic	Referring to a combination of social and economic factors, such as the education, income, and work status of individuals or communities.[5]
Soil carbon	The carbon content of soils, which can be from organic or inorganic sources. Related terms: Soil organic carbon, Soil organic matter.[1]
Soil organic carbon	The organic carbon content of soil organic matter. Soil organic matter and soil organic carbon in soil result from an imbalance between the supply of raw materials, such as plant, microbial, and animal parts and the decay of those materials by the soil microbial community and other biogeochemical processes.[2] Related term: Soil organic matter.

Term	Definition
Soil organic matter	Organic material (e.g., carbon and other elements such as nitrogen) in soils. Soil organic matter results from an imbalance between the supply of raw materials such as plant, microbial, and animal parts and the decay of those materials by the soil microbial community. Soil organic matter forms the basis of life on Earth, enabling persistence and growth of the entire biosphere and can be considered in terms of its carbon content (e.g., soil organic carbon).[2] Related term: Soil organic carbon.
Special Report on Emissions Scenarios (SRES)	A set of emissions scenarios from the Intergovernmental Panel on Climate Change Special Report on Emissions Scenarios, released in 2000, that describe a wide range of potential future socioeconomic conditions and resulting emissions.[5] Related term: Scenario.
Stakeholder	An individual or group that is directly or indirectly affected by or interested in the outcomes of decisions.[2]
Statistical downscaling	See Downscaling.
Storm surge	The temporary increase, at a particular locality, in the height of the sea due to extreme meteorological conditions (low atmospheric pressure and/or strong winds). The storm surge is defined as being the excess above the level expected from the tidal variation alone at that time and place.[2]
Stressor	A factor that negatively affects people and natural, managed, and socioeconomic systems. Multiple stressors can have compounded effects, such as when economic or market stress combines with drought to negatively impact farmers.[2]
Subsidence	Sinking of the ground because of underground material movement. Subsidence is most often caused by the removal of water, oil, natural gas, or mineral resources out of the ground by pumping, fracking, or mining activities. Subsidence can also be caused by natural events such as earthquakes, soil compaction, glacial isostatic adjustment, erosion, sinkhole formation, and the addition of water to fine soils deposited by wind.[86] Related term: Permafrost.
Subsistence	Taken broadly, refers to any human system that seeks to secure survival and flourish within particular ecosystems. In some legal and policy contexts, the term may be used more narrowly to refer to the provision of food that is a necessary part of a household's or a community's regular diet or to legal entitlements to harvesting rights in particular situations. In some contexts, subsistence means the harvest or use of naturally produced renewable resources for direct personal or family consumption, such as food, shelter, fuel, clothing, tools, or transportation, or for production of handicrafts for customary and traditional trade, barter, or sharing.[23] Related term: Food sovereignty.
Surveillance (health)	The collection, analysis, interpretation, and dissemination of health data.[5] Related term: Health system / Healthcare system.
Sustainable development	Development that meets the needs of the present without compromising the ability of future generations to meet their own needs and that balances social, economic, and environmental concerns.[7]
Thermokarst	Characteristic landforms that result from the thawing of ice-rich permafrost or the melting of massive ground ice.[2]
Threshold	The value of a parameter summarizing a system, or a process affecting a system, at which a qualitatively different system behavior emerges. Beyond this value, the system may not conform to statistical relationships that described it previously. For example, beyond a threshold level of ocean acidification, wide-scale collapse of coral ecosystems may occur.[2] Related term: Tipping point.

Term	Definition
Tipping point	The point at which a change in the climate triggers a significant environmental event, which may be permanent, such as widespread bleaching of corals or the melting of very large ice sheets.[2] Related term: Threshold.
Transpiration (biogeochemistry)	The evaporation of water through plant leaves.[2]
Trauma	An adverse physical or psychological state caused by physical injury or mental stress.[5]
Tundra	A type of biome common to extreme northern and southern latitudes where tree growth is inhibited by low temperatures and short growing seasons.[2]
Turbidity (hydrology)	A measure of the level of particles such as sediment, plankton, or organic by-products in a body of water. As the turbidity of water increases, it becomes denser and less clear due to a higher concentration of these light-blocking particles.[87]
Uncertainty (statistical)	An expression of the degree to which a quantity or process is unknown. In statistics, a term used to describe the range of possible values around a best estimate, sometimes expressed in terms of probability or likelihood. Uncertainty about the future climate arises from the complexity of the climate system and the ability of models to represent it, as well as the inability to predict the decisions that society will make. There also is uncertainty about how climate change, in combination with other stressors, will affect people and natural systems.[2]
Underrepresented community	A community that has limited or no access to resources, is not well represented or meaningly involved in decision-making, or is otherwise disenfranchised. These communities may include people who are socioeconomically disadvantaged, people with limited English proficiency, geographically isolated or educationally disenfranchised people, people of color as well as ethnic and national-origin minorities, women and children, individuals with disabilities and others with access and functional needs, and seniors.[1,88] Related term: Underserved community.
Under-resourced community	See Underserved community.
Underserved community	A community that, due to continuous systemic discrimination, under- or disinvestments, and limited access to efficient, healthy, and affordable services and infrastructure, experiences disproportionate environmental and climatic harms and risks and lacks access to adequate resources to mitigate, respond to, and recover from impacts. Increased vulnerability may be attributable to harmful environmental, health, economic, or social conditions—or to a lack of support for positive conditions—within these populations or places. The term describes situations where disproportionate vulnerability is often due to discrimination based on geography; access to authority or representation in governance; or social identities, including race, ethnicity, gender, culture, economic status, or ability.[1,89,90]
Unhoused	US Code defines a person or persons experiencing homelessness (i.e., an unhoused person or people) as an individual or family who lack(s) a fixed, regular, and adequate nighttime residence, such as those living in emergency shelters, transitional housing, or places not meant for habitation.[91] Related term: Unsheltered.
United Nations Framework Convention on Climate Change (UNFCCC)	An international environmental treaty adopted on May 9, 1992, and ratified on March 21, 1994. The objective of the UNFCCC is to stabilize greenhouse gas concentrations in the atmosphere at a level that would prevent dangerous anthropogenic interference with the climate system.[2]

Term	Definition
Unsheltered	An *unsheltered* unhoused person (i.e., a person experiencing homelessness) resides in a place not meant for human habitation, such as cars, parks, sidewalks, or abandoned buildings. A *sheltered* unhoused person resides in an emergency shelter or in transitional housing or supportive housing for unhoused persons who originally came from a place not meant for human habitation or emergency shelters.[92] Related term: Unhoused.
Urban heat island effect	The tendency for higher air temperatures to persist in urban areas because of heat absorbed and emitted by buildings and asphalt, tending to make cities warmer than the surrounding countryside.[2]
Urban infrastructure	See Infrastructure and Built environment.
Vapor pressure deficit (VPD)	The difference between how much moisture is in the air and the amount of moisture in the air at saturation (i.e., at 100% relative humidity) (Ch. 21 of NCA4).[4] Related term: Water vapor.
Vector (disease)	An organism, such as an insect, that transmits disease-causing microorganisms such as viruses or bacteria. Vector-borne diseases include, for example, malaria, Lyme disease, Zika, and chikungunya.[1,2] Related term: Zoonotic disease.
Volatile organic compounds (VOCs)	An important class of organic chemical air pollutants that evaporate readily at ambient air conditions. Other terms used to represent VOCs are hydrocarbons, reactive organic gases, and non-methane volatile organic compounds (NMVOCs). NMVOCs are major contributors—together with nitrogen oxides and carbon monoxide—to the formation of photochemical oxidants such as ozone.[6] Related terms: Precursor emissions, Air pollution.
Vulnerability (climate)	The degree to which physical, biological, and socioeconomic systems are susceptible to and unable to cope with adverse impacts of climate change.[2]
Vulnerable community	Communities of people who face disproportionate and unequal risks from projected and realized climate change impacts and who are least able to anticipate, cope with, and recover from these adverse impacts. Socioeconomic factors may include, but are not limited to, income, educational attainment, race and ethnicity, and age.[1,89] Related terms: Frontline community, Overburdened community.
Water cycle	The cycle in which water evaporates from the ocean and the land surface, is carried over the Earth in atmospheric circulation as water vapor, condenses to form clouds, precipitates over the ocean and land as rain or snow—which on land can be intercepted by trees and vegetation, potentially accumulating as snow or ice—provides runoff on the land surface, infiltrates into soils, recharges groundwater, discharges into streams, and ultimately flows into the oceans as rivers, polar glaciers, and ice sheets, from which it will eventually evaporate again. The various systems involved in the water cycle are usually referred to as hydrological systems.[6]
Water quality	Water quality can be thought of as a measure of the suitability of water for a particular use, such as for drinking water or supporting aquatic organisms and ecosystems, based on selected physical, chemical, and biological characteristics.[93,94]
Water stress	Water stress occurs when demand for water by people and ecosystems exceeds available supply.[2]
Water vapor	Water in the atmosphere in its vapor (gaseous) form. This gas absorbs and emits infrared radiation, which traps heat energy near Earth's surface.[95]
Watershed	An area of land that drains water to a particular stream, river, lake, bay, or ocean.[5]

Term	Definition
Weather	The state of the atmosphere, mainly with respect to its effects on life and human activities. As distinguished from climate, weather consists of short-term (minutes to days) variations in the atmosphere. Popularly, weather is thought of in terms of temperature, humidity, precipitation, cloudiness, visibility, and wind.[15] Related term: Climate.
Well-being (human)	A state of existence that fulfills various human needs, including material living conditions and quality of life, as well as the ability to pursue one's goals, to thrive, and to feel satisfied with one's life.[7]
Wetlands	Soils that are inundated or saturated by water at a frequency and duration sufficient to support—and that do support under normal circumstances—a prevalence of vegetation typically adapted for life in saturated conditions. Tidal wetlands are influenced by ocean tides and may be saturated with salt water or fresh water. Terrestrial wetlands are nontidal and are saturated with fresh water.[2]
Wildfire	A wildland fire originating from an unplanned ignition, such as lightning, volcanos, unauthorized and accidental human-caused fires, and prescribed fires that are declared wildfires.[96] Related terms: Wildfire intensity, Wildfire severity.
Wildfire intensity	The product of the available heat of combustion per unit of ground and the rate of spread of the fire, interpreted as the heat released per unit of time for each unit length of fire edge.[96] Related terms: Wildfire, Wildfire severity.
Wildfire severity	The effect that wildfire has on vegetation, soils, buildings, watersheds, and similar physical features of the landscape.[97] Related terms: Wildfire, Wildfire intensity.
Wildland–urban interface (WUI)	The line, area, or zone where structures and other human development meet or intermingle with undeveloped wildland or vegetation.[96]
Woody encroachment (woody plants and shrubs)	Refers to woody plants increasing in abundance or dominance in grasslands or other non-forested ecosystems.[2]
Zoonotic disease	A disease that can spread to people from other vertebrate animals. Examples of zoonotic diseases include Lyme disease, West Nile virus infection, Rocky Mountain spotted fever, and rabies.[5] Related term: Vector.

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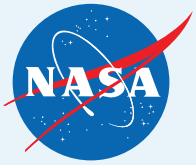















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