Key Message 22.2

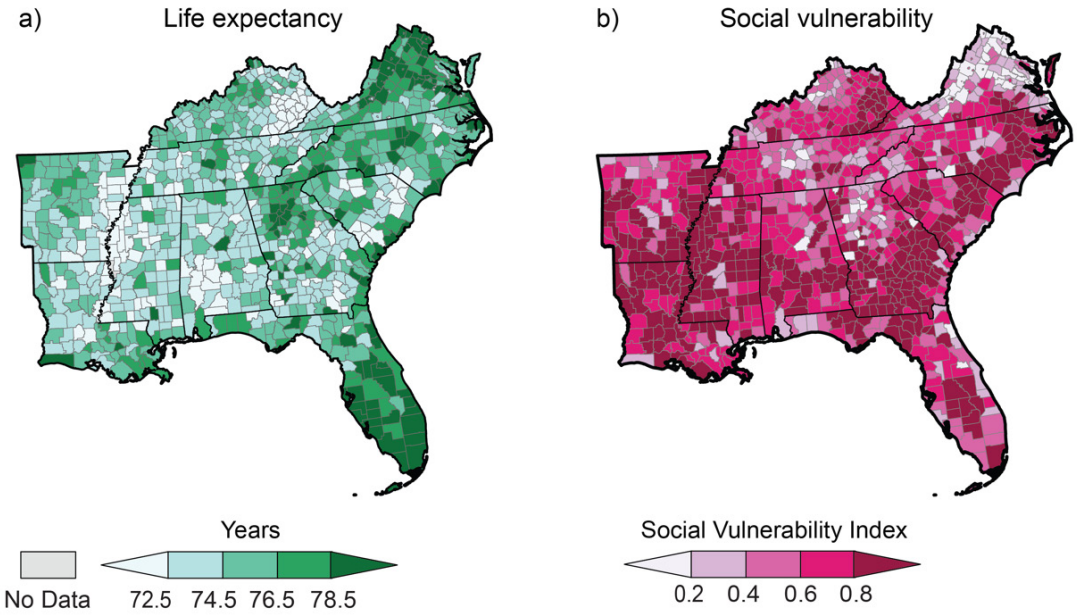
Climate Change Worsens Human Health and Widens Health Inequities

Human health and climate stressors are intimately linked in the Southeast (*very high confidence*). Community characteristics such as racial and ethnic population, chronic disease prevalence, age, and socioeconomic status can influence how climate change exacerbates, ameliorates, or introduces new health issues (*very high confidence*). Climate change is already impacting health in the region (*very likely*, *very high confidence*). There are effective strategies to address the health impacts of climate change in the Southeast that have multiple benefits across social and environmental contexts (*high confidence*).

Underlying Health Issues and History in the Southeast

Public health status is an important indicator of vulnerability to climate stressors,[190,195] and Southeasterners are consistently ranked among the unhealthiest in the Nation, with shorter life expectancies than the US average (Figure 22.8).[196] Health disparities in the Southeast are related to various social determinants of health, such as lack of access to healthcare, low socioeconomic status, and poor health behaviors (e.g., smoking and drug and alcohol abuse).[197] Sedentary lifestyles are reinforced by the quality of the surrounding built environment: the Southeast is home to 8 of the 10 least-walkable cities,[198] 15 of the 20 most dangerous cities for pedestrians,[199] and 4 of the top 10 deadliest states for cyclists in the United States.[200]

Present-Day Health Inequities



Present-day health inequities in the Southeast exacerbate climate-related risks.

Figure 22.8. (**left**) Southeastern states rank among the lowest in the Nation for life expectancy, although there is considerable variation within the region and within individual states. These patterns in life expectancy are reflected in estimates of social vulnerability (**right**)—a measure of how societal stressors like poverty, crowded housing, older populations, and lack of access to transportation may diminish a community's ability to avoid human distress and financial damages in a disaster like those made worse by climate change. Figure credits: (left) Groundwork USA, NOAA NCEI, and CISESS NC; life expectancy data from University of Wisconsin Population Health Institute, County Health Rankings & Roadmaps 2022, www.countyhealthrankings.org; (right) Science Museum of Virginia, NOAA NCEI, and CISESS NC.

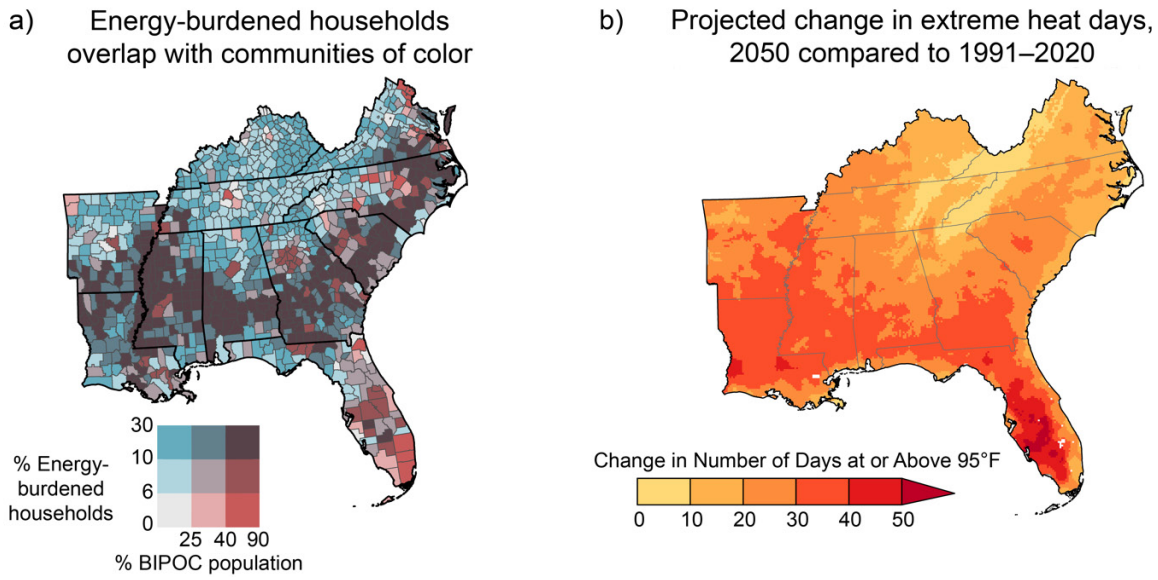
The Southeast has more Black residents than any other NCA region,[40] and health-related challenges faced by communities with majority Black populations differ from those with majority White, Hispanic, or Asian populations.[201] Communities with majority Black populations tend to have even lower life expectancies and less access to resources that promote health, such as grocery stores, safe places to exercise, and quality healthcare than whiter and wealthier populations.[202] These communities also have fewer opportunities for economic prosperity (Figure 22.12), fewer employment opportunities, limited access to quality education, and higher unemployment rates, all of which shape health outcomes.[11] Black communities in the Southeast, therefore, shoulder a disproportionate level of health risk associated with climate change.[3,12]

Keeping Cool as Temperatures Rise

Extreme heat affects everyone, but particularly at risk are pregnant people;[203,204,205] people with heart and lung conditions;[206,207] older adults and young children;[208,209] people with mental health conditions;[210,211] outdoor workers in construction, agriculture, and the service industry;[212,213] athletes;[214,215,216] and populations who lack adequate shelter or are incarcerated.[217,218]

Southeasterners rely on air-conditioning to cool living spaces, and air-conditioning demand is expected to grow across the Southeast as the climate warms.[219] However, air-conditioning prevalence varies along racial and economic lines.[220] Furthermore, the Southeast has high rates of households that experience energy insecurity.[221] While the Southeast has the lowest energy rates in the US, households there pay the country's highest energy bills.[222] High energy bills disproportionately impact rural and under-resourced residents, elderly residents on fixed incomes, and communities of color (Figure 22.9).[222] Historical *de facto* as well as *de jure* segregation policies such as redlining—the New Deal–era practice of classifying communities with significant Black, Asian, and immigrant populations as hazardous for financial investment—neighborhood housing covenants, and urban renewal have had lingering effects on frontline communities in the Southeast, resulting in their low proportion of homes that are energy efficient and affordable.[222] There is evidence that the number of blackout events (power outages) affecting more than 1,000 residents for more than one hour due to increasing energy demands and extreme weather events is increasing.[223,224,225] The Southeast has experienced many such blackout events annually and during the warm season (May–September) since 2011 (Figure 22.10).[226]

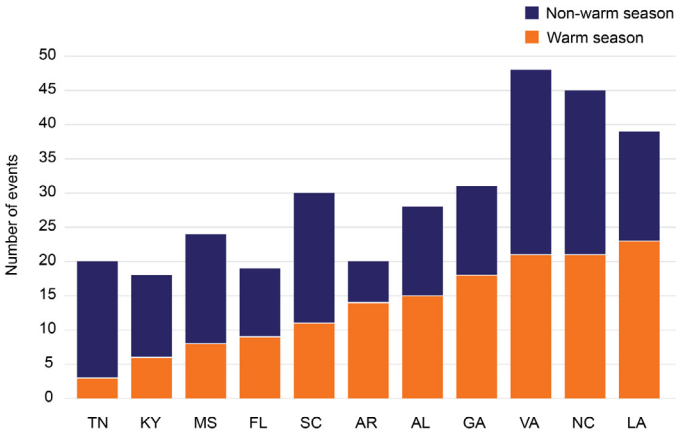
Inequitable Heat Burden and Future Heat Exposure



Projected increases in heat extremes disproportionately affect communities of color and other energy-burdened groups.

Figure 22.9. Present-day inequities will be amplified by the increased threat of extreme heat in the future. Panel (**a**) shows overlap between the percentage of the population that is BIPOC (Black, Indigenous, and People of Color) and the percentage of low- and moderate-income households with a high energy burden, or households that spend a disproportionately high amount of money on energy costs relative to their income. The dark purple areas show high overlaps between BIPOC households and high energy burden. Panel (**b**) shows the projected increase in the number of extreme heat days (maximum temperature at or above 95°F) in 2050 relative to 1991–2020 under a high scenario (SSP3-7.0). Figure credits: (a) adapted from Bryan 2020;[227] (b) NOAA NCEI and CISESS NC.

Blackouts Affecting More than 1,000 Residents for More Than 1 Hour (2011–2021)



Warm-season blackouts add to heat-related risks for residents in Southeast.

Figure 22.10. For several Southeast states, major blackout events occur most often during the warm season (May–September). Major blackouts during the warm season generally occur during heatwaves, placing people at higher risk of heat exposure and heat-related illness because they do not have access to air-conditioning. The figure shows reported major blackout events—defined as electrical grid failures affecting more than 1,000 residents for more than 1 hour—in Southeast states during 2011–2021. Data are presented as warm season (orange, May through September) and non-warm season (blue, October through April). Figure credit: Georgia Institute of Technology, Groundwork USA, CDC, NOAA NCEI, and CISESS NC.

Public cooling centers are temporary health interventions for those without adequate air-conditioned shelter on exceptionally hot days (KM 15.3). However, in some areas of the Southeast, these centers are not located within walking distance of the populations most in need.[228] Furthermore, the Southeast has the lowest public transportation access for households without a private vehicle.[229]

Heatwaves in the Southeast are happening more frequently and are occurring during a longer heat season, with some cities also showing increasing trends in their duration and intensity (Ch. 2).[3,230,231] The number of extreme warm days (above 95°F) is expected to continue increasing with every increment of global warming (Figure 22.9b; Ch. 2). Wet-bulb globe temperature (WBGT)—which measures the combined effects of temperature, humidity, wind, and sunlight on thermal comfort and which may be a better metric for the Southeast than more traditional measures of extreme heat[232,233]—has already increased due to anthropogenic climate change in parts of the region[234,235] and is expected to increase across the region throughout this century.[230,235] Additional heat stress within cities can be attributed to the urban heat island effect (Figure A4.4), whereby cities experience warmer temperatures than outlying rural areas and some neighborhoods within a city are hotter than others.[236,237] Heat island intensities across the Southeast are systematically higher in formerly redlined communities[5] and in counties with higher proportions of Black, Hispanic, and Asian residents, people with education no higher than a high school diploma, people with lower median incomes, and single-parent households.[238] However, there is a lack of consistent and appropriate thresholds used to evaluate heat risk. For example, most work-related heat illnesses across five Southeast states occurred below the heat index range designated as dangerous by the National Weather Service.[239]

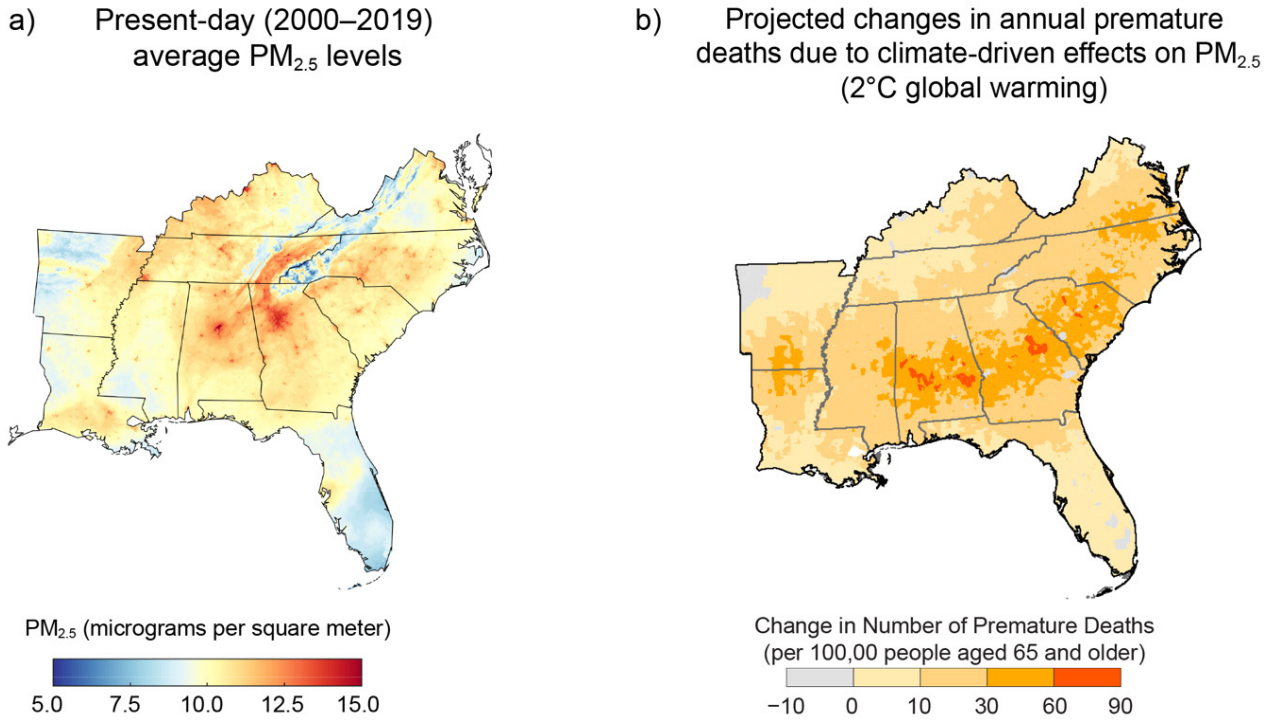
Climate change is increasing the risk of multiple dangerous weather events occurring simultaneously or in close proximity, resulting in worsened health effects (Ch. 15). An example of this is when a heatwave occurred after Hurricane Laura devastated the coast of Louisiana in 2020, resulting in at least eight deaths due to heat and an increased risk of heat-related illness, particularly for those who lost electricity and outdoor workers assisting with the recovery.[240]

In response to heat threats, Miami has institutionalized the first city heat officer to coordinate heat preparedness and response efforts to reduce impacts to the most vulnerable.

Blowing in the Wind

In the Southeast, climate change threatens Clean Air Act improvements by creating favorable conditions for increases in smog[241,242,243] and wildland fire emissions.[244,245,246] The Southeast already has significant amounts of particulate matter ($PM_{2.5}$; Figure 22.11a) as a result of anthropogenic pollutants[247] and extensive vegetation,[248] and the associated health effects are experienced disproportionately by communities of color and populations with lower socioeconomic status (Ch. 14).[249,250] Future premature deaths due to $PM_{2.5}$ in the region could be avoided through significant emissions reductions, even when considering future warming (Figure 22.11b; KM 14.3).[3,251,252] This is particularly relevant to the Southeast, which is projected to have the highest number of premature deaths due to climate-induced increases in $PM_{2.5}$ and ozone exposure.[3,251,252]

Current $PM_{2.5}$ Levels and Projected Change in Deaths Due to $PM_{2.5}$ at 2°C of Global Warming



Rising levels of air pollution from a warming climate pose profound threats to human health.

Figure 22.11. (**a**) Present-day (2000–2019) patterns of particulate matter ($PM_{2.5}$) pollution in the air are associated with excess mortality. (**b**) Potential future patterns (projected changes at 2°C of global warming relative to the 1986–2005 average) of premature deaths in people aged 65 and older due to $PM_{2.5}$ show that even when accounting for reduced particulate emissions in the future due to developments such as vehicle electrification, the Southeast is particularly sensitive to increases in $PM_{2.5}$ from increased temperature alone. (a) Adapted from van Donkelaar et al. 2019.[247] (This is an unofficial adaptation of an article that appeared in an ACS publication. ACS has not endorsed the content of this adaptation or the context of its use.) (b) Adapted from EPA 2021.[3]

In addition, airborne pollen can pose significant health risks to populations living in the southeastern United States.[253] Since 1992 in Atlanta, tree pollen concentrations have increased by approximately 4% in the spring and 10% in the fall, and weed pollen has increased by approximately 5% in the spring.[254] Some species of trees and weeds are exhibiting an earlier and longer pollen season, correlating with warmer spring temperatures.[254] Pollen increases pose significant health risks, including aggravating respiratory conditions such as asthma, which has been linked to a loss of school and work days (KM 14.4). These health risks are expected to worsen as pollen seasons shift earlier and lengthen due to climate change (KM 14.4; Figure 8.2).

Fire Danger

Wildfire risk disproportionately disrupts the lives of socioeconomically disadvantaged communities in the Southeast.[2] As more people inhabit forested areas, there is an attendant increase in wildfire risks to human health and property.[255] More hot days may also exacerbate soil moisture deficits, leading to heightened wildfire risk in the region.[244,256] Rural, mountainous portions of the Southeast are more exposed to and less equipped for mitigating wildfire.[257]

Forest managers conduct controlled, low-intensity fires, known as prescribed burns, to reduce the amount of deadwood and vegetation, thereby managing wildfire risk.[258] While the impacts of wildfires on air quality are widely recognized (KM 14.2), less is known about the impacts of prescribed burns versus wildfires on air quality.[246,259] Prescribed burns reduce the risk of wildfire damage to the environment, homes, and infrastructure, although areas with intensive prescribed burning tend to be near communities with higher social vulnerability scores, which subsequently experience more negative health outcomes from the smoke.[260,261] As conditions favorable for wildfire and unfavorable for prevention become a greater risk for southeastern communities due to a warming and drying climate,[256,262] communities may need to invest in more robust equipment and infrastructure. In 2016, wildfires in western North Carolina and eastern Tennessee highlighted the connection between exceptional drought and fire in the Appalachians.[263] Power outages and damage to PVC pipelines that supplied water to sprinkler systems led to a lack of water to combat fires, resulting in more significant damages.[264,265] That year, nearly 50% of US wildfires occurred in the Southeast, yet these fires contributed to only 29% of the total area burned that year, indicating that southeastern wildfires are smaller.[244,246,258]

Rolling Red Tides

Harmful algal blooms (HABs), also known as red tides or brown tides, occur in fresh, brackish, and salt water.[266] HABs result from the overgrowth of algae due to runoff water containing excess nutrients from agriculture and lawn maintenance, rising water temperatures, and other land-use development.[267] Since 2011, large masses of sargassum, which can fall under a HAB classification, have been increasing from Florida across the Caribbean, causing harm to coastal social–ecological systems. This problem could be intensified by rising temperatures from climate change.[268,269] HABs have significant negative impacts on human and animal health, as well as broad-reaching environmental and economic effects.[270,271,272,273]

Humans may experience various health issues from HAB exposure, such as diarrhea and headache.[273] HAB events also threaten national and local economies, as tourist areas become less desirable to visit.[271] Fisheries and aquaculture industries suffer from the loss of marine life and decreased species diversity as ecosystems are disrupted and hypoxic conditions occur,[274,275,276] and consumers are potentially exposed to seafood poisoning.[277,278] On Florida's Gulf Coast, prolonged algal events have caused a devaluation of coastal properties.[270,272]

More Than Just a Bug Bite

Temperature and precipitation changes are anticipated to shift the geographic distribution and season of certain disease-carrying mosquitoes and ticks in the Southeast (KMs 15.1, 8.2). For ticks that carry diseases such as Lyme and Rocky Mountain spotted fever, models project varying shifts in ecosystem suitability in the Southeast depending on the species, land-use changes, and host abundance.[279,280,281,282,283] Of particular concern are mosquito-borne diseases such as chikungunya, dengue, malaria, West Nile virus, and Zika virus. All have been documented in the Southeast and pose potential risks to human health.[284] Black and under-resourced neighborhoods in Chatham County, Georgia, were identified as hotspots for West Nile virus, as well as being home to communities with limited understanding of personal risk and protective measures against mosquitoes.[285,286]

The Mind–Climate Connection

The Southeast is home to 5 out of the 10 highest-ranked states for the prevalence of mental illness[287] and 8 out of the 10 lowest-ranked states for access to mental healthcare services.[288]

Climate change significantly affects mental health as a result of 1) acute disaster events such as hurricanes, floods, and wildfires (KM 15.1); 2) long-term changes such as drought[289] and heat stress;[210] and 3) existential threats of long-lasting climate change impacts that make people feel less secure in their physical environment.[290] Those who are either directly impacted by or concerned about the threat of climate change to themselves or others may experience "eco-anxiety" or "climate anxiety."[291,292]

While extreme weather events commonly occur in the Southeast, climate change has increased their frequency and magnitude (Ch. 2), causing residents to face repeated trauma and displacement at an unprecedented level, which can lead to stress and the onset of new psychiatric disorders or the worsening of preexisting mental health conditions,[293] especially among children and under-resourced and BIPOC residents.[290,294,295] The Florida Department of Health in Monroe County conducted an evaluation of its emergency shelter effectiveness in serving people with particular access and functional needs and found significant room for improvement, leading to updates to strategic planning processes and procedures related to the operation and communication of specialty emergency shelters to ensure more equitable access to shelter services.

Key Message 22.3

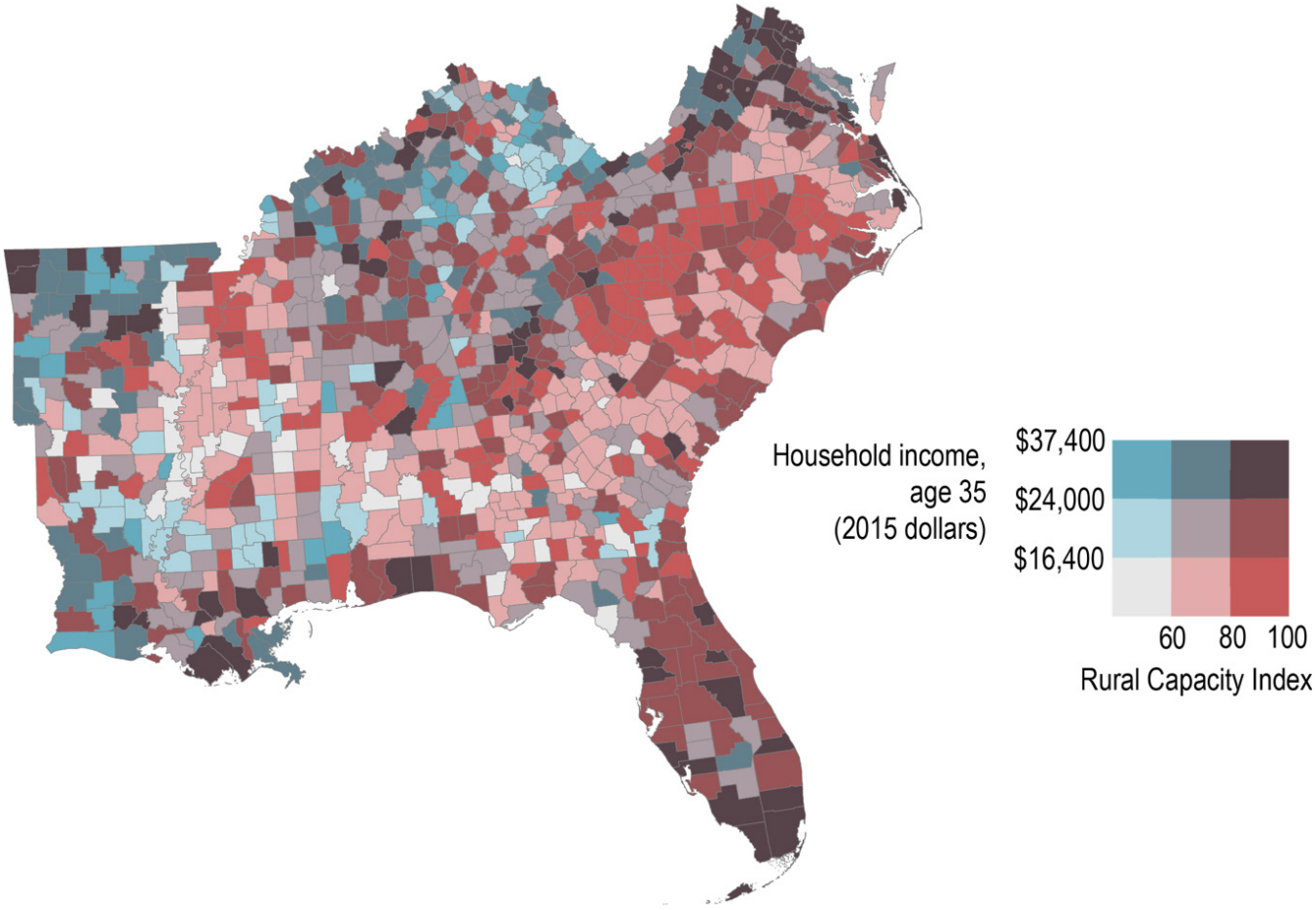
Climate Change Disproportionately Damages Southeastern Jobs, Households, and Economic Security

Over the last few decades, economic growth in the Southeast has been concentrated in and around urban centers (*high confidence*) that depend on climate-sensitive infrastructure and regional connections to thrive (*medium confidence*). Simultaneously, rural and place-based economies that rely on the region's ecosystems are particularly at risk from current and future climate changes (*very likely*, *high confidence*). Global warming is expected to worsen climate-related impacts on economic systems, labor, and regional supply chains in the Southeast, with disproportionate effects on frontline communities (*very likely*, *high confidence*). A coordinated approach that recognizes present-day inequities and the interdependencies between rural and urban communities will be necessary to secure the region's economic vitality (*very likely*, *high confidence*).

Economic Risks in the Southeast: "Less Money, More Problems"

Across the Southeast, disaster losses have increased over the last several decades, primarily due to rapid growth in hazardous areas that are driven, in part, by national, state, and local policies that incentivize development in such areas.[166,296,297] Rising disaster costs negatively impact local and regional economies, some of which are already affected by limited upward economic mobility for their population, as well as by limited administrative, institutional, and social capacity (Figure 22.12). Moreover, these multisectoral impacts are expected to worsen substantially due to climate change,[298] especially in the Southeast region (Figures 22.13, 22.14, 19.1; KM 19.1).

Household Income and Rural Capacity for Action

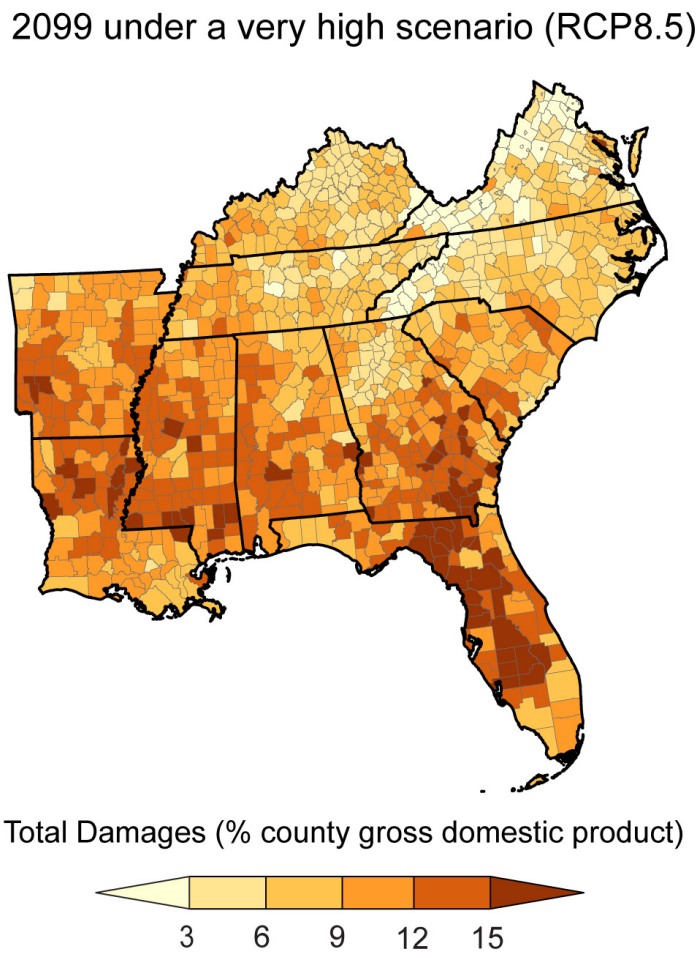


Counties where low-income households overlap with limited community capacity (shown in light gray) highlight rural climate risk challenges.

Figure 22.12. In the Southeast, children born to parents who make the lowest incomes also tend to earn low incomes as adults (blue hues), especially within frontline communities. These pockets of limited generational upward mobility may also overlap with lower scores on the Rural Capacity Index (red hues), as measured by under-resourced governance structures and limited public participation in civic processes like voting.[64] This lack of resources may leave these communities more at risk from damage due to climate change. Figure credit: EPA, Groundwork USA, NOAA NCEI, and CISESS NC.

Losses attributed to climate change are expected to increase as rapid development continues to occur in hazardous areas, particularly along coasts (Figure 22.4b),[299] while rural residents face increasing levels of isolation and economic decline (Figure 22.12).[62]

Projected Annual Economic Damages from Unmitigated Climate Change



The Southeast region faces substantial economic risks from climate change impacts.

Figure 22.13. Direct annual climate damages, as measured by the percent of county GDP, are projected to be especially large in the Southeast. The map shows damages under a very high scenario (RCP8.5) at the end of the century. Adapted from Hsiang et al. 2017.[300]

Regional Impacts of Extreme Weather Events

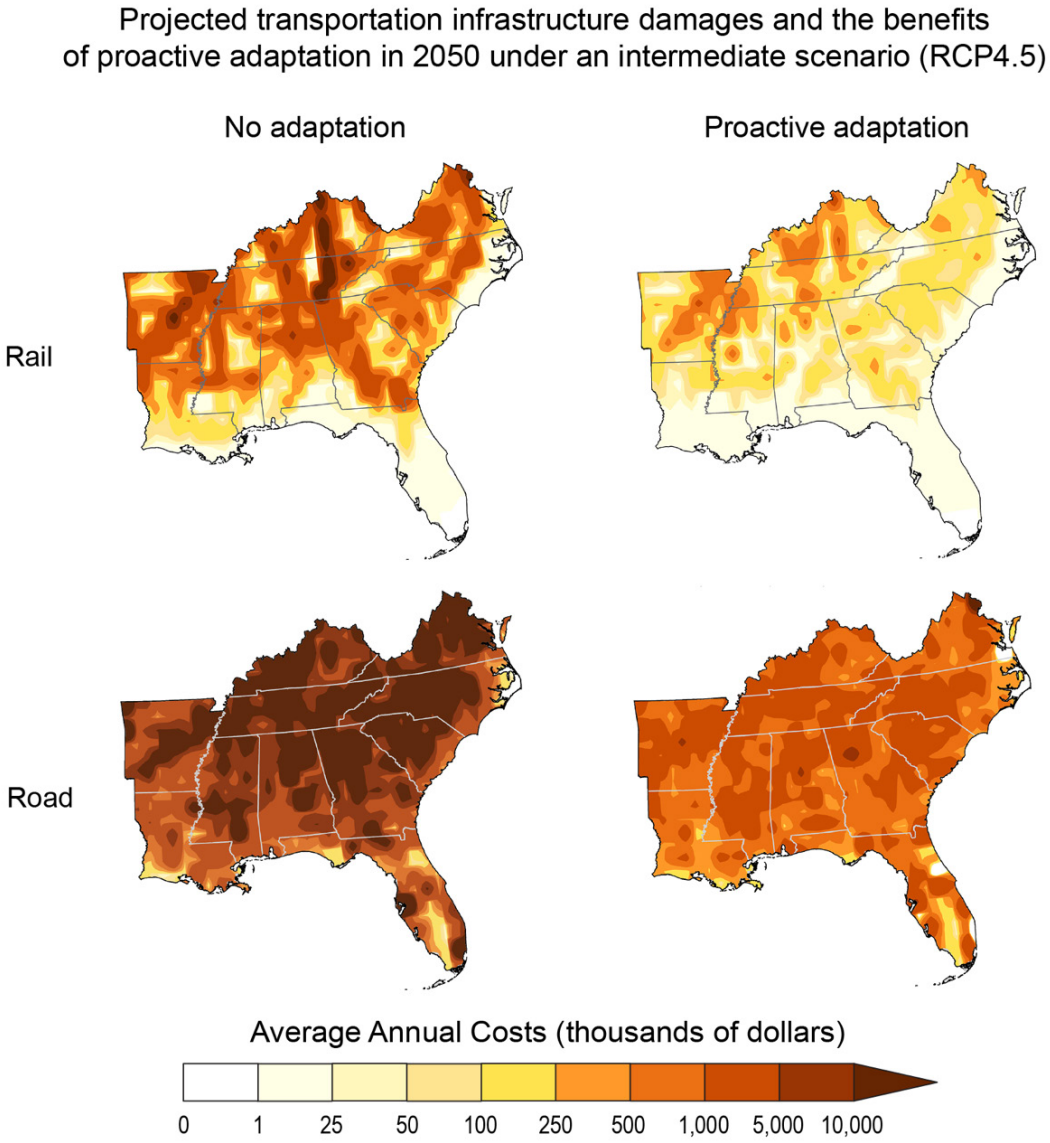
The Southeast is impacted by a wide variety of extreme weather events.

Figure 22.14. The impacts of weather and climate extremes can be seen in photos from the Southeast (**clockwise from top left**): A flooded neighborhood in Kissimmee, Florida, is shown after Hurricane Ian (2022), which heavily impacted local livelihoods. Drought conditions in Alabama (2016) directly impacted farmers' incomes and potentially increased prices for customers. Regional drought-induced low-flow conditions on the Mississippi River caused barges and towboats to become stranded for several days (2022). Flood damage in northeast Arkansas impacted transportation infrastructure and crops and may have impacted supply chains (2017). Image credits: (top left) Robert Kaufmann/FEMA, DHS; (top right) Bruce Dupree, Alabama Extension [CC0 1.0]; (bottom left) Sonny Perdue, USDA; (bottom right) adapted from NASA Earth Observatory.

Place-based economies that are located in hazardous areas and are reliant on unique ecological systems (e.g., aquaculture, farming, and recreation/tourism) face numerous challenges, including the uncertainties associated with the stability of freshwater and saltwater ecosystem services that support business and cultural attachment to place.[301] For example, some fishing communities are facing threats to fishing infrastructure due to sea level rise and more intense coastal storms, as well as threats to fisheries stock habitats that are vulnerable to the effects of a changing climate, such as increasing bottom-water temperatures.[142,302,303] Meanwhile, inland towns and cities with ecotourism attractions also face significant economic losses due to increased flash flooding,[73,108] including lower-income rural areas in Appalachia, as exemplified by the 2022 floods in eastern Kentucky. Rapidly growing urban centers in the Southeast are increasingly vulnerable to drought and the challenges tied to the provision of water for residents and businesses.[304,305,306,307] The Southeast is more drought-prone than other parts of the eastern US due to higher rates of evapotranspiration.[308,309] Evapotranspiration is expected to increase due to future climate warming (Ch. 2). Alabama cities' drought plans were evaluated as less comprehensive and lacking pre-drought preparation compared to those of California cities.[152] In rural, agriculturally dependent economies, increased heat, drought, and water-laden tropical storms currently threaten the productivity of crops and livestock (KM 22.4),[310,311] as well as the health and livelihoods of workers, who tend to be Latino migrants.[312] Future global warming will increase this threat, potentially further reducing labor productivity and costing billions

of dollars, particularly in the already hot and humid Southeast (KM 2.2).[212,313] The Southeast's economy relies on the region's ports, rivers, rail, air, and road networks, which are at risk from sea level rise, flooding, extreme heat, drought, and other climate-related hazards.[61,314] However, proactive adaptation can offset potential future climate-related damages substantially (Figures 22.13, 22.15, 22.17). Unplanned disruptions to these systems can potentially affect consumer pricing of goods, services, and livelihoods throughout the region and elsewhere (Figure 22.16).[315,316]

Proactive Adaptation Offsets Future Transportation Infrastructure Costs



Proactive adaptation to climate change could save millions of dollars in future transportation infrastructure costs.

Figure 22.15. Future climate change impacts (under RCP4.5) may cost US transportation infrastructure billions in damages by 2050, with especially high costs in the Southeast. The **left panels** show the additional annual average system costs (as compared to 1986–2005 in 2018 dollars) to rail infrastructure (**top**) and road networks (**bottom**) in 2050, assuming no adaptation. Proactive adaptation—anticipating climate risks and investing up front in strengthening these systems before damage occurs—could reduce significantly, but not eliminate, these costs (**right panels**). Proactive adaptation strategies include temperature sensors for railroad tracks and working to reduce disruption times for roads undergoing repairs. Adapted from Neumann et al. 2021[317] [CC BY 4.0].

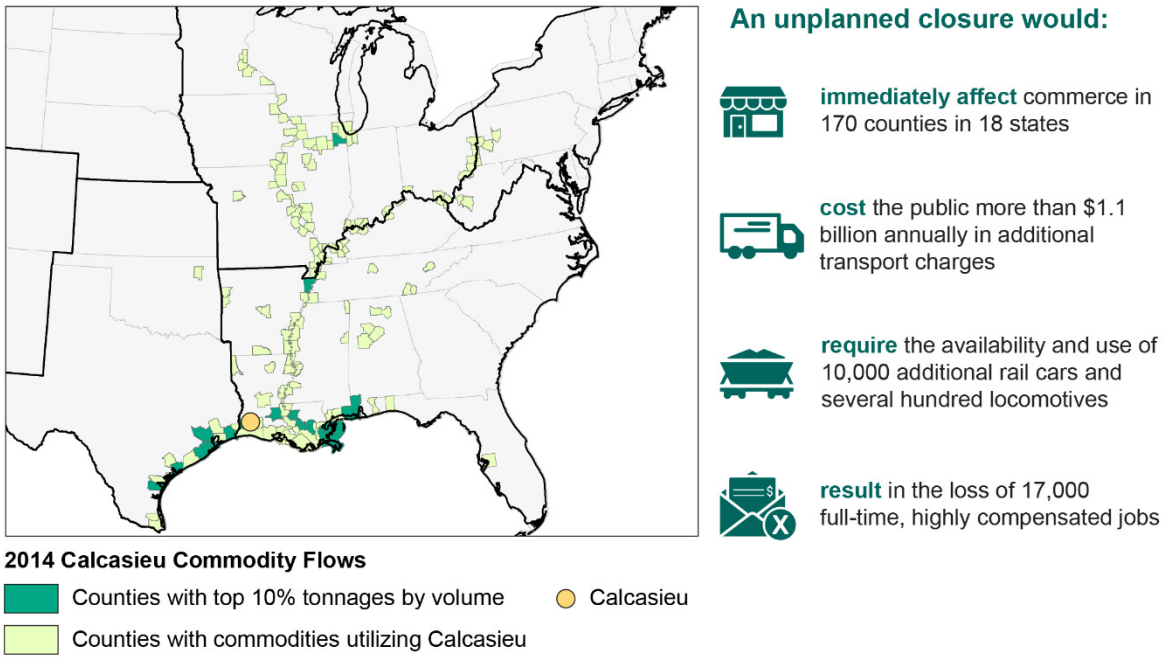
Supply Chain Impacts Affect Places Outside the Southeast

There is an urgent need to address climate change risks to global supply chains (Focus on Risks to Supply Chains; KM 19.1).[318] In the Southeast, climate change–induced transportation infrastructure risks affect all modes (e.g., air, water, highway, rail, and even pipelines; Figures 22.15, 22.16; Ch. 13). Transportation agencies across the region appear to be planning for infrastructure improvements on different schedules and often lack the capacity to include climate data in the planning process (Ch. 13).[319] Coordinated and proactive adaptation strategies could offset significant future damage to these systems (Figures 22.15, 22.17).[317,320,321]

Many Southeast roadways and rail lines are located along waterways and frequently cross bodies of water, making them vulnerable to potential floods and heat-related impacts. High future costs are expected if no adaptive investments are made today (Figures 22.15, 22.17).[317] Inland navigation and the Mississippi River are critical to supply chains in the Southeast and much of the central portion of the United States, as evidenced by the 2021 closure of the Interstate 40 bridge over the Mississippi River at Memphis, Tennessee.[322] Unscheduled lock outages resulting from floods, droughts, earthquakes, or hurricanes can cause cascading impacts. For example, an unplanned outage of the Calcasieu Lock in southern Louisiana would affect economies in 170 counties and 18 states (Figure 22.16).[315,323] In the Southeast, manufacturing facilities for industries such as automotive (including electric vehicles and charging stations),[324] solar panels, agriculture,[325] and construction often rely on parts or materials originating from other locations, including some from international sources. The Mississippi River serves as a gateway to the Nation for imports of such materials and exports of goods such as agricultural products. In recent years, low-flow conditions due to regional droughts on Southeast waterways such as the Mississippi have halted or delayed the movement of barges carrying bulk goods, with regional and national implications (Figures 22.14, 22.16).[326,327]

Disruptions can impact not only the delivery of finished goods and products to customers but also production and the livelihoods of individuals working in jobs dependent on materials from other locations that may not arrive in time, leading to revenue loss and even potential job loss if disruptions become regular and significant enough. The impacts of climate change on supply chains include not only disruption to systems and additional costs associated with the transportation of goods but also potential health impacts to workers in industries that require working outdoors, such as agriculture,[325] fisheries, construction, and last-mile delivery,[328,329] who may be exposed to extreme heat or cold. Workers in these jobs may require additional heating or cooling or adjustments in shift times to avoid exposure to adverse weather conditions (KM 22.2; Ch. 19).[330]

Expected Impacts of an Unplanned Calcasieu Navigation Lock Closure

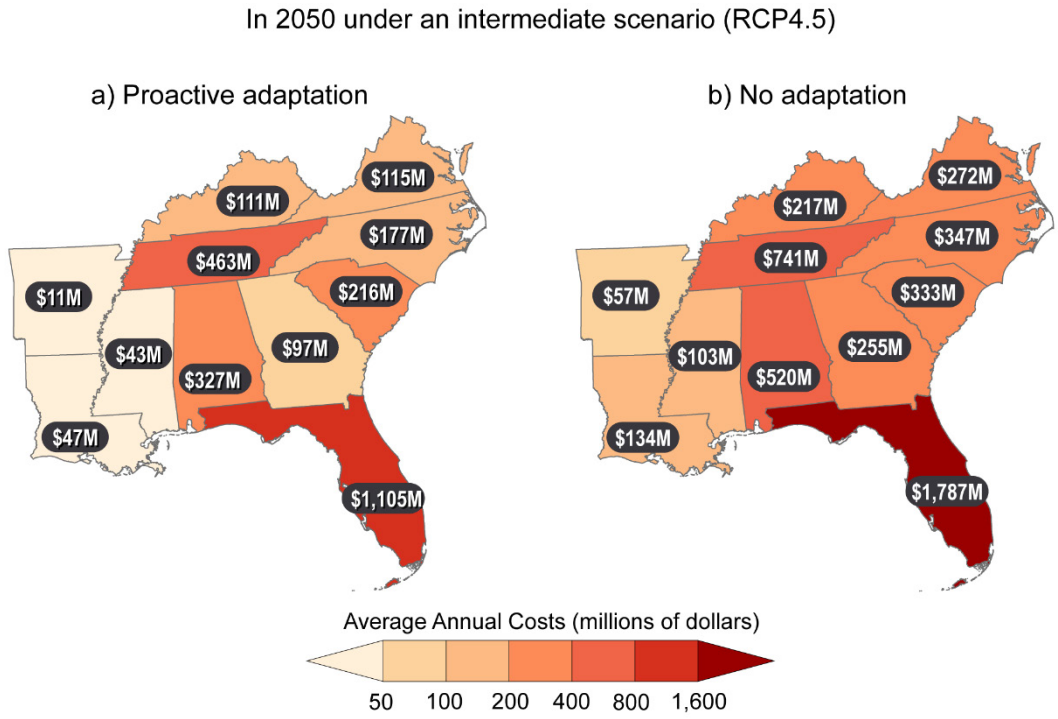


An unplanned closure of the Calcasieu Navigation Lock would have impacts that extend well beyond the Southeast.

Figure 22.16. The commodity flow impacts associated with an unplanned shutdown of Calcasieu Lock extend well outside the Southeast, affecting 170 counties across 18 states. Weather and climate extremes such as regional drought and low-flow conditions on the Mississippi River can result in unplanned shutdowns of the Calcasieu Lock. Adapted with permission from Burton et al. 2017.[315]

Furthermore, the Southeast is a hub of activity for oil refineries that provide fuel to the eastern half of the United States.[331] Climate change is expected to negatively impact not only refineries that are located along the Gulf Coast but also the distribution networks of the petroleum products that many rely on for emergency services, backup power generation, air travel, and more.[60,332,333]

Projected Annual Energy Infrastructure Costs



Proactively investing in strengthening our electrical infrastructure offsets significant future costs due to climate change damage.

Figure 22.17. The Southeast faces some of the highest economic risks related to energy infrastructure damage without proactive adaptation measures in place—such as energy utilities and policymakers' anticipating climate risks to electrical grid infrastructure and investing upfront in strengthening these systems in advance of any damages. As shown in the maps, in 2050 under an intermediate scenario (RCP4.5), proactive adaptation (**a**) could save as much as twice the total costs (in 2017 dollars) of no adaptation (**b**). These costs could be passed onto consumers. Adapted from Fant et al. 2020[320] [CC BY 4.0].

Securing Economic Vitality

Protecting businesses and urban and rural infrastructure investments may require adopting a combination of adaptation measures (KM 22.1). However, to avoid unintended disparities in service provision, these infrastructure investments should consider the needs of frontline communities in their design criteria.[334] For instance, Charleston, South Carolina, has explored questions surrounding the appropriate selection of adaptation measures, including protection techniques such as a seawall versus a greater reliance on nature-based solutions.

Justly transitioning to a low-carbon economy provides opportunities for businesses[335] as well as labor,[336] assuming that marginalized populations and women are included in this workforce to avoid the inequities of our current energy labor markets.[337] Business and governmental agencies could commit to workforce programs for employees in the oil, gas, and coal-producing industries,[336,338] as workforce training in green technology must address challenges associated with transitioning away from economies that are closely tied to a community's way of life.[339,340] Additionally, ecosystem restoration and nature-based green infrastructure solutions (e.g., urban forestry, stormwater retention gardens, green roofs) may also provide meaningful job opportunities (Ch. 19).[341] Key to adapting to climate change and leveraging new opportunities is the need for training and workforce development, which will require investment and prioritization (Ch. 19).

Key Message 22.4

Agriculture Faces Growing Threats, but Innovations Offer Help

Changes in temperature, drought, extreme rainfall, and sea levels are already threatening the Southeast's agriculture and other food-related systems (*likely*, *very high confidence*). Moreover, these climate-related hazards are expected to worsen with every increment of global warming, disproportionately harm farmers and small-scale operations, and increase the competition between urban and rural communities for valuable resources such as water and land (*high confidence*, *very likely*). However, innovative agricultural techniques such as precision farming show promise for adapting to future climate changes in the region (*likely*, *high confidence*).

Agriculture is critical to the economy of the Southeast through its production of food and fiber and employment. In the United States as a whole, agriculture, food, and related industries contributed $1.26 trillion (in 2022 dollars; a 5.2% share) to the gross domestic product in 2019.[342] In the Southeast, nearly 500,000 farms produced market sales of more than $83.8 billion (in 2022 dollars),[343] and the region's agricultural products are consumed locally and exported throughout the United States and the world.[344] Food systems distribute agricultural products throughout the region, although food deserts are present in urban and rural areas.[345] Disparities in food distribution are especially pronounced in areas with concentrations of Black, Indigenous, and under-resourced communities.[345]

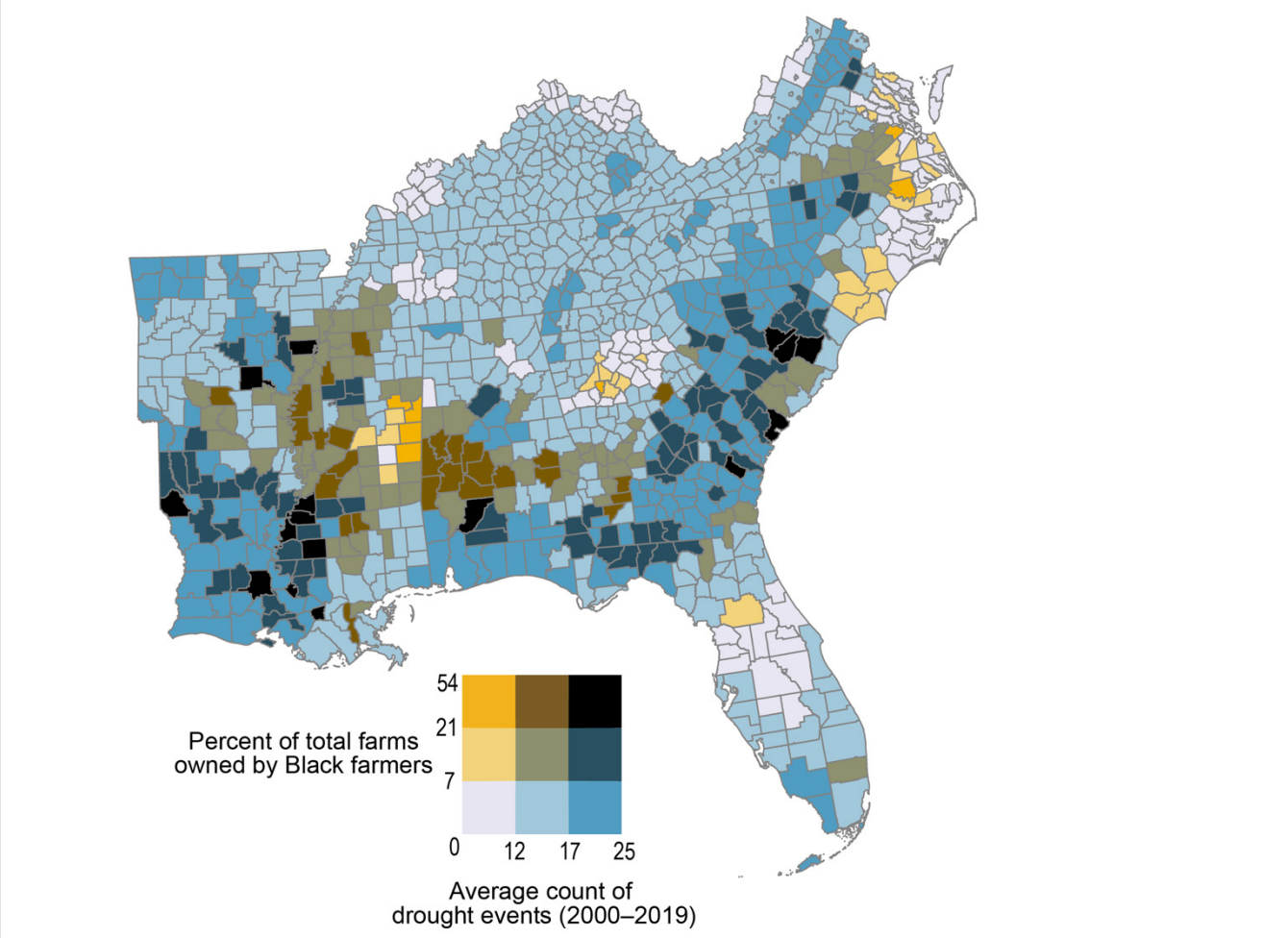
Climate Stressors on Agriculture and Food Systems

Climate change stresses agriculture and food systems (Ch. 11). Threats from a changing climate include both direct threats through impacts of climate extremes on crops, forests, ecosystems, and livestock and indirect threats through impediments to transportation, the health of outdoor workers and animals, degradation and loss of natural ecosystems, reduced productivity and loss of traditional crops, increased threats from invasive species and weeds, and loss of livelihood for vulnerable communities such as rural BIPOC farmers. For example, increased average and extreme high temperatures[346] have led to increased heat stress on livestock[325,347] and outdoor workers. Warmer winter temperatures have reduced the number of chill hours (the total number of hours a plant experiences temperatures below 45°F over the winter months), which are essential for fruit production,[348] and have caused unusually early blooming of crops such as peaches and blueberries, which makes them vulnerable to damaging frost events. In spite of warmer winters, however, the change in the average date of the last spring frost is not consistent across the region.[349]

Higher temperatures, particularly overnight temperatures, have reduced crop yields,[350] and these impacts are projected to worsen with additional global warming (Figure 22.19; Ch. 11). They have also led to an increase in the occurrence of drought in the region (Figure 22.18).[351,352,353] The Southeast is the only region in the eastern half of the United States that is prone to extreme drought,[308] and flash droughts occur with higher frequency there than in any other region.[354] Longer-term droughts in the Southeast appear to be increasing in severity but do not appear to be occurring more frequently.[355] Changes in climate conditions have also contributed to increased pressure by invasive species that have resulted in crop yield losses and damaged productive natural ecosystems.[356,357] Increases in the frequency of heavy rain events[358] and lengthening of dry spells between rain events at some locations in the region[359,360,361] make water resources unpredictable. Hurricanes and tropical storm winds, as well as increasing accumulated rainfall in coastal areas, pose unique threats to agriculture.[92,362] For example, following Hurricane Florence, swine feces markers were detected in surface waters in North Carolina, suggesting that management practices should be examined in areas at risk of increased extreme precipitation.[363] Rising sea levels have increased saltwater intrusion in coastal aquifers, reducing the extent of available forests and farmland[130,131] and threatening

seafood harvesting in estuaries by altering the salinity and turbidity in freshwater streams and marine nurseries.[364] Extreme weather and coastal stressors have also disrupted food distribution by closing ports and highways,[365,366,367] reduced the catch of fish, and diminished crop production.[140]

Droughts and Black Farmers in the Southeast



The Southeast's Black farmers face disproportionate weather and climate risks.

Figure 22.18. In the Southeast, areas with a higher number of drought events from 2000 through 2019 often overlapped with counties that are home to relatively higher proportions of Black producers, as identified in the 2017 USDA Census of Agriculture. The Southeast has the highest proportion of Black producers when compared to any other National Climate Assessment region, highlighting how disparities in climate risks require innovation and equitable adaptation, especially for those producers who have smaller operations and fewer resources to adopt new technologies. Figure credit: Groundwork USA, University of Georgia, NOAA NCEI, and CISESS NC.

Disproportionate Impacts on Under-Resourced Communities

Climate stressors such as drought have a disproportionate impact on small-scale, Black, Indigenous, and economically disadvantaged farmers, who are more concentrated in the Southeast compared to other NCA regions (Figure 22.18).[368,369,370] These groups are under-resourced, making adaptation to climate change more difficult.[371] Knowledge gaps in best practices for small-farm management complicate information-sharing among communities across the region. Access to broadband in rural areas may limit producers' ability to monitor their fields and make appropriate management decisions.[372,373] Small-farm owners also have limited financial resources, which means they have less ability to invest in necessary farm equipment, insurance,

and other risk-reduction methods such as irrigation that could mitigate climate stress and reduce farmland value losses.[374,375] Small-scale farmers and those with limited resources may find targeted USDA programs as well as innovative techniques such as organic farming and agroforestry to be well-suited to use on their smaller farms in the future.[376,377]

Competition for Resources

Southeastern agriculture and food systems are further stressed by land, water, and resource competition between urban and rural areas.[378] Competition is highlighted by decades of lawsuits in the Southeast involving the appropriate distribution of water resources among municipal water users in large cities, agricultural producers using irrigation to protect against drought, and coastal fisheries that rely on balanced salinity levels to maintain the health of estuarine systems.[379] Sprawl is expanding into farmland, reducing the land available for food production and increasing the area affected by urban heat islands.[380] Similarly, native forests have been developed or replaced by commercial forests, which may lack biodiversity and ecosystem resilience.[381]

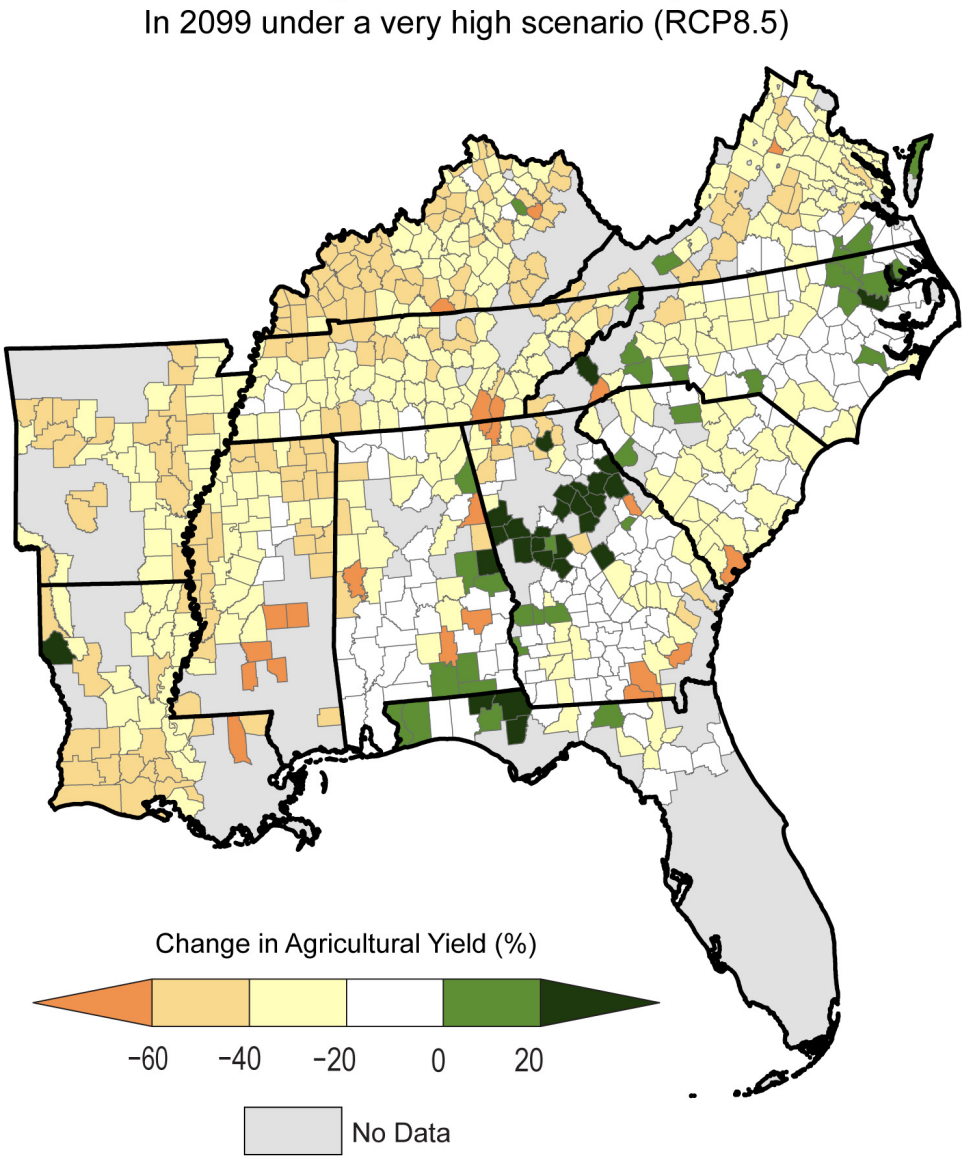
Regional Dependencies

Climate stressors in other regions can have cascading effects on the Southeast and in turn the entire United States. For example, sea level rise is expected to hinder the operation of ports where food, other agricultural products, and other needed supplies are imported and exported (KM 22.3). Additionally, low and high flows from droughts and floods may hamper the movement of food and agricultural products within and through the region, especially in highly urban and rural areas.[382,383] Climate extremes can also reduce crop yields elsewhere and thus the availability of food products for the Southeast, potentially increasing stress on under-resourced populations through cost hikes and decreasing access to nutritious food.[384,385]

How Agriculture and Food Systems Are Adapting in the Southeast

Agricultural producers are using various techniques to respond to increased climate stress, which is expected to result in decreased crop yields in many parts of the Southeast (Figure 22.19).[300] Precision agriculture can minimize water use through the timely and appropriate irrigation of crops based on growth stage and soil moisture.[386] The use of cover crops to preserve soil moisture and nutrients reduces the impacts of soil erosion and the leaching of nitrate into waterways and coastal estuaries, as well as the need for expensive inputs of fertilizer and irrigation water (Ch. 11).[387,388,389] Other innovative agricultural techniques such as organic farming, advanced grazing management, silvopasture, agroforestry, and other agroecological systems (Box 22.3) also show promise for adapting to future climate changes in the region through a reduction in emissions of greenhouse gases and increased carbon sequestration in the soil and vegetation.[376] New crops such as olives and satsuma citrus have been introduced to some areas to take advantage of the shifting plant hardiness zones and favorable market value of the crops.[390,391,392,393] Genetically modified organisms and new cultivars of perennial crops can contribute to reduced emissions of greenhouse gases through reductions in fieldwork and may reduce the need for inputs such as pesticides, as well as provide additional resilience to expected increases in temperature and drought that may threaten long-term yields.[394,395,396] A longer growing season also allows some producers to grow two crops in a year instead of one, reducing the likelihood of a weather catastrophe destroying a year's harvest in a single event.[397]

Projected Changes in Agricultural Yields Under Unmitigated Climate Change



Agricultural yields are expected to decrease under very high warming.

Figure 22.19. Agricultural yields (area-weighted average for corn, wheat, soybeans, and cotton) in the Southeast are expected to decrease due to the warmer climate in the future by 2099 under a very high scenario (RCP8.5). Some areas, however, may see yield increases due to less severe climate changes in these places, as well as limited impacts due to sea level rise and tropical storm damage. Decreases in crop yield are expected to negatively impact regional and national food supplies while threatening agricultural lifestyles and traditions. Adapted from Hsiang et al. 2017.[300]

Box 22.3. Indigenous Stewardship of Southeast Ecosystems: Rivercane

Rivercane (*Arundinaria gigantea*) is a Tribal cultural keystone species[398] and one of only three North American native bamboos. Once abundant and now critically endangered at just 2% of its original range, the species is still found throughout the Southeast.[399] Tribal Nations including the Cherokee, Chickasaw, Chitimacha, Choctaw, Houma, Koasati, and Seminole[400] value rivercane in cultural lifeways. It is used for food, textiles, basketry, medicine, weapons and hunting, and musical instruments. Many Tribal elders have a relationship with rivercane as a non-human relative.[401] Before settler colonialism, rivercane formed canebrakes, thickets of grasses that extended for miles, forming a feature from the South's deepest history.

Native peoples actively managed or tended canebrakes through consistent thinning to provide habitat and the required culms (stems) for cultural uses.[401] Canebrakes competed with European agriculture: cattle readily ate cane, particularly young shoots; pigs rooted for rhizomes,[402] killing the plant; and crops were planted where cane once thrived. Urbanization, removal of fire from the landscape as a management practice, overgrazing by cattle, and lack of public knowledge of rivercane's indigenousness have led to the plant's diminishment. The significantly reduced range of the rivercane is now further threatened by invasive species that are thriving under climate change.[403] Where it still exists, rivercane provides prime habitat for more than 50 animal species,[400] and at least six species require rivercane to complete their life cycles.[404]

Rivercane provides ecosystem benefits such as soil and water quality improvements and river and stream bank stabilization.[405] Rivercane produces seeds during rare mass fruiting events, the timing of which is unknown. For this reason, controlled reproduction has been limited and requires more research if the plant is to thrive in the future.[401] Current efforts are underway to restore rivercane, especially large swaths of canebrakes, as part of Tribal efforts to maintain sovereignty and cultural continuance.

> *I feel like we have to educate the public of Cherokee culture, foods, and artisan resources. It is not just rivercane affected by climate change, loss of habitat, and the public's lack of understanding of their cultural significance to our Tribal members, and other Tribes of the Southeast. — Mary W. Thompson, Eastern Band of Cherokee Indians*[406]

Rivercane in North America

Rivercane, a native bamboo, is culturally important to many Tribes in the Southeast.

Figure 22.20. (**left**) Rivercane grows by the French Broad River in Buncombe County, North Carolina. (**right**) Basket weaver Ramses King (Mississippi Band of Choctaw Indians) creates a "double-weave" basket (2014). The significantly reduced range of rivercane, largely due to land cover changes and agriculture, is now further threatened by invasive species that are thriving under climate change. Photo credits: (left) © Adam Griffith, Revitalization of Traditional Cherokee Artisan Resources; (right) Lance Cheung, USDA.

Traceable Accounts

Process Description

Author selection for the Southeast chapter began with assessing the geographic distribution, career level, and academic expertise of the individuals listed in the Federal Register Notice nomination list. The chapter lead author (CL) then also assessed a number of other characteristics including demographics and previous experience with National Climate Assessment (NCA) chapter development. Initial invitations were sent following US Global Change Research Program (USGCRP) guidance. The CL extended multiple rounds of invitations until the final list of authors for the Zero Order Draft (ZOD) was complete in February 2022, achieving a distribution of career stages, expertise, and geographic representation. Additional authors were added after ZOD reviews from USGCRP agencies were assessed. Author team meetings were held virtually and were used primarily to gather consensus on the direction of the chapter content. In preparation for the public engagement workshops that were held in January and February 2022, the author team worked through the format of the engagement and how feedback would be gathered and summarized. The CL also gathered ZOD feedback from regionally focused organizations: the Southeast Sustainability Directors Network (January 18, 2022) and the Southeast and Caribbean Disaster Resilience Partnership (January 26, 2022), as well as a youth-focused event put on by the Youth Environmental Alliance in Higher Education (February 15, 2022).

Subsequent drafts of this report reflected changes and edits agreed upon by a simple majority of authors in response to several dozen comments and suggestions from public, National Academies, and USGCRP Agency reviews. Consensus on chapter-wide changes was usually unanimous, with very few changes needing considerable discussion. The largest changes to the chapter occurred during the drafting of the Fourth Order Draft (4OD), as this was the draft that would need to respond to a large number of public and National Academies comments. Many of the changes would be instituted during the All-Author Meeting in April 2023. Review Editor Tisha Holmes ratified that the changes satisfied all public and NASEM comments before submission of the 4OD for Technical Support Unit editorial review.

Key Message 22.1

Regional Growth Increases Climate Risks

Description of Evidence Base

Population growth and land-use change in the Southeast have been widely reported on in a variety of contexts, including in previous NCAs. This evidence has only gotten more detailed since NCA4.[19]

The relationship between global warming and increases in regional sea level trends has recently been substantially improved, allowing for highly detailed descriptions of future relative sea level and thus flood risks.[51] Other advances related to projections of future rainfall intensity, duration, and frequency tied to both nontropical[100] and tropical systems[92] have greatly improved our understanding of future changes in the Southeast, including its potential downstream impacts on frontline communities.[13,53]

A wide body of quantitative research and qualitative practice has shown that the proactive adoption of risk reduction measures can significantly reduce future losses tied to natural hazards, including those exacerbated by a changing climate.[154] Furthermore, there is widespread agreement that natural hazards and climate change is disproportionately impacting socially vulnerable populations.[3] Planning and the distribution of funding have the potential to significantly reduce hazard risk, including that associated with climate change. However, the application of land-use planning techniques varies widely, and access to external grant funding is more often obtained by wealthier communities.[16,17]

Major Uncertainties and Research Gaps

Projections of future population are based on many assumptions. Research on how future land-use change will exacerbate particular climate stressors in southeastern cities and across the region could help inform the best use of interventions and application of growth strategies. There have been limited analyses of adaptation activities in the Southeast, data inputs used, and evaluation of impacts. Downscaling global climate change models to inform geospatially targeted adaptation tools and techniques at the neighborhood and parcel scale is improving. However, the use of this downscaled information requires continued refinement to improve accuracy; in addition, better processes for sharing this information would help local officials, including low-wealth jurisdictions with limited staff and technical expertise. There still exists uncertainty regarding how future intensification of storms will impact design standards, such as determining the appropriate design standard in an era of climate change, who makes these decisions, and who pays for the additional costs. These questions apply to housing, public facilities, and infrastructure. It remains uncertain how well communities are reducing hazard risk when accounting for both individual projects (which have been captured effectively in terms of future losses avoided) and ongoing development, which includes a variety of standards, ordinances, and public investments. There is limited literature estimating sub-daily precipitation metric projections for the Southeast. The degree to which future land use and urbanization will exacerbate or overpower climate change–intensified risks at the local level, especially in frontline communities, is under-explored in the current literature.

Description of Confidence and Likelihood

Population trends from the US Census Bureau are highly reliable through time and space, and as such, we ascribe *very high confidence* to reporting their data as well as future population estimates that virtually without exception agree on continued regional growth, warranting a *very likely* assessment. Risk management and assessment literature is extremely consistent on how sprawl and development relate to natural disaster risk, earning these statements *very high confidence* and *likely* assessments. That governance structures of varying scales are using outdated and/or limited information on climate-related risks is a well-reported feature within the flooding, disaster preparedness, and urban planning literature, so we assign *high confidence* to these statements. There is overwhelming consensus that climate adaptation efforts are concentrated in wealthier, more resourced communities, and therefore we assign assessments of *high confidence* and *likely*. There is overwhelming consensus that under-resourced, older, and marginalized communities are at higher and increasing risk from present and future climate extremes, although the risk in rural areas is less fully assessed quantitatively, thus resulting in our assignment of *high confidence* and *likely*.

Key Message 22.2

Climate Change Worsens Human Health and Widens Health Inequities

Description of Evidence Base

There is strong evidence and consensus that climate change is already affecting the health and well-being of populations in the Southeast.[19] There is also strong evidence and consensus that climate-related environmental health stressors are projected to worsen.[19]

There is evidence that residents in the Southeast have poorer health in general compared to other US regions[196] and have limited access to healthcare resources.[202,288]

It is well established that there are preexisting inequities in health and healthcare access, safe and affordable housing, and access to resources to adapt to climate change, and that these inequities are associated with communities with a high proportion of under-resourced and BIPOC (Black, Indigenous, and People of Color) residents.[3,12,202,220]

The occurrence and projection of more frequent and intense extreme heat events are well documented by temperature models of the Southeast.[3,230,231] The literature assesses the disproportionate health impacts of heat on those most affected, including people who work outdoors,[212,213] student and nonstudent athletes,[214,215,216] and those who do not have adequate housing or cannot afford the energy costs of air-conditioning their homes.[218,220,222]

The literature outlines the causal pathway of how climate change is compromising air quality in the Southeast as a result of increasing favorable conditions for wildfires,[244,245,246,256,262] longer and more intense pollen seasons,[253,254,407] and increased production of smog,[241,242,243] as well as the subsequent health impacts. There is some evidence that warmer temperatures are associated with an increase in harmful algal bloom events,[267] which occur in fresh, brackish, and salt water, commonly occur in coastal areas in Florida, and can have detrimental effects on ecosystems, affecting plant, animal, and human health.[273]

The literature has established that climate change broadens the geographic distribution and season of certain disease-carrying mosquitoes and ticks, particularly in the Southeast, for tick-borne illnesses such as Lyme disease[281,282,283] and mosquito-borne illnesses such as West Nile virus and Zika virus.[284]

Mental health data have established that the Southeast ranks worst among all regions of the US in the prevalence of mental illness and access to mental health care services,[287,288] which is of particular concern as extreme weather events occur more frequently and intensely in the Southeast, causing displacement and stress.[293]

Major Uncertainties and Research Gaps

The degree to which health will be affected by climate change and climate adaptations is uncertain, due to various compounding factors that can influence health effects. There are few studies that quantify the health impacts of climate adaptation interventions in the Southeast, so there is a limited understanding of effective public health strategies for addressing climate change.

Because there is limited data on pollen and vector-borne diseases in the Southeast, it is challenging to fully understand the impacts of climate change on these disease exposures.

There is also limited quantitative data on the mental health impacts of climate change. This information tends to rely on survey data, qualitative data, and anecdotal information.

Description of Confidence and Likelihood

There is a high degree of agreement in the scientific literature that climate change will impact and is already impacting extreme temperature and precipitation events, air quality, water quality, the spread of vector-borne diseases, and the prevalence of algal blooms, all of which have an impact on the health of people in the Southeast, as evidenced by health outcome information including health impact assessments of recent events, health projections of future events, and environmental health trends in the Southeast. Based on this information, the authors assigned *very high confidence* that the changes in temperature and precipitation due to climate change, in conjunction with changes in air quality, water quality, the spread of vector-borne diseases, and the prevalence of algal blooms, will impact, and is *very likely* already impacting, the health and well-being of people in the Southeast.

It is well established that the conditions in which people live and work have an impact on health, which is understood as the social determinants of health. It is also well established by the literature and lived experience that marginalized populations will experience disproportionate health impacts, as that is seen consistently across public health and particularly in environmental health. For this reason, as well as because of the breadth of literature on the disproportionate impacts of climate change on the health of marginalized populations, the authors assigned *very high confidence* that community characteristics such as

racial and ethnic population, chronic disease prevalence, age, and socioeconomic status, can influence how climate change exacerbates, ameliorates, or introduces new health issues, widening the gap in health status.

Based on models of health impacts under varying climate scenarios, it is well-established that lower emission scenarios will result in less severe health outcomes. The literature is less established on the health benefits of climate adaptation efforts, as there is not a breadth of literature or evaluations on this topic, although from the literature that is available it is apparent that climate adaptation actions can improve health. For this reason, the authors assigned *high confidence* that climate mitigation and adaptation efforts can save lives and reduce the public health burden of climate change, particularly around reducing air pollutants and targeting already-marginalized communities, which is where the literature is more established.

Key Message 22.3

Climate Change Disproportionately Damages Southeastern Jobs, Households, and Economic Security

Description of Evidence Base

There is a rapidly growing literature presenting both qualitative and quantitative evidence that livelihoods across the Southeast are already being impacted by climate change in a variety of important ways (Ch. 19),[298] including place-based economies such as construction, tourism, and agriculture and aquaculture (e.g., fisheries are being impacted not only by significant hurricanes but also by geographical shifts among species in ocean waters),[408,409] as well as systems like transportation infrastructure[317] and electrical grid infrastructure[320] that undergird the distribution of goods and services in these places. Extreme weather-related disruptions and adverse working conditions created by climate change can affect both people and infrastructure systems that support local and regional economies by impacting the local community as well as regional and global supply chains.[326,327] References and figures included in Chapter 19 were instrumental to establishing author team consensus around key statements related to economic impacts being relatively larger in the Southeast than in other NCA regions.

Major Uncertainties and Research Gaps

Localized impacts on inland agriculture and tourism are not fully understood to date. The relocation of individuals and households away from climate-affected areas to other locations and their need to establish new livelihoods are not well understood, nor is the effectiveness of federal funding to support the construction of new settlements in less hazardous areas. The degree to which small and midsized businesses are adapting to climate change–related threats remains uncertain. The extent to which climate changes will impact large-scale agriculture is fairly well established, but the fiscal impact on small-scale family farms is not as well understood. There is limited research on the low-flow conditions and projections related to drought and its impacts on the Mississippi River and its tributaries as well as on the potential impacts to economies, despite how disruptive the events are to the regional, national, and global economy.

Description of Confidence and Likelihood

Based on the author team consensus reached through evaluating the evidence base presented in the literature as well as through direct and related experience in recent extreme weather and climate events impacting the Southeast, the authors have assigned *high confidence* to the statements surrounding the concentration of economic growth in urban centers, the climate-related risks to place-based economies that rely on ecosystems and to southeastern economies and labor, and the need for coordinated strategies

to prepare for the shocks and stressors of the future. *Medium confidence* was assigned to the evaluation of the extent to which urban centers depend on the interregional connections to more rural places and other urban centers due to limited peer-reviewed literature in this area. While there are reports and white papers on this subject from nonprofits and research think tanks that largely agree on the potential for disruptions to these systems to have impacts on both rural and urban centers, limited peer-reviewed studies seeking to isolate urban/rural dependencies in the face of climate change support at least *medium confidence*. Projections of future climate impacts in the Southeast are particularly robust in their evaluation of future heat and extreme precipitation risks; we assign *very likely* and *high confidence* to our Key Message statements that seek to link climate impacts to economic outcomes in the Southeast. Chapter 19 (Economics) was especially helpful in establishing our *very likely* and *high confidence* assessments.

Key Message 22.4

Agriculture Faces Growing Threats, but Innovations Offer Help

Description of Evidence Base

Evidence of trends in temperature, precipitation, and growing season are well documented in sources such as the NOAA National Centers for Environmental Information's Climate at a Glance Tool and in the scientific literature.[346,350] This literature base is extensive and covers individual states, the Southeast region, the United States, and the globe. Earlier concerns about temperature trends from satellite observations, which did not match surface-based observations, have largely been resolved by improved calibration of satellite measurements.

Trends in precipitation show changes in both amount and temporal and spatial distribution that are more difficult to separate out due to the nature of precipitation in the Southeast and its ties to sub-grid-scale processes like convection and tropical systems.[358,359,360,361] Evidence of trends in drought are less certain because of the combination of interacting contributions from temperature, precipitation variability, and soil characteristics, but are becoming more apparent in recent modeling efforts that are documented in the scientific literature.[351,352]

The impacts of climate variability and change on agricultural production have been well documented in the scientific literature in agricultural journals in recent years.[350,356] More work is ongoing as better methods for collecting in-field measurements are used to fine-tune the relationships between plant physiology and climate variables.

The assessment of the impacts of climate change on the health of workers and livestock, transportation pathways for agricultural production, and economic losses to both large-production farmers and small BIPOC farming communities has increased greatly in the last four years and is being reported in scientific journal articles in health, infrastructure, economic, and other social science–oriented journals.[325,347]

Many examples of agricultural producers implementing climate adaptation in farming exist, suggesting a willingness to address the impacts of a changing climate across diverse land ownerships.

Major Uncertainties and Research Gaps

There is significant uncertainty regarding the ability of crop species to keep pace with changes in climate (based on temperature and precipitation), although plant breeders have a long history of producing new hybrids that can improve responses to changing climate conditions. The ability of new crops to be productive in an altered climate is also uncertain due to concurrent changes in temperature, precipitation,

humidity, and soil characteristics, which interact with plant growth patterns. This leads to considerable uncertainty in the extent to which changes in crop choice and management can adapt to the future climate.

There is also uncertainty in the knowledge of carbon interactions between soils and crops, but numerous studies are underway to better document these interactions to improve future predictions.[376]

Since agriculture is a global endeavor, changes in market pricing and availability of inputs such as fertilizer, as well as outputs such as crop variety and yield, interact in a way that hinders the prediction of future agricultural outputs, droughts, and the economic effects of agricultural sales.[410] As a result, economic impacts on both large-scale farmers and economically disadvantaged farmers with small-scale operations are difficult to predict with *high confidence*.

Description of Confidence and Likelihood

Based on the high degree of agreement in agricultural and climate science journal articles in the scientific literature and assessments of recent events, there is *very high confidence* that the interactions of warming temperatures, precipitation changes, sea level, and drought with insect pests, invasive plants, and plant pathogens are already threatening the region's agriculture and food-related systems and will *likely* lead to decreased yields of many crops and production of other agricultural goods.[356,357] Evaluations of recent past storm events coupled with the strong agreement in related journal articles resulted in an assignment of *very high confidence* that rising sea levels and impacts from tropical storms will disrupt coastal and port activities.[325,347] Studies by social scientists published in the literature also demonstrate that small-scale BIPOC producers, as well as those who have limited financial resources, will be disproportionately affected by climate-related hazards;[366,367] on that basis, the authors have described this as *very likely* with *high confidence* in the expected impacts. Additionally, based on examples in the scientific literature of adaptations that producers are already making in response to changes in the climate, the authors assigned a level of *high confidence* that producers in the Southeast will be able to adapt to those changes using techniques such as precision agriculture, changes in crop type, and innovative management of fisheries, livestock, and ecosystems, and a likelihood level of *likely* was assigned based on less agreement in the scientific literature about the degree to which they will be able to do so.[386,390,394]

References

1. Aaronson, D., J. Faber, D. Hartley, B. Mazumder, and P. Sharkey, 2021: The long-run effects of the 1930s HOLC "redlining" maps on place-based measures of economic opportunity and socioeconomic success. *Regional Science and Urban Economics*, **86**, 103622. https://doi.org/10.1016/j.regsciurbeco.2020.103622

2. Davies, I.P., R.D. Haugo, J.C. Robertson, and P.S. Levin, 2018: The unequal vulnerability of communities of color to wildfire. *PLoS ONE*, **13** (11), 0205825. https://doi.org/10.1371/journal.pone.0205825

3. EPA, 2021: Climate Change and Social Vulnerability in the United States: A Focus on Six Impacts. EPA 430-R-21-003. U.S. Environmental Protection Agency. https://www.epa.gov/cira/social-vulnerability-report

4. Gonzalez, D.J.X., A. Nardone, A.V. Nguyen, R. Morello-Frosch, and J.A. Casey, 2023: Historic redlining and the siting of oil and gas wells in the United States. *Journal of Exposure Science & Environmental Epidemiology*, **33** (1), 76–83. https://doi.org/10.1038/s41370-022-00434-9

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

6. Holifield, R., 2023: American landscapes of environmental injustice. In: *The Routledge Companion to the American Landscape*. Post, C.W., A.L. Greiner, and G.L. Buckley, Eds. Taylor & Francis, 10. https://doi.org/10.4324/9781003121800-8

7. KC, B., J.M. Shepherd, and C.J. Gaither, 2015: Climate change vulnerability assessment in Georgia. *Applied Geography*, **62**, 62–74. https://doi.org/10.1016/j.apgeog.2015.04.007

8. Lane, H.M., R. Morello-Frosch, J.D. Marshall, and J.S. Apte, 2022: Historical redlining is associated with present-day air pollution disparities in U.S. cities. *Environmental Science & Technology Letters*, **9** (4), 345–350. https://doi.org/10.1021/acs.estlett.1c01012

9. Lee, E.K., G. Donley, T.H. Ciesielski, I. Gill, O. Yamoah, A. Roche, R. Martinez, and D.A. Freedman, 2022: Health outcomes in redlined versus non-redlined neighborhoods: A systematic review and meta-analysis. *Social Science & Medicine*, **294**, 114696. https://doi.org/10.1016/j.socscimed.2021.114696

10. Liu, J., L.P. Clark, M.J. Bechle, A. Hajat, S.Y. Kim, A.L. Robinson, L. Sheppard, A.A. Szpiro, and J.D. Marshall, 2021: Disparities in air pollution exposure in the United States by race/ethnicity and income, 1990–2010. *Environmental Health Perspectives*, **129** (12), 127005. https://doi.org/10.1289/ehp8584

11. O'Connell, H.A., 2012: The impact of slavery on racial inequality in poverty in the contemporary U.S. South. *Social Forces*, **90** (3), 713–734. https://doi.org/10.1093/sf/sor021

12. Shepherd, M. and B. KC, 2015: Climate change and African Americans in the USA. *Geography Compass*, **9** (11), 579–591. https://doi.org/10.1111/gec3.12244

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

14. Jurjonas, M., E. Seekamp, L. Rivers, and B. Cutts, 2020: Uncovering climate (in)justice with an adaptive capacity assessment: A multiple case study in rural coastal North Carolina. *Land Use Policy*, **94**, 104547. https://doi.org/10.1016/j.landusepol.2020.104547

15. Ueland, J. and B. Warf, 2006: Racialized topographies: Altitude and race in southern cities. *Geographical Review*, **96** (1), 50–78. https://doi.org/10.1111/j.1931-0846.2006.tb00387.x

16. Smith, G. and O. Vila, 2020: A national evaluation of state and territory roles in hazard mitigation: Building local capacity to implement FEMA hazard mitigation assistance grants. *Sustainability*, **12** (23), 10013. https://doi.org/10.3390/su122310013

17. Vilá, O., G. Smith, B. Cutts, S. Gyawali, and S. Bhattarai, 2022: Equity in FEMA hazard mitigation assistance programs: The role of state hazard mitigation officers. *Environmental Science & Policy*, **136**, 632–641. https://doi.org/10.1016/j.envsci.2022.07.027

18. Cain, C., 2021: Ch. 33. Developing climatic capacity in rural places. In: *Investing In Rural Prosperity*. Dumont, A. and D.P. Davis, Eds. Federal Reserve Bank of St. Louis, 475–486. https://www.stlouisfed.org/-/media/project/frbstl/stlouisfed/files/pdfs/community-development/investing-rural/chapters/chapter33.pdf

19. Carter, L.M., A. Terando, K. Dow, K. Hiers, K.E. Kunkel, A. Lascurain, D.C. Marcy, M.J. Osland, and P.J. Schramm, 2018: Ch. 19. Southeast. In: *Impacts, Risks, and Adaptation in the United States: Fourth National Climate Assessment, Volume II*. Reidmiller, D.R., C.W. Avery, D.R. Easterling, K.E. Kunkel, K.L.M. Lewis, T.K. Maycock, and B.C. Stewart, Eds. U.S. Global Change Research Program, Washington, DC, USA, 743–808. https://doi.org/10.7930/nca4.2018.ch19

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

21. Whyte, K., 2018: Ch. 16. Food sovereignty, justice, and Indigenous peoples: An essay on settler colonialism and collective continuance. In: *The Oxford Handbook of Food Ethics*. Barnhill, A., M. Budolfson, and T. Doggett, Eds. Oxford University Press, 345–366. https://doi.org/10.1093/oxfordhb/9780199372263.013.34

22. Whyte, K.P., 2013: Justice forward: Tribes, climate adaptation and responsibility. *Climatic Change*, **120** (3), 517–530. https://doi.org/10.1007/s10584-013-0743-2

23. Emanuel, R.E., 2018: Climate change in the Lumbee River watershed and potential impacts on the Lumbee Tribe of North Carolina. *Journal of Contemporary Water Research & Education*, **163** (1), 79–93. https://doi.org/10.1111/j.1936-704x.2018.03271.x

24. Emanuel, R., L. Rivers, B. Cutts, and G. Blank, 2020: Data Analytics for Environmental Justice and Indigenous Rights: Early Warning Systems or Blind Spots? Earth and Space Science Open Archive. https://doi.org/10.1002/essoar.10501690.1

25. Emanuel, R.E., 2017: Flawed environmental justice analyses. *Science*, **357** (6348), 260–260. https://doi.org/10.1126/science.aao2684

26. Redvers, N., Y. Celidwen, C. Schultz, O. Horn, C. Githaiga, M. Vera, M. Perdrisat, L. Mad Plume, D. Kobei, M.C. Kain, A. Poelina, J.N. Rojas, and B.S. Blondin, 2022: The determinants of planetary health: An Indigenous consensus perspective. *The Lancet Planetary Health*, **6** (2), 156–163. https://doi.org/10.1016/s2542-5196(21)00354-5

27. Bartels, W.-L., C.A. Furman, D.C. Diehl, F.S. Royce, D.R. Dourte, B.V. Ortiz, D.F. Zierden, T.A. Irani, C.W. Fraisse, and J.W. Jones, 2013: Warming up to climate change: A participatory approach to engaging with agricultural stakeholders in the Southeast US. *Regional Environmental Change*, **13** (1), 45–55. https://doi.org/10.1007/s10113-012-0371-9

28. Buckley, G.A. and M.M. Moore-Driskell, 2021: Challenges in teaching climate science literacy in Alabama, Part I: Climate change and the Southeast U.S. warming hole. *Journal of Sustainability Studies*, **2** (1). https://ir.una.edu/work/ns/9825ae03-4f07-414b-a81b-ee4d92b71867

29. Lee, H., K. Calvin, D. Dasgupta, G. Krinner, A. Mukherji, P. Thorne, C. Trisos, J. Romero, P. Aldunce, K. Barrett, G. Blanco, W.W.L.C. Cheung, S.L. Connors, F. Denton, A. Diongue-Niang, D. Dodman, M. Garschagen, O. Geden, B. Hayward, C. Jones, F. Jotzo, T. Krug, R. Lasco, J.-Y. Lee, V. Masson-Delmotte, M. Meinshausen, K. Mintenbeck, A. Mokssit, F.E.L. Otto, M. Pathak, A. Pirani, E. Poloczanska, H.-O. Pörtner, A. Revi, D.C. Roberts, J. Roy, A.C. Ruane, J. Skea, P.R. Shukla, R. Slade, A. Slangen, Y. Sokona, A.A. Sörensson, M. Tignor, D. van Vuuren, Y.-M. Wei, H. Winkler, P. Zhai, and Z. Zommers, 2023: Summary for policymakers. In: *Synthesis Report of the IPCC Sixth Assessment Report*. Arias, P., M. Bustamante, I. Elgizouli, G. Flato, M. Howden, C. Méndez, J. Pereira, R. Pichs-Madruga, S.K. Rose, Y. Saheb, R. Sánchez, D. Ürge-Vorsatz, C. Xiao, and N. Yassaa, Eds. Cambridge University Press, Cambridge, UK and New York, NY, USA. https://report.ipcc.ch/ar6syr/pdf/IPCC_AR6_SYR_SPM.pdf

30. McNeal, K.S., J.K.L. Hammerman, J.A. Christiansen, and F.J. Carroll, 2014: Climate change education in the southeastern U.S. through public dialogue: Not just preaching to the choir. *Journal of Geoscience Education*, **62** (4), 631–644. https://doi.org/10.5408/13-061.1

31. Monroe, M.C., A. Oxarart, and R.R. Plate, 2013: A role for environmental education in climate change for secondary science educators. *Applied Environmental Education & Communication*, **12** (1), 4–18. https://doi.org/10.1080/1533015x.2013.795827

32. Panos, A. and M.B. Sherry, 2023: Ch. 7. Storying climate change: Discursive possibilities for teaching climate justice literacies. In: *Critical Perspectives on Global Literacies: Bridging Research and Practice*. Kerkhoff, S.N. and H.A. Spires, Eds. Routledge, 124–139. https://doi.org/10.4324/9781003320142

33. Stewart, H. 2022: Co-Developing Climate-Smart Strategies: Enhancing Resiliency Among Alabama Row Crop Producers and Agricultural Stakeholders. Master of Science in Rural Sociology, Auburn University. https://etd.auburn.edu//handle/10415/8323

34. Rudd, M.A., A.F.P. Moore, D. Rochberg, L. Bianchi-Fossati, M.A. Brown, D. D'Onofrio, C.A. Furman, J. Garcia, B. Jordan, J. Kline, L.M. Risse, P.L. Yager, J. Abbinett, M. Alber, J.E. Bell, C. Bhedwar, K.M. Cobb, J. Cohen, M. Cox, M. Dormer, N. Dunkley, H. Farley, J. Gambill, M. Goldstein, G. Harris, M. Hopkinson, J.-A. James, S. Kidd, P. Knox, Y. Liu, D.C. Matisoff, M.D. Meyer, J.D. Mitchem, K. Moore, A.J. Ono, J. Philipsborn, K.M. Sendall, F. Shafiei, M. Shepherd, J. Teebken, and A.N. Worley, 2018: Climate research priorities for policy-makers, practitioners, and scientists in Georgia, USA. *Environmental Management*, **62** (2), 190–209. https://doi.org/10.1007/s00267-018-1051-4

35. Meerow, S. and L. Keith, 2022: Planning for extreme heat. *Journal of the American Planning Association*, **88** (3), 319–334. https://doi.org/10.1080/01944363.2021.1977682

36. Sobel, R.S. and P.T. Leeson, 2006: Government's response to Hurricane Katrina: A public choice analysis. *Public Choice*, **127** (1), 55–73. https://doi.org/10.1007/s11127-006-7730-3

37. Crowley, J., 2021: Social vulnerability factors and reported post-disaster needs in the aftermath of Hurricane Florence. *International Journal of Disaster Risk Science*, **12** (1), 13–23. https://doi.org/10.1007/s13753-020-00315-5

38. Shultz, J.M., E.J. Trapido, J.P. Kossin, C. Fugate, L. Nogueira, A. Apro, M. Patel, V.J. Torres, C.K. Ettman, Z. Espinel, and S. Galea, 2022: Hurricane Ida's impact on Louisiana and Mississippi during the COVID-19 Delta surge: Complex and compounding threats to population health. *The Lancet Regional Health - Americas*, **12**, 100286. https://doi.org/10.1016/j.lana.2022.100286

39. Sanders, M.C., 2021: Equity in addressing climate change: Using law and policy to serve frontline communities. *Traumatology*, **27**, 48–51. https://doi.org/10.1037/trm0000284

40. U.S. Census Bureau, 2021: Race and Ethnicity in the United States: 2010 Census and 2020 Census. U.S. Department of Commerce, U.S. Census Bureau. https://www.census.gov/library/visualizations/interactive/race-and-ethnicity-in-the-united-state-2010-and-2020-census.html

41. Jiang, L., B.C. O'Neill, H. Zoraghein, and S. Dahlke, 2020: Population scenarios for U.S. states consistent with Shared Socioeconomic Pathways. *Environmental Research Letters*, **15** (9), 094097. https://doi.org/10.1088/1748-9326/aba5b1

42. Nowak, D.J. and E.J. Greenfield, 2018: US urban forest statistics, values, and projections. *Journal of Forestry*, **116** (2), 164–177. https://doi.org/10.1093/jofore/fvx004

43. Hamilton, H., R.L. Smyth, B.E. Young, T.G. Howard, C. Tracey, S. Breyer, D.R. Cameron, A. Chazal, A.K. Conley, C. Frye, and C. Schloss, 2022: Increasing taxonomic diversity and spatial resolution clarifies opportunities for protecting US imperiled species. *Ecological Applications*, **32** (3), e2534. https://doi.org/10.1002/eap.2534

44. Strader, S.M., 2018: Spatiotemporal changes in conterminous US wildfire exposure from 1940 to 2010. *Natural Hazards*, **92** (1), 543–565. https://doi.org/10.1007/s11069-018-3217-z

45. Freeman, A.C. and W.S. Ashley, 2017: Changes in the US hurricane disaster landscape: The relationship between risk and exposure. *Natural Hazards*, **88** (2), 659–682. https://doi.org/10.1007/s11069-017-2885-4

46. Ferguson, A.P. and W.S. Ashley, 2017: Spatiotemporal analysis of residential flood exposure in the Atlanta, Georgia metropolitan area. *Natural Hazards*, **87** (2), 989–1016. https://doi.org/10.1007/s11069-017-2806-6

47. Ashley, W.S., A.M. Haberlie, and V.A. Gensini, 2023: The future of supercells in the United States. *Bulletin of the American Meteorological Society*, **104** (1), E1–E21. https://doi.org/10.1175/bams-d-22-0027.1

48. Strader, S.M., W.S. Ashley, T.J. Pingel, and A.J. Krmenec, 2017: Observed and projected changes in United States tornado exposure. *Weather, Climate, and Society*, **9** (2), 109–123. https://doi.org/10.1175/wcas-d-16-0041.1

49. U.S. Census Bureau, 2019: Coastline America. U.S. Department of Commerce, U.S. Census Bureau. https://www.census.gov/library/visualizations/2019/demo/coastline-america.html

50. Collins, E.L., G.M. Sanchez, A. Terando, C.C. Stillwell, H. Mitasova, A. Sebastian, and R.K. Meentemeyer, 2022: Predicting flood damage probability across the conterminous United States. *Environmental Research Letters*, **17** (3), 034006. https://doi.org/10.1088/1748-9326/ac4f0f

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

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

53. Titus, J.G., 2023: Population in floodplains or close to sea level increased in US but declined in some counties—Especially among black residents. *Environmental Research Letters*, **18** (3), 034001. https://doi.org/10.1088/1748-9326/acadf5

54. Smith, A.B. 2020: U.S. Billion-dollar Weather and Climate Disasters, 1980 - Present. National Oceanic and Atmospheric Administration, National Centers for Environmental Information. https://doi.org/10.25921/stkw-7w73

55. Howe, P.D., M. Mildenberger, J.R. Marlon, and A. Leiserowitz, 2015: Geographic variation in opinions on climate change at state and local scales in the USA. *Nature Climate Change*, **5** (6), 596–603. https://doi.org/10.1038/nclimate2583

56. Marlon, J., L. Neyens, M. Jefferson, P. Howe, M. Mildenberger, and A. Leiserowitz, 2022: Yale Climate Opinion Maps 2021. Yale Program on Climate Change Communication. https://climatecommunication.yale.edu/visualizations-data/ycom-us/

57. Richardson, J., B. Mitchell, and J. Franco, 2019: Shifting Neighborhoods: Gentrification and Cultural Displacement in American Cities. National Community Reinvestment Coalition. https://ncrc.org/gentrification/

58. Wilbanks, T.J. and R.W. Kates, 2010: Beyond adapting to climate change: Embedding adaptation in responses to multiple threats and stresses. *Annals of the Association of American Geographers*, **100** (4), 719–728. https://doi.org/10.1080/00045608.2010.500200

59. Jufri, F.H., V. Widiputra, and J. Jung, 2019: State-of-the-art review on power grid resilience to extreme weather events: Definitions, frameworks, quantitative assessment methodologies, and enhancement strategies. *Applied Energy*, **239**, 1049–1065. https://doi.org/10.1016/j.apenergy.2019.02.017

60. Schaeffer, R., A.S. Szklo, A.F. Pereira de Lucena, B.S. Moreira Cesar Borba, L.P. Pupo Nogueira, F.P. Fleming, A. Troccoli, M. Harrison, and M.S. Boulahya, 2012: Energy sector vulnerability to climate change: A review. *Energy*, **38** (1), 1–12. https://doi.org/10.1016/j.energy.2011.11.056

61. DOT, 2019: Rural Public Transportation Systems. U.S. Department of Transportation, Washington, DC. https://www.transportation.gov/mission/health/Rural-Public-Transportation-Systems

62. Gutierrez, K.S. and C.E. LePrevost, 2016: Climate justice in rural southeastern United States: A review of climate change impacts and effects on human health. *International Journal of Environmental Research and Public Health*, **13** (2), 189. https://doi.org/10.3390/ijerph13020189

63. Hendricks, M.D. and S. Van Zandt, 2021: Unequal protection revisited: Planning for environmental justice, hazard vulnerability, and critical infrastructure in communities of color. *Environmental Justice*, **14** (2), 87–97. https://doi.org/10.1089/env.2020.0054

64. Hernandez, P., B. Daigle, T. Preston, K. Pohl, K. Smith, B. Powell, and S. Story, 2022: A Rural Capacity Map. Headwaters Economics, Bozeman, MT. https://headwaterseconomics.org/equity/rural-capacity-map/

65. Allen, M., L. Gillespie-Marthaler, M. Abkowitz, and J. Camp, 2020: Evaluating flood resilience in rural communities: A case-based assessment of Dyer County, Tennessee. *Natural Hazards*, **101** (1), 173–194. https://doi.org/10.1007/s11069-020-03868-2

66. Allen, T., J. Behr, A. Bukvic, R.S.D. Calder, K. Caruson, C. Connor, C. D'Elia, D. Dismukes, R. Ersing, R. Franklin, J. Goldstein, J. Goodall, S. Hemmerling, J. Irish, S. Lazarus, D. Loftis, M. Luther, L. McCallister, K. McGlathery, M. Mitchell, W. Moore, C.R. Nichols, K. Nunez, M. Reidenbach, J. Shortridge, R. Weisberg, R. Weiss, L.D. Wright, M. Xia, K. Xu, D. Young, G. Zarillo, and J.C. Zinnert, 2021: Anticipating and adapting to the future impacts of climate change on the health, security and welfare of low elevation coastal zone (LECZ) communities in southeastern USA. *Journal of Marine Science and Engineering*, **9** (11), 1196. https://doi.org/10.3390/jmse9111196

67. Kunkel, K.E., S.E. Stevens, L.E. Stevens, and T.R. Karl, 2020: Observed climatological relationships of extreme daily precipitation events with precipitable water and vertical velocity in the contiguous United States. *Geophysical Research Letters*, **47** (12), 2019GL086721. https://doi.org/10.1029/2019gl086721

68. Neupane, B., T.M. Vu, and A.K. Mishra, 2020: Evaluation of land-use, climate change, and low-impact development practices on urban flooding. *Hydrological Sciences Journal*, **65** (S3), 1729–1742. https://doi.org/10.1080/02626667.2021.1954650

69. Chakraborty, J., W. Collins Timothy, C. Montgomery Marilyn, and E. Grineski Sara, 2014: Social and spatial inequities in exposure to flood risk in Miami, Florida. *Natural Hazards Review*, **15** (3), 04014006. https://doi.org/10.1061/(asce)nh.1527-6996.0000140

70. Collins, T.W., S.E. Grineski, J. Chakraborty, and A.B. Flores, 2019: Environmental injustice and Hurricane Harvey: A household-level study of socially disparate flood exposures in Greater Houston, Texas, USA. *Environmental Research*, **179**, 108772. https://doi.org/10.1016/j.envres.2019.108772

71. Tate, E., M.A. Rahman, C.T. Emrich, and C.C. Sampson, 2021: Flood exposure and social vulnerability in the United States. *Natural Hazards*, **106** (1), 435–457. https://doi.org/10.1007/s11069-020-04470-2

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

73. Khajehei, S., A. Ahmadalipour, W. Shao, and H. Moradkhani, 2020: A place-based assessment of flash flood hazard and vulnerability in the contiguous United States. *Scientific Reports*, **10** (1), 1–12. https://doi.org/10.1038/s41598-019-57349-z

74. FEMA, 2022: Flood Risk Disclosure: Model State Requirements for Disclosing Flood Risk During Real Estate Transactions. U.S. Department of Homeland Security, Federal Emergency Management Agency. https://www.fema.gov/sites/default/files/documents/fema_state-flood-risk-disclosure-best-practices_07142022.pdf

75. Harvard Joint Center for Housing Studies, 2022: America's Rental Housing 2022. Harvard University. https://www.jchs.harvard.edu/americas-rental-housing-2022

76. Bathi, J.R. and H.S. Das, 2016: Vulnerability of coastal communities from storm surge and flood disasters. *International Journal of Environmental Research and Public Health*, **13** (2), 239. https://doi.org/10.3390/ijerph13020239

77. Kusenbach, M., J.L. Simms, and G.A. Tobin, 2010: Disaster vulnerability and evacuation readiness: Coastal mobile home residents in Florida. *Natural Hazards*, **52** (1), 79–95. https://doi.org/10.1007/s11069-009-9358-3

78. Emrich, C.T., S.K. Aksha, and Y. Zhou, 2022: Assessing distributive inequities in FEMA's disaster recovery assistance fund allocation. *International Journal of Disaster Risk Reduction*, **74**, 102855. https://doi.org/10.1016/j.ijdrr.2022.102855

79. Thomson, H., H.B. Zeff, R. Kleiman, A. Sebastian, and G.W. Characklis, 2023: Systemic financial risk arising from residential flood losses. *Earth's Future*, **11** (4), e2022EF003206. https://doi.org/10.1029/2022ef003206

80. Wilson, B., E. Tate, and C.T. Emrich, 2021: Flood recovery outcomes and disaster assistance barriers for vulnerable populations. *Frontiers in Water*, **3**, 752307. https://doi.org/10.3389/frwa.2021.752307

81. Gourevitch, J.D., C. Kousky, Y. Liao, C. Nolte, A.B. Pollack, J.R. Porter, and J.A. Weill, 2023: Unpriced climate risk and the potential consequences of overvaluation in US housing markets. *Nature Climate Change*, **13** (3), 250–257. https://doi.org/10.1038/s41558-023-01594-8

82. Chew, G.L., J. Wilson, F.A. Rabito, F. Grimsley, S. Iqbal, T. Reponen, M.L. Muilenberg, P.S. Thorne, D.G. Dearborn, and R.L. Morley, 2006: Mold and endotoxin levels in the aftermath of Hurricane Katrina: A pilot project of homes in New Orleans undergoing renovation. *Environmental Health Perspectives*, **114** (12), 1883–1889. https://doi.org/10.1289/ehp.9258

83. Ebi, K.L., J. Vanos, J.W. Baldwin, J.E. Bell, D.M. Hondula, N.A. Errett, K. Hayes, C.E. Reid, S. Saha, J. Spector, and P. Berry, 2021: Extreme weather and climate change: Population health and health system implications. *Annual Review of Public Health*, **42** (1), 293–315. https://doi.org/10.1146/annurev-publhealth-012420-105026

84. Vorhees, L., J. Harrison, M. O'Driscoll, C. Humphrey, and J. Bowden, 2022: Climate change and onsite wastewater treatment systems in the coastal Carolinas: Perspectives from wastewater managers. *Weather, Climate, and Society*, **14** (4), 1287–1305. https://doi.org/10.1175/wcas-d-21-0192.1

85. Paterson, D.L., H. Wright, and P.N.A. Harris, 2018: Health risks of flood disasters. *Clinical Infectious Diseases*, **67** (9), 1450–1454. https://doi.org/10.1093/cid/ciy227

86. Ramesh, B., M.A. Jagger, B. Zaitchik, K.N. Kolivras, S. Swarup, L. Deanes, and J.M. Gohlke, 2021: Emergency department visits associated with satellite observed flooding during and following Hurricane Harvey. *Journal of Exposure Science & Environmental Epidemiology*, **31** (5), 832–841. https://doi.org/10.1038/s41370-021-00361-1

87. Stearns, D. and K. Sircar, 2019: National unintentional carbon monoxide poisoning estimates using hospitalization and emergency department data. *The American Journal of Emergency Medicine*, **37** (3), 421–426. https://doi.org/10.1016/j.ajem.2018.06.002

88. Alderman, K., L.R. Turner, and S. Tong, 2012: Floods and human health: A systematic review. *Environment International*, **47**, 37–47. https://doi.org/10.1016/j.envint.2012.06.003

89. Melin, K. and N. Conte, 2018: Community pharmacists as first responders in Puerto Rico after Hurricane Maria. *Journal of the American Pharmacists Association*, **58** (2), 149. https://doi.org/10.1016/j.japh.2017.12.014

90. Azziz-Baumgartner, E., A. Wolkin, C. Sanchez, T. Bayleyegn, S. Young, S. Kieszak, K. Oberst, D. Batts, C.C. Thomas, and C. Rubin, 2005: Impact of Hurricane Ivan on pharmacies in Baldwin County Alabama. *Journal of the American Pharmacists Association*, **45** (6), 670–675. https://doi.org/10.1331/154434505774909634

91. Tarabochia-Gast, A.T., D.R. Michanowicz, and A.S. Bernstein, 2022: Flood risk to hospitals on the United States Atlantic and Gulf Coasts from hurricanes and sea level rise. *GeoHealth*, **6** (10), e2022GH000651. https://doi.org/10.1029/2022gh000651

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

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

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

95. Balaguru, K., W. Xu, C.-C. Chang, L.R. Leung, D.R. Judi, S.M. Hagos, M.F. Wehner, J.P. Kossin, and M. Ting, 2023: Increased U.S. coastal hurricane risk under climate change. *Science Advances*, **9** (14), 0259. https://doi.org/10.1126/sciadv.adf0259

96. Garner, A.J., R.E. Kopp, and B.P. Horton, 2021: Evolving tropical cyclone tracks in the North Atlantic in a warming climate. *Earth's Future*, **9** (12), e2021EF002326. https://doi.org/10.1029/2021ef002326

97. Hotakainen, R., 2021: Ida's rapid intensification an ominous sign of climate future. *E&E News*, August 30, 2021. https://www.eenews.net/articles/idas-rapid-intensification-an-ominous-sign-of-climate-future/

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

99. Balaguru, K., G.R. Foltz, L.R. Leung, W. Xu, D. Kim, H. Lopez, and R. West, 2022: Increasing hurricane intensification rate near the US Atlantic coast. *Geophysical Research Letters*, **49** (20), e2022GL099793. https://doi.org/10.1029/2022gl099793

100. Bishop, D.A., A.P. Williams, and R. Seager, 2019: Increased fall precipitation in the southeastern United States driven by higher-intensity, frontal precipitation. *Geophysical Research Letters*, **46** (14), 8300–8309. https://doi.org/10.1029/2019gl083177

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

102. Mahoney, K., D.L. Jackson, P. Neiman, M. Hughes, L. Darby, G. Wick, A. White, E. Sukovich, and R. Cifelli, 2016: Understanding the role of atmospheric rivers in heavy precipitation in the southeast United States. *Monthly Weather Review*, **144** (4), 1617–1632. https://doi.org/10.1175/mwr-d-15-0279.1

103. Maxwell, J.T., P.A. Knapp, J.T. Ortegren, D.L. Ficklin, and P.T. Soulé, 2017: Changes in the mechanisms causing rapid drought cessation in the southeastern United States. *Geophysical Research Letters*, **44** (24), 12476–12483. https://doi.org/10.1002/2017gl076261

104. Miller, D.K., D. Hotz, J. Winton, and L. Stewart, 2018: Investigation of atmospheric rivers impacting the Pigeon River Basin of the southern Appalachian Mountains. *Weather and Forecasting*, **33** (1), 283–299. https://doi.org/10.1175/waf-d-17-0060.1

105. Miller, D.K., C.F. Miniat, R.M. Wooten, and A.P. Barros, 2019: An expanded investigation of atmospheric rivers in the southern Appalachian Mountains and their connection to landslides. *Atmosphere*, **10** (2), 71. https://doi.org/10.3390/atmos10020071

106. Mahajan, S., Q. Tang, N.D. Keen, J.-C. Golaz, and L.P. van Roekel, 2022: Simulation of ENSO teleconnections to precipitation extremes over the United States in the high-resolution version of E3SM. *Journal of Climate*, **35** (11), 3371–3393. https://doi.org/10.1175/jcli-d-20-1011.1

107. Patricola, C.M., J.P. O'Brien, M.D. Risser, A.M. Rhoades, T.A. O'Brien, P.A. Ullrich, D.A. Stone, and W.D. Collins, 2020: Maximizing ENSO as a source of western US hydroclimate predictability. *Climate Dynamics*, **54** (1), 351–372. https://doi.org/10.1007/s00382-019-05004-8

108. Alipour, A., A. Ahmadalipour, and H. Moradkhani, 2020: Assessing flash flood hazard and damages in the southeast United States. *Journal of Flood Risk Management*, **13** (2), 12605. https://doi.org/10.1111/jfr3.12605

109. Debbage, N. and J.M. Shepherd, 2019: Urban influences on the spatiotemporal characteristics of runoff and precipitation during the 2009 Atlanta flood. *Journal of Hydrometeorology*, **20** (1), 3–21. https://doi.org/10.1175/jhm-d-18-0010.1

110. Forney, R.K., N. Debbage, P. Miller, and J. Uzquiano, 2022: Urban effects on weakly forced thunderstorms observed in the Southeast United States. *Urban Climate*, **43**, 101161. https://doi.org/10.1016/j.uclim.2022.101161

111. Liu, J. and D. Niyogi, 2019: Meta-analysis of urbanization impact on rainfall modification. *Scientific Reports*, **9** (1), 7301. https://doi.org/10.1038/s41598-019-42494-2

112. McLeod, J., M. Shepherd, and C.E. Konrad, 2017: Spatio-temporal rainfall patterns around Atlanta, Georgia and possible relationships to urban land cover. *Urban Climate*, **21**, 27–42. https://doi.org/10.1016/j.uclim.2017.03.004

113. Naylor, J. and A.D. Kennedy, 2021: Variability in isolated convective activity between Louisville, Kentucky, and nearby rural locations. *Earth Interactions*, **25** (1), 33–45. https://doi.org/10.1175/ei-d-20-0012.1

114. Bhatia, K., G. Vecchi, H. Murakami, S. Underwood, and J. Kossin, 2018: Projected response of tropical cyclone intensity and intensification in a global climate model. *Journal of Climate*, **31** (20), 8281–8303. https://doi.org/10.1175/jcli-d-17-0898.1

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

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

117. Wright, D.B., T.R. Knutson, and J.A. Smith, 2015: Regional climate model projections of rainfall from U.S. landfalling tropical cyclones. *Climate Dynamics*, **45** (11), 3365–3379. https://doi.org/10.1007/s00382-015-2544-y

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

119. Martel, J.L., F.P. Brissette, P. Lucas-Picher, M. Troin, and R. Arsenault, 2021: Climate change and rainfall intensity–duration–frequency curves: Overview of science and guidelines for adaptation. *Journal of Hydrologic Engineering*, **26** (10), 03121001. https://doi.org/10.1061/(asce)he.1943-5584.0002122

120. Cook, L.M., S. McGinnis, and C. Samaras, 2020: The effect of modeling choices on updating intensity-duration-frequency curves and stormwater infrastructure designs for climate change. *Climatic Change*, **159** (2), 289–308. https://doi.org/10.1007/s10584-019-02649-6

121. Miro, M., A.T. DeGaetano, T. Lopez-Cantu, C. Samaras, M. Webber, and K.R. Grocholski, 2021: Developing Future Projected Intensity-Duration-Frequency (IDF) Curves: A Technical Report on Data, Methods, and IDF Curves for the Chesapeake Bay Watershed and Virginia. TL-A1365-1. RAND Corporation, Santa Monica, CA, 62 pp. https://doi.org/10.7249/tla1365-1

122. Lopez-Cantu, T. and C. Samaras, 2018: Temporal and spatial evaluation of stormwater engineering standards reveals risks and priorities across the United States. *Environmental Research Letters*, **13** (7), 074006. https://doi.org/10.1088/1748-9326/aac696

123. Vu, T.M. and A.K. Mishra, 2019: Nonstationary frequency analysis of the recent extreme precipitation events in the United States. *Journal of Hydrology*, **575**, 999–1010. https://doi.org/10.1016/j.jhydrol.2019.05.090

124. Jalowska, A.M., T.L. Spero, and J.H. Bowden, 2021: Projecting changes in extreme rainfall from three tropical cyclones using the design-rainfall approach. *npj Climate and Atmospheric Science*, **4** (1), 1–8. https://doi.org/10.1038/s41612-021-00176-9

125. Bin, O. and J.B. Kruse, 2006: Real estate market response to coastal flood hazards. *Natural Hazards Review*, **7** (4), 137–144. https://doi.org/10.1061/(asce)1527-6988(2006)7:4(137)

126. Wang, Z., S. Zlatanova, and P. van Oosterom, 2017: Path planning for first responders in the presence of moving obstacles with uncertain boundaries. *IEEE Transactions on Intelligent Transportation Systems*, **18** (8), 2163–2173. https://doi.org/10.1109/tits.2016.2634079

127. Gori, A., R. Blessing, A. Juan, S. Brody, and P. Bedient, 2019: Characterizing urbanization impacts on floodplain through integrated land use, hydrologic, and hydraulic modeling. *Journal of Hydrology*, **568**, 82–95. https://doi.org/10.1016/j.jhydrol.2018.10.053

128. Ghanbari, M., M. Arabi, S. Kao, J. Obeysekera, and W. Sweet, 2021: Climate change and changes in compound coastal-riverine flooding hazard along the U.S. coasts. *Earth's Future*, **9** (5), e2021EF002055. https://doi.org/10.1029/2021ef002055

129. Fiaschi, S. and S. Wdowinski, 2020: Local land subsidence in Miami Beach (FL) and Norfolk (VA) and its contribution to flooding hazard in coastal communities along the U.S. Atlantic coast. *Ocean & Coastal Management*, **187**, 105078. https://doi.org/10.1016/j.ocecoaman.2019.105078

130. Smart, L.S., P.J. Taillie, B. Poulter, J. Vukomanovic, K.K. Singh, J.J. Swenson, H. Mitasova, J.W. Smith, and R.K. Meentemeyer, 2020: Aboveground carbon loss associated with the spread of ghost forests as sea levels rise. *Environmental Research Letters*, **15** (10), 104028. https://doi.org/10.1088/1748-9326/aba136

131. Tully, K., K. Gedan, R. Epanchin-Niell, A. Strong, E.S. Bernhardt, T. BenDor, M. Mitchell, J. Kominoski, T.E. Jordan, S.C. Neubauer, and N.B. Weston, 2019: The invisible flood: The chemistry, ecology, and social implications of coastal saltwater intrusion. *BioScience*, **69** (5), 368–378. https://doi.org/10.1093/biosci/biz027

132. Gibson, N., S. McNulty, C. Miller, M. Gavazzi, E. Worley, D. Keesee, and D. Hollinger, 2021: Identification, Mitigation, and Adaptation to Salinization on Working Lands in the U.S. Southeast. Gen. Tech. Rep. SRS-259. U.S. Department of Agriculture, Forest Service, Southern Research Station, Asheville, NC, 69 pp. https://doi.org/10.2737/srs-gtr-259

133. CO-OPS, 2023: Annual High Tide Flooding Outlook. National Oceanic and Atmospheric Administration, National Ocean Service, Center for Operational Oceanographic Products and Services, accessed August 15, 2023. https://tidesandcurrents.noaa.gov/high-tide-flooding/annual-outlook.html

134. Findling, M.T.G., R.J. Blendon, J.M. Benson, and C. Miller, 2022: The unseen picture: Issues with health care, discrimination, police and safety, and housing experienced by Native American populations in rural America. *The Journal of Rural Health*, **38** (1), 180–186. https://doi.org/10.1111/jrh.12517

135. Ching, A., L. Morrison, and M. Kelley, 2020: Living with natural hazards: Tropical storms, lava flows and the resilience of island residents. *International Journal of Disaster Risk Reduction*, **47**, 101546. https://doi.org/10.1016/j.ijdrr.2020.101546

136. Farrell, J., P.B. Burow, K. McConnell, J. Bayham, K. Whyte, and G. Koss, 2021: Effects of land dispossession and forced migration on Indigenous peoples in North America. *Science*, **374** (6567), 4943. https://doi.org/10.1126/science.abe4943

137. King, D.N., J. Goff, and A. Skipper, 2007: Māori environmental knowledge and natural hazards in Aotearoa-New Zealand. *Journal of the Royal Society of New Zealand*, **37** (2), 59–73. https://doi.org/10.1080/03014220709510536

138. Oliver-Smith, A., 2009: *Sea Level Rise and the Vulnerability of Coastal Peoples: Responding to the Local Challenges of Global Climate Change in the 21st Century*. *InterSecTions: 'Interdisciplinary Security ConnecTions'*. United Nations University, Institute for Environment and Human Security, Bonn, Germany. https://www.unisdr.org/files/14028_4097.pdf

139. Burnette, C.E., 2018: Family and cultural protective factors as the bedrock of resilience and growth for Indigenous women who have experienced violence. *Journal of Family Social Work*, **21** (1), 45–62. https://doi.org/10.1080/10522158.2017.1402532

140. Weiskopf, S.R., M.A. Rubenstein, L.G. Crozier, S. Gaichas, R. Griffis, J.E. Halofsky, K.J. Hyde, T.L. Morelli, J.T. Morisette, R.C. Muñoz, A.J. Pershing, D.L. Petersone, R. Poudel, M.D. Staudinger, A.E. Sutton-Grier, L. Thompson, J. Vose, J.F. Weltzin, and K.P. Whyte, 2020: Climate change effects on biodiversity, ecosystems, ecosystem services, and natural resource management in the United States. *Science of The Total Environment*, **733**, 137782. https://doi.org/10.1016/j.scitotenv.2020.137782

141. Whitney, C.K., A. Frid, B.K. Edgar, J. Walkus, P. Siwallace, I.L. Siwallace, and N.C. Ban, 2020: "Like the plains people losing the buffalo": Perceptions of climate change impacts, fisheries management, and adaptation actions by Indigenous peoples in coastal British Columbia, Canada. *Ecology and Society*, **25** (4), 33. https://doi.org/10.5751/es-12027-250433

142. Rogers, L.A., R. Griffin, T. Young, E. Fuller, K.S. Martin, and M.L. Pinsky, 2019: Shifting habitats expose fishing communities to risk under climate change. *Nature Climate Change*, **9** (7), 512–516. https://doi.org/10.1038/s41558-019-0503-z

143. Pearson, J., G. Jackson, and K.E. McNamara, 2023: Climate-driven losses to Indigenous and local knowledge and cultural heritage. *The Anthropocene Review*, **10** (2), 343–366. https://doi.org/10.1177/20530196211005482

144. Anderson, D.G., T.G. Bissett, S.J. Yerka, J.J. Wells, E.C. Kansa, S.W. Kansa, K.N. Myers, R.C. DeMuth, and D.A. White, 2017: Sea-level rise and archaeological site destruction: An example from the southeastern United States using DINAA (Digital Index of North American Archaeology). *PLoS ONE*, **12** (11), e0188142. https://doi.org/10.1371/journal.pone.0188142

145. Osland, M.J., B. Chivoiu, N.M. Enwright, K.M. Thorne, G.R. Guntenspergen, J.B. Grace, L.L. Dale, W. Brooks, N. Herold, J.W. Day, F.H. Sklar, and C.M. Swarzenzki, 2022: Migration and transformation of coastal wetlands in response to rising seas. *Science Advances*, **8** (26), 5174. https://doi.org/10.1126/sciadv.abo5174

146. Aune, K.T., D. Gesch, and G.S. Smith, 2020: A spatial analysis of climate gentrification in Orleans Parish, Louisiana post-Hurricane Katrina. *Environmental Research*, **185**, 109384. https://doi.org/10.1016/j.envres.2020.109384

147. Bonjour, R., 2019: Flooding the cities: How land use policies contribute to climate gentrification. *Seton Hall Legislative Journal*, **44** (1), 91–114. https://scholarship.shu.edu/shlj/vol44/iss1/4

148. Marandi, A. and K.L. Main, 2021: Vulnerable city, recipient city, or climate destination? Towards a typology of domestic climate migration impacts in US cities. *Journal of Environmental Studies and Sciences*, **11** (3), 465–480. https://doi.org/10.1007/s13412-021-00712-2

149. Evans, L.E., N. Dolšak, M.T. Plog, and A. Prakash, 2020: Native American tribal governments, cross-sectoral climate policy, and the role of intertribal networks. *Climatic Change*, **160** (1), 35–43. https://doi.org/10.1007/s10584-019-02641-0

150. Constible, J., 2022: Hazard planners aren't planning for heat hazards. *Natural Resources Defense Council Blog*. https://www.nrdc.org/bio/juanita-constible/hazard-planners-arent-planning-heat-hazards

151. Horney, J., M. Nguyen, D. Salvesen, C. Dwyer, J. Cooper, and P. Berke, 2017: Assessing the quality of rural hazard mitigation plans in the southeastern United States. *Journal of Planning Education and Research*, **37** (1), 56–65. https://doi.org/10.1177/0739456x16628605

152. Moore, M., P. Chaney, E. Brantley, and C. Burton, 2021: Drought management plans of major cities in Alabama v. California. *Southeastern Geographer*, **61**, 31–48. https://doi.org/10.1353/sgo.2021.0003

153. Moore, M.K. 2019: Drought Management Plans in Major Cities of the Southeastern U.S. v. Western U.S. Master of Science, Auburn University. https://etd.auburn.edu//handle/10415/6686

154. Mach, K.J. and A.R. Siders, 2021: Reframing strategic, managed retreat for transformative climate adaptation. *Science*, **372** (6548), 1294–1299. https://doi.org/10.1126/science.abh1894

155. Weber, A., 2021: Building resilience, BRIC by BRIC. Natural Resources Defense Council. https://www.nrdc.org/experts/anna-weber/building-resilience-bric-bric

156. FEMA, 2021: 2022–2026 FEMA Strategic Plan: Building the FEMA Our Nation Needs and Deserves. U.S. Department of Homeland Security, Federal Emergency Management Agency. https://www.fema.gov/about/strategic-plan

157. FEMA, 2021: FEMA Resources for Climate Resilience. U.S. Department of Homeland Security, Federal Emergency Management Agency. https://www.fema.gov/sites/default/files/documents/fema_resources-climate-resilience.pdf

158. IPCC, 2012: *Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation. A Special Report of Working Groups I and II of the Intergovernmental Panel on Climate Change*. Field, C.B., V. Barros, T.F. Stocker, D. Qin, D.J. Dokken, K.L. Ebi, M.D. Mastrandrea, K.J. Mach, G.-K. Plattner, S.K. Allen, M. Tignor, and P.M. Midgley, Eds. Cambridge University Press, Cambridge, UK and New York, NY, USA, 582 pp. https://www.ipcc.ch/report/managing-the-risks-of-extreme-events-and-disasters-to-advance-climate-change-adaptation/

159. Meerow, S. and S.C. Woodruff, 2020: Seven principles of strong climate change planning. *Journal of the American Planning Association*, **86** (1), 39–46. https://doi.org/10.1080/01944363.2019.1652108

160. Woodruff, S., A.O. Bowman, B. Hannibal, G. Sansom, and K. Portney, 2021: Urban resilience: Analyzing the policies of U.S. cities. *Cities*, **115**, 103239. https://doi.org/10.1016/j.cities.2021.103239

161. Woodruff, S., S. Meerow, P. Gilbertson, B. Hannibal, M. Matos, M. Roy, M. Malecha, S. Yu, and P. Berke, 2021: Is flood resilience planning improving? A longitudinal analysis of networks of plans in Boston and Fort Lauderdale. *Climate Risk Management*, **34**, 100354. https://doi.org/10.1016/j.crm.2021.100354

162. Freudenberg, R., E. Calvin, L. Tolkoff, and D. Brawley, 2016: Buy-In for Buyouts: The Case for Managed Retreat from Flood Zones. Lincoln Institute of Land and Policy, Cambridge, MA. https://www.lincolninst.edu/sites/default/files/pubfiles/buy-in-for-buyouts-full.pdf

163. Godschalk, D.R., A. Rose, E. Mittler, K. Porter, and C.T. West, 2009: Estimating the value of foresight: Aggregate analysis of natural hazard mitigation benefits and costs. *Journal of Environmental Planning and Management*, **52** (6), 739–756. https://doi.org/10.1080/09640560903083715

164. Mach, K.J., C.M. Kraan, M. Hino, A.R. Siders, E.M. Johnston, and C.B. Field, 2019: Managed retreat through voluntary buyouts of flood-prone properties. *Science Advances*, **5** (10), 8995. https://doi.org/10.1126/sciadv.aax8995

165. Berke, P.R., W. Lyles, and G. Smith, 2014: Impacts of federal and state hazard mitigation policies on local land use policy. *Journal of Planning Education and Research*, **34** (1), 60–76. https://doi.org/10.1177/0739456x13517004

166. Burby, R.J., 2006: Hurricane Katrina and the paradoxes of government disaster policy: Bringing about wise governmental decisions for hazardous areas. *The ANNALS of the American Academy of Political and Social Science*, **604** (1), 171–191. https://doi.org/10.1177/0002716205284676

167. Butler, W.H., R.E. Deyle, and C. Mutnansky, 2016: Low-regrets incrementalism: Land use planning adaptation to accelerating sea level rise in Florida's coastal communities. *Journal of Planning Education and Research*, **36** (3), 319–332. https://doi.org/10.1177/0739456x16647161

168. Smith, G., J. Whitehead, N. Kaza, J. Park, J. Pine, R. Kolar, D. Sandler, and E. Thomas, 2013: Aggregate Flood Hazard Risk Reduction Scoping Project. U.S. Department of Homeland Security, Coastal Resilience Center. http://coastalhazardscenter.org/dev/wp-content/uploads/2013/12/Final_GS_12_16_13.pdf

169. Young, A.W., 2018: How to retreat: The necessary transition from buyouts to leasing. *Coastal Management*, **46** (5), 527–535. https://doi.org/10.1080/08920753.2018.1498716

170. McGhee, D.J., S.B. Binder, and E.A. Albright, 2020: First, do no harm: Evaluating the vulnerability reduction of post-disaster home buyout programs. *Natural Hazards Review*, **21** (1), 05019002. https://doi.org/10.1061/(asce)nh.1527-6996.0000337

171. Zavar, E. and L.A. Fischer, 2021: Fractured landscapes: The racialization of home buyout programs and climate adaptation. *Current Research in Environmental Sustainability*, **3**, 100043. https://doi.org/10.1016/j.crsust.2021.100043

172. Clark, M.B., E. Nkonya, and G.L. Galford, 2022: Flocking to fire: How climate and natural hazards shape human migration across the United States. *Frontiers in Human Dynamics*, **4**, 886545. https://doi.org/10.3389/fhumd.2022.886545

173. Smith, G.P. and M.T. Nguyen, 2021: University-public partnerships for disaster recovery: Promoting community resilience through research, teaching, and engagement. *Journal of Community Engagement and Scholarship*, **14** (1), 4. https://jces.ua.edu/articles/10.54656/NPFV8067

174. Baker, C.K., S.B. Binder, A. Greer, P. Weir, and K. Gates, 2018: Integrating community concerns and recommendations into home buyout and relocation policy. *Risk, Hazards & Crisis in Public Policy*, **9** (4), 455–479. https://doi.org/10.1002/rhc3.12144

175. Binder, S.B. and A. Greer, 2018: Exploring the Role of Implementing Agencies in Home Buyouts: Process, Equity, and Inclusion in Program Design and Implementation. Natural Hazards Center Quick Response Grant Report Series, 281. University of Colorado Boulder, Natural Hazards Center, Boulder, CO. https://hazards.colorado.edu/quick-response-report/exploring-the-role-of-implementing-agencies-in-home-buyouts-process-equity-and-inclusion-in-program-design-and-implementation

176. de Vries, D.H. and J.C. Fraser, 2012: Citizenship rights and voluntary decision making in post-disaster U.S. floodplain buyout mitigation programs. *International Journal of Mass Emergencies and Disasters*, **30** (1). https://hdl.handle.net/11245/1.369610

177. Elliott, J.R., P.L. Brown, and K. Loughran, 2020: Racial inequities in the federal buyout of flood-prone homes: A nationwide assessment of environmental adaptation. *Socius*, **6**, 2378023120905439. https://doi.org/10.1177/2378023120905439

178. Fraser, J., R. Elmore, D. Godschalk, and W. Rohe, 2003: Implementing Floodplain Land Acquisition Programs in Urban Localities. University of North Carolina at Chapel Hill, Center for Urban & Regional Studies, Chapel Hill, NC. https://www.academia.edu/27892388/implementing_floodplain_land_acquisition_programs_in_urban_localities

179. Nguyen, C.N., 2020: Homeowners' choice when the government proposes a managed retreat. *International Journal of Disaster Risk Reduction*, **47**, 101543. https://doi.org/10.1016/j.ijdrr.2020.101543

180. Flink, C.A., 2020: *The Greenway Imperative: Connecting Communities and Landscapes for a Sustainable Future*. University of Florida Press, 344 pp. https://upf.com/book.asp?id=9781683401155#

181. Highfield, W., A. Kayode, S. Brody, C. Shepard, and L. Verdone, 2019: Strategic Property Buyouts to Enhance Flood Resilience: Creating a Model for Flood Risk Reduction, Community Protection and Environmental Gains. The Nature Conservancy, Washington, DC. https://www.nature.org/content/dam/tnc/nature/en/documents/harveybuyoutsummary.pdf

182. Kihslinger, R., A. Streitwieser, M. Lerner, N. Moraga-Lewy, K. James-Kavanaugh, D. Salvesen, J. Anagnost, T. Chandler, C. Foster, and S. Liu, 2017: Floodplain Buyouts: An Action Guide for Local Governments on How to Maximize Community Benefits, Habitat Connectivity, and Resilience. Environmental Law Institute and University of North Carolina at Chapel Hill, Washington, DC and Chapel Hill, NC. https://www.eli.org/sites/default/files/eli-pubs/actionguide-web.pdf

183. Keenan, J.M., T. Hill, and A. Gumber, 2018: Climate gentrification: From theory to empiricism in Miami-Dade County, Florida. *Environmental Research Letters*, **13** (5), 054001. https://doi.org/10.1088/1748-9326/aabb32

184. Taylor, Z.J. and M.B. Aalbers, 2022: Climate gentrification: Risk, rent, and restructuring in Greater Miami. *Annals of the American Association of Geographers*, **112** (6), 1685–1701. https://doi.org/10.1080/24694452.2021.2000358

185. Treuer, G., K. Broad, and R. Meyer, 2018: Using simulations to forecast homeowner response to sea level rise in South Florida: Will they stay or will they go? *Global Environmental Change*, **48**, 108–118. https://doi.org/10.1016/j.gloenvcha.2017.10.008

186. Anguelovski, I., J.J.T. Connolly, H. Cole, M. Garcia-Lamarca, M. Triguero-Mas, F. Baró, N. Martin, D. Conesa, G. Shokry, C.P. del Pulgar, L.A. Ramos, A. Matheney, E. Gallez, E. Oscilowicz, J.L. Máñez, B. Sarzo, M.A. Beltrán, and J.M. Minaya, 2022: Green gentrification in European and North American cities. *Nature Communications*, **13** (1), 3816. https://doi.org/10.1038/s41467-022-31572-1

187. Melix, B.L., A. Jackson, W. Butler, T. Holmes, and C.K. Uejio, 2022: Locating neighborhood displacement risks to climate gentrification pressures in three coastal counties in Florida. *The Professional Geographer*, **75** (1), 31–43. https://doi.org/10.1080/00330124.2022.2087695

188. Gardiner, E.P., D.D. Herring, and J.F. Fox, 2019: The U.S. Climate Resilience Toolkit: Evidence of progress. *Climatic Change*, **153** (4), 477–490. https://doi.org/10.1007/s10584-018-2216-0

189. Resilient Cities Network, 2022: Resilient Cities Network [Website]. https://resilientcitiesnetwork.org/

190. APHA, 2021: Climate Change and Health Playbook: Adaptation Planning for Justice, Equity, Diversity and Inclusion. American Public Health Association. https://apha.org/topics-and-issues/climate-change/jedi

191. Grace-McCaskey, C.A., S.C. Pearce, L. Harris, M. Corra, and K.J. Evans, 2021: Finding voices in the floods of Freedom Hill: Innovating solutions in Princeville, North Carolina. *Journal of Environmental Studies and Sciences*, **11** (3), 341–351. https://doi.org/10.1007/s13412-021-00701-5

192. Blue, V.E., 2000: Reclaiming sacred ground: How Princeville is recovering from the flood of 1999. *NC Crossroads*, **4** (3). https://www.ncpedia.org/anchor/reclaiming-sacred-ground-how

193. Jadid, R., B.M. Montoya, V. Bennett, and M.A. Gabr, 2020: Effect of repeated rise and fall of water level on seepage-induced deformation and related stability analysis of Princeville levee. *Engineering Geology*, **266**, 105458. https://doi.org/10.1016/j.enggeo.2019.105458

194. Phillips, B., P.A. Stukes, and P. Jenkins, 2012: Freedom Hill is not for sale—And neither is the Lower Ninth Ward. *Journal of Black Studies*, **43** (4), 405–426. https://doi.org/10.1177/0021934711425489

195. Ebi, K.L. and J.J. Hess, 2020: Health risks due to climate change: Inequity in causes and consequences. *Health Affairs*, **39** (12), 2056–2062. https://doi.org/10.1377/hlthaff.2020.01125

196. Dwyer-Lindgren, L., A. Bertozzi-Villa, R.W. Stubbs, C. Morozoff, J.P. Mackenbach, F.J. van Lenthe, A.H. Mokdad, and C.J.L. Murray, 2017: Inequalities in life expectancy among US counties, 1980 to 2014: Temporal trends and key drivers. *JAMA Internal Medicine*, **177** (7), 1003–1011. https://doi.org/10.1001/jamainternmed.2017.0918

197. Gong, G., S.G. Phillips, C. Hudson, D. Curti, and B.U. Philips, 2019: Higher US rural mortality rates linked to socioeconomic status, physician shortages, and lack of health insurance. *Health Affairs*, **38** (12), 2003–2010. https://doi.org/10.1377/hlthaff.2019.00722

198. Walk Score, 2022: Most Walkable Cities in the United States, Canada, and Australia on Walk Score. Redfin. https://www.walkscore.com/cities-and-neighborhoods/

199. Smart Growth America, 2021: Dangerous by Design. Smart Growth America and National Complete Streets Coalition, 38 pp. https://smartgrowthamerica.org/resources/dangerous-by-design-2021-report/

200. NHTSA, n.d.: Fatality Analysis Reporting System. U.S. Department of Transportation, National Highway Traffic Safety Administration, accessed November 28, 2022. https://www.nhtsa.gov/crash-data-systems/fatality-analysis-reporting-system

201. Meyer, P.A., P.W. Yoon, and R.B. Kaufmann, 2013: Introduction: CDC Health Disparities and Inequalities Report—United States, 2013. *Morbidity and Mortality Weekly Report*, **62** (3), 3–5. http://www.cdc.gov/mmwr/pdf/other/su6203.pdf

202. Yearby, R., 2018: Racial disparities in health status and access to healthcare: The continuation of inequality in the United States due to structural racism. *The American Journal of Economics and Sociology*, **77** (3–4), 1113–1152. https://doi.org/10.1111/ajes.12230

203. Savitz, D.A. and H. Hu, 2021: Ambient heat and stillbirth in northern and central Florida. *Environmental Research*, **199**, 111262. https://doi.org/10.1016/j.envres.2021.111262

204. Son, J.-Y., H.M. Choi, M.L. Miranda, and M.L. Bell, 2022: Exposure to heat during pregnancy and preterm birth in North Carolina: Main effect and disparities by residential greenness, urbanicity, and socioeconomic status. *Environmental Research*, **204**, 112315. https://doi.org/10.1016/j.envres.2021.112315

205. Syed, S., T.L. O'Sullivan, and K.P. Phillips, 2022: Extreme heat and pregnancy outcomes: A scoping review of the epidemiological evidence. *International Journal of Environmental Research and Public Health*, **19** (4), 2412. https://doi.org/10.3390/ijerph19042412

206. Cheng, J., Z. Xu, H. Bambrick, V. Prescott, N. Wang, Y. Zhang, H. Su, S. Tong, and W. Hu, 2019: Cardiorespiratory effects of heatwaves: A systematic review and meta-analysis of global epidemiological evidence. *Environmental Research*, **177**, 108610. https://doi.org/10.1016/j.envres.2019.108610

207. Uejio, C.K., A.P. Joiner, E. Gonsoroski, J.D. Tamerius, J. Jung, T.P. Moran, and A.H. Yancey, 2022: The association of indoor heat exposure with diabetes and respiratory 9-1-1 calls through emergency medical dispatch and services documentation. *Environmental Research*, **212**, 113271. https://doi.org/10.1016/j.envres.2022.113271

208. Sheffield, P.E., M.T. Herrera, E.J. Kinnee, and J.E. Clougherty, 2018: Not so little differences: Variation in hot weather risk to young children in New York City. *Public Health*, **161**, 119–126. https://doi.org/10.1016/j.puhe.2018.06.004

209. Ebi, K.L., A. Capon, P. Berry, C. Broderick, R. de Dear, G. Havenith, Y. Honda, R.S. Kovats, W. Ma, A. Malik, N.B. Morris, L. Nybo, S.I. Seneviratne, J. Vanos, and O. Jay, 2021: Hot weather and heat extremes: Health risks. *The Lancet*, **398** (10301), 698–708. https://doi.org/10.1016/s0140-6736(21)01208-3

210. Nori-Sarma, A., S. Sun, Y. Sun, K.R. Spangler, R. Oblath, S. Galea, J.L. Gradus, and G.A. Wellenius, 2022: Association between ambient heat and risk of emergency department visits for mental health among US adults, 2010 to 2019. *JAMA Psychiatry*, **79** (4), 341–349. https://doi.org/10.1001/jamapsychiatry.2021.4369

211. Thompson, R., R. Hornigold, L. Page, and T. Waite, 2018: Associations between high ambient temperatures and heat waves with mental health outcomes: A systematic review. *Public Health*, **161**, 171–191. https://doi.org/10.1016/j.puhe.2018.06.008

212. Atlantic Council, 2021: Extreme Heat: The Economic and Social Consequences for the United States. Atlantic Council's Adrienne Arsht Rockefeller Foundation Resilience Center, Washington, DC. https://www.atlanticcouncil.org/wp-content/uploads/2021/08/Extreme-Heat-Report-2021.pdf

213. Dahl, K. and R. Licker, 2021: Too Hot to Work: Assessing the Threats Climate Change Poses to Outdoor Workers. Union of Concerned Scientists, Cambridge, MA. https://doi.org/10.47923/2021.14236

214. Adams, W.M., 2019: Exertional heat stroke within secondary school athletics. *Current Sports Medicine Reports*, **18** (4), 149–153. https://doi.org/10.1249/jsr.0000000000000585

215. Cooper, E.R., M.S. Ferrara, D.J. Casa, J.W. Powell, S.P. Broglio, J.E. Resch, and R.W. Courson, 2016: Exertional heat illness in American football players: When is the risk greatest? *Journal of Athletic Training*, **51** (8), 593–600. https://doi.org/10.4085/1062-6050-51.8.08

216. Yeargin, S.W., T.P. Dompier, D.J. Casa, R.M. Hirschhorn, and Z.Y. Kerr, 2019: Epidemiology of exertional heat illnesses in National Collegiate Athletic Association athletes during the 2009–2010 through 2014–2015 academic years. *Journal of Athletic Training*, **54** (1), 55–63. https://doi.org/10.4085/1062-6050-504-17

217. Holt, D., 2015: Heat in US Prisons and Jails: Corrections and the Challenge of Climate Change. Columbia Law School, Sabin Center for Climate Change Law, New York, NY, 144 pp. https://nicic.gov/heat-us-prisons-and-jails-corrections-and-challenge-climate-change

218. Schwarz, L., E.M. Castillo, T.C. Chan, J.J. Brennan, E.S. Sbiroli, G. Carrasco-Escobar, A. Nguyen, R.E.S. Clemesha, A. Gershunov, and T. Benmarhnia, 2022: Heat waves and emergency department visits among the homeless, San Diego, 2012–2019. *American Journal of Public Health*, **112** (1), 98–106. https://doi.org/10.2105/ajph.2021.306557

219. Obringer, R., R. Nateghi, D. Maia-Silva, S. Mukherjee, V. Cr, D.B. McRoberts, and R. Kumar, 2022: Implications of increasing household air conditioning use across the United States under a warming climate. *Earth's Future*, **10** (1), e2021EF002434. https://doi.org/10.1029/2021ef002434

220. Romitti, Y., I. Sue Wing, K.R. Spangler, and G.A. Wellenius, 2022: Inequality in the availability of residential air conditioning across 115 US metropolitan areas. *PNAS Nexus*, **1** (4), 210. https://doi.org/10.1093/pnasnexus/pgac210

221. EIA. 2020: Forms EIA-457A and EIA-457C of the 2015 Residential Energy Consumption Survey. U.S. Energy Information Administration, Office of Energy Demand and Integrated Statistics. https://www.eia.gov/consumption/residential/data/2020/hc/pdf/hc%2011.1.pdf

222. Bryan, W. and M. Kelley, 2021: Energy Insecurity Fundamentals for the Southeast. Southeast Energy Efficiency Alliance, 19 pp. https://issuu.com/seealliance/docs/report_energyinsecurity_02_15_2021_v1

223. Stone Jr., B., E. Mallen, M. Rajput, A. Broadbent, E.S. Krayenhoff, G. Augenbroe, and M. Georgescu, 2021: Climate change and infrastructure risk: Indoor heat exposure during a concurrent heat wave and blackout event in Phoenix, Arizona. *Urban Climate*, **36**, 100787. https://doi.org/10.1016/j.uclim.2021.100787

224. Stone Jr., B., E. Mallen, M. Rajput, C.J. Gronlund, A.M. Broadbent, E.S. Krayenhoff, G. Augenbroe, M.S. O'Neill, and M. Georgescu, 2021: Compound climate and infrastructure events: How electrical grid failure alters heat wave risk. *Environmental Science & Technology*, **55** (10), 6957–6964. https://doi.org/10.1021/acs.est.1c00024

225. van Vliet, M.T.H., J.R. Yearsley, F. Ludwig, S. Vögele, D.P. Lettenmaier, and P. Kabat, 2012: Vulnerability of US and European electricity supply to climate change. *Nature Climate Change*, **2** (9), 676–681. https://doi.org/10.1038/nclimate1546

226. Mallen, E., 2022: U.S. Blackout Tracker. Urban Climate Lab, accessed November 18, 2022. https://urbanclimate.gatech.edu/current-projects/blackout-tracker/

227. Bryan, W.D., 2020: Energy Insecurity in the Southeast [Story Map]. Southeast Energy Efficiency Alliance, accessed August 16, 2023. https://storymaps.arcgis.com/stories/ce22fa68b37141f388d8df06c9bd4fb1

228. Allen, M., J. Hoffman, J.L. Whytlaw, and N. Hutton, 2022: Assessing Virginia cooling centers as a heat mitigation strategy. *Journal of Emergency Management*, **20** (3), 205–224. https://doi.org/10.5055/jem.0671

229. Tomer, A. and R. Puentes, 2011: Transit Access and Zero-Vehicle Households. The Brookings Institution. https://www.brookings.edu/research/transit-access-and-zero-vehicle-households/

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

231. EPA, 2021: Climate Change Indicators: Heat Waves. U.S. Environmental Protection Agency. https://www.epa.gov/climate-indicators/climate-change-indicators-heat-waves

232. Heo, S., M.L. Bell, and J.-T. Lee, 2019: Comparison of health risks by heat wave definition: Applicability of wet-bulb globe temperature for heat wave criteria. *Environmental Research*, **168**, 158–170. https://doi.org/10.1016/j.envres.2018.09.032

233. Rennie, J.J., M.A. Palecki, S.P. Heuser, and H.J. Diamond, 2021: Developing and validating heat exposure products using the U.S. Climate Reference Network. *Journal of Applied Meteorology and Climatology*, **60** (4), 543–558. https://doi.org/10.1175/jamc-d-20-0282.1

234. Knutson, T.R. and J.J. Ploshay, 2016: Detection of anthropogenic influence on a summertime heat stress index. *Climatic Change*, **138** (1), 25–39. https://doi.org/10.1007/s10584-016-1708-z

235. Li, C., X. Zhang, F. Zwiers, Y. Fang, and A.M. Michalak, 2017: Recent very hot summers in northern hemispheric land areas measured by wet bulb globe temperature will be the norm within 20 years. *Earth's Future*, **5** (12), 1203–1216. https://doi.org/10.1002/2017ef000639

236. Oke, T.R., 1982: The energetic basis of the urban heat island. *Quarterly Journal of the Royal Meteorological Society*, **108** (455), 1–24. https://doi.org/10.1002/qj.49710845502

237. Shandas, V., J. Voelkel, J. Williams, and J. Hoffman, 2019: Integrating satellite and ground measurements for predicting locations of extreme urban heat. *Climate*, **7** (1), 5. https://doi.org/10.3390/cli7010005

238. Benz, S.A. and J.A. Burney, 2021: Widespread race and class disparities in surface urban heat extremes across the United States. *Earth's Future*, **9** (7), e2021EF002016. https://doi.org/10.1029/2021ef002016

239. Shire, J., A. Vaidyanathan, M. Lackovic, and T. Bunn, 2020: Association between work-related hyperthermia emergency department visits and ambient heat in five southeastern states, 2010–2012—A case-crossover study. *GeoHealth*, **4** (8), 2019GH000241. https://doi.org/10.1029/2019gh000241

240. Lancet Countdown, 2020: Compounding Crises of Our Time During Hurricane Laura. 2020 Case Study 1. Lancet Countdown. https://www.lancetcountdownus.org/2020-case-study-1/

241. Baublitz, C.B., A.M. Fiore, O.E. Clifton, J. Mao, J. Li, G. Correa, D.M. Westervelt, L.W. Horowitz, F. Paulot, and A.P. Williams, 2020: Sensitivity of tropospheric ozone over the Southeast USA to dry deposition. *Geophysical Research Letters*, **47** (7), 2020GL087158. https://doi.org/10.1029/2020gl087158

242. Fu, T.M. and H. Tian, 2019: Climate change penalty to ozone air quality: Review of current understandings and knowledge gaps. *Current Pollution Reports*, **5** (3), 159–171. https://doi.org/10.1007/s40726-019-00115-6

243. Zhang, Y. and Y. Wang, 2016: Climate-driven ground-level ozone extreme in the fall over the southeast United States. *Proceedings of the National Academy of Sciences of the United States of America*, **113** (36), 10025–10030. https://doi.org/10.1073/pnas.1602563113

244. Brey, S.J., E.A. Barnes, J.R. Pierce, C. Wiedinmyer, and E.V. Fischer, 2018: Environmental conditions, ignition type, and air quality impacts of wildfires in the southeastern and western United States. *Earth's Future*, **6** (10), 1442–1456. https://doi.org/10.1029/2018ef000972

245. Guan, S., D.C. Wong, Y. Gao, T. Zhang, and G. Pouliot, 2020: Impact of wildfire on particulate matter in the southeastern United States in November 2016. *Science of The Total Environment*, **724**, 138354. https://doi.org/10.1016/j.scitotenv.2020.138354

246. Jaffe, D.A., S.M. O'Neill, N.K. Larkin, A.L. Holder, D.L. Peterson, J.E. Halofsky, and A.G. Rappold, 2020: Wildfire and prescribed burning impacts on air quality in the United States. *Journal of the Air & Waste Management Association*, **70** (6), 583–615. https://doi.org/10.1080/10962247.2020.1749731

247. van Donkelaar, A., R.V. Martin, C. Li, and R.T. Burnett, 2019: Regional estimates of chemical composition of fine particulate matter using a combined geoscience-statistical method with information from satellites, models, and monitors. *Environmental Science & Technology*, **53** (5), 2595–2611. https://doi.org/10.1021/acs.est.8b06392

248. Pye, H.O.T., C.K. Ward-Caviness, B.N. Murphy, K.W. Appel, and K.M. Seltzer, 2021: Secondary organic aerosol association with cardiorespiratory disease mortality in the United States. *Nature Communications*, **12** (1), 7215. https://doi.org/10.1038/s41467-021-27484-1

249. Boing, A.F., P. deSouza, A.C. Boing, R. Kim, and S.V. Subramanian, 2022: Air pollution, socioeconomic status, and age-specific mortality risk in the United States. *JAMA Network Open*, **5** (5), e2213540. https://doi.org/10.1001/jamanetworkopen.2022.13540

250. Colmer, J., I. Hardman, J. Shimshack, and J. Voorheis, 2020: Disparities in $PM_{2.5}$ air pollution in the United States. *Science*, **369** (6503), 575–578. https://doi.org/10.1126/science.aaz9353

251. Fann, N.L., C.G. Nolte, M.C. Sarofim, J. Martinich, and N.J. Nassikas, 2021: Associations between simulated future changes in climate, air quality, and human health. *JAMA Network Open*, **4** (1), e2032064. https://doi.org/10.1001/jamanetworkopen.2020.32064

252. Saari, R.K., Y. Mei, E. Monier, and F. Garcia-Menendez, 2019: Effect of health-related uncertainty and natural variability on health impacts and cobenefits of climate policy. *Environmental Science & Technology*, **53** (3), 1098–1108. https://doi.org/10.1021/acs.est.8b05094

253. Anderegg, W.R.L., J.T. Abatzoglou, L.D.L. Anderegg, L. Bielory, P.L. Kinney, and L. Ziska, 2021: Anthropogenic climate change is worsening North American pollen seasons. *Proceedings of the National Academy of Sciences of the United States of America*, **118** (7), e2013284118. https://doi.org/10.1073/pnas.2013284118

254. Manangan, A., C. Brown, S. Saha, J. Bell, J. Hess, C. Uejio, S. Fineman, and P. Schramm, 2021: Long-term pollen trends and associations between pollen phenology and seasonal climate in Atlanta, Georgia (1992–2018). *Annals of Allergy, Asthma & Immunology*, **127** (4), 471–480. https://doi.org/10.1016/j.anai.2021.07.012

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

256. Gao, P., A.J. Terando, J.A. Kupfer, J. Morgan Varner, M.C. Stambaugh, T.L. Lei, and J. Kevin Hiers, 2021: Robust projections of future fire probability for the conterminous United States. *Science of The Total Environment*, **789**, 147872. https://doi.org/10.1016/j.scitotenv.2021.147872

257. Andersen, L.M. and M.M. Sugg, 2019: Geographic multi-criteria evaluation and validation: A case study of wildfire vulnerability in western North Carolina, USA following the 2016 wildfires. *International Journal of Disaster Risk Reduction*, **39**, 101123. https://doi.org/10.1016/j.ijdrr.2019.101123

258. James, N.A., K.L. Abt, G.E. Frey, X. Han, and J.P. Prestemon, 2020: Fire in the Southern Appalachians: Understanding Impacts, Interventions, and Future Fire Events. e-Gen. Tech. Rep. SRS-249. U.S. Department of Agriculture, Forest Service, Southern Research Station, Asheville, NC, 34 pp. https://doi.org/10.2737/srs-gtr-249

259. Haikerwal, A., F. Reisen, M.R. Sim, M.J. Abramson, C.P. Meyer, F.H. Johnston, and M. Dennekamp, 2015: Impact of smoke from prescribed burning: Is it a public health concern? *Journal of the Air & Waste Management Association*, **65** (5), 592–598. https://doi.org/10.1080/10962247.2015.1032445

260. Afrin, S. and F. Garcia-Menendez, 2021: Potential impacts of prescribed fire smoke on public health and socially vulnerable populations in a southeastern U.S. state. *Science of The Total Environment*, **794**, 148712. https://doi.org/10.1016/j.scitotenv.2021.148712

261. Afrin, S. and F. Garcia-Menendez, 2020: The influence of prescribed fire on fine particulate matter pollution in the southeastern United States. *Geophysical Research Letters*, **47** (15), e2020GL088988. https://doi.org/10.1029/2020gl088988

262. Kupfer, J.A., A.J. Terando, P. Gao, C. Teske, and J.K. Hiers, 2020: Climate change projected to reduce prescribed burning opportunities in the south-eastern United States. *International Journal of Wildland Fire*, **29** (9), 764–778. https://doi.org/10.1071/wf19198

263. Park Williams, A., B.I. Cook, J.E. Smerdon, D.A. Bishop, R. Seager, and J.S. Mankin, 2017: The 2016 southeastern U.S. drought: An extreme departure from centennial wetting and cooling. *Journal of Geophysical Research: Atmospheres*, **122** (20), 10888–10905. https://doi.org/10.1002/2017jd027523

264. Gabbert, B., 2016: Analyzing the fire that burned into Gatlinburg. *Wildfire Today*, December 5, 2016. https://wildfiretoday.com/2016/12/05/analyzing-the-fire-that-burned-into-gatlinburg/

265. Gaines, J., 2018: Gatlinburg wildfire, two-year mark: Safety changes made, rebuilding continues. *Knox News*, November 27, 2018. https://www.knoxnews.com/story/news/2018/11/28/gatlinburg-wildfire-sevier-county-smoky-mountains-two-years-later/2029279002/

266. Dai, Y., S. Yang, D. Zhao, C. Hu, W. Xu, D.M. Anderson, Y. Li, X.-P. Song, D.G. Boyce, L. Gibson, C. Zheng, and L. Feng, 2023: Coastal phytoplankton blooms expand and intensify in the 21st century. *Nature*, **615** (7951), 280–284. https://doi.org/10.1038/s41586-023-05760-y

267. Anderson, D.M., E. Fensin, C.J. Gobler, A.E. Hoeglund, K.A. Hubbard, D.M. Kulis, J.H. Landsberg, K.A. Lefebvre, P. Provoost, M.L. Richlen, J.L. Smith, A.R. Solow, and V.L. Trainer, 2021: Marine harmful algal blooms (HABs) in the United States: History, current status and future trends. *Harmful Algae*, **102**, 101975. https://doi.org/10.1016/j.hal.2021.101975

268. Gobler, C.J., 2020: Climate change and harmful algal blooms: Insights and perspective. *Harmful Algae*, **91**, 101731. https://doi.org/10.1016/j.hal.2019.101731

269. Heil, C.A. and A.L. Muni-Morgan, 2021: Florida's harmful algal bloom (HAB) problem: Escalating risks to human, environmental and economic health with climate change. *Frontiers in Ecology and Evolution*, **9**, 646080. https://doi.org/10.3389/fevo.2021.646080

270. Bechard, A., 2020: External costs of harmful algal blooms using hedonic valuation: The impact of *Karenia brevis* on Southwest Florida. *Environmental and Sustainability Indicators*, **5**, 100019. https://doi.org/10.1016/j.indic.2020.100019

271. Bechard, A., 2020: The economic impacts of harmful algal blooms on tourism: An examination of Southwest Florida using a spline regression approach. *Natural Hazards*, **104** (1), 593–609. https://doi.org/10.1007/s11069-020-04182-7

272. Bechard, A., 2021: Gone with the wind: Declines in property values as harmful algal blooms are blown towards the shore. *The Journal of Real Estate Finance and Economics*, **62** (2), 242–257. https://doi.org/10.1007/s11146-020-09749-6

273. Vigar, M., M. Thuneibat, A. Jacobi, and V.A. Roberts, 2021: Summary Report–One Health Harmful Algal Bloom System (OHHABS), United States, 2019. U.S. Department of Health and Human Services, Atlanta, GA, 26 pp. https://stacks.cdc.gov/view/cdc/112313

274. Brown, A.R., M. Lilley, J. Shutler, C. Lowe, Y. Artioli, R. Torres, E. Berdalet, and C.R. Tyler, 2020: Assessing risks and mitigating impacts of harmful algal blooms on mariculture and marine fisheries. *Reviews in Aquaculture*, **12** (3), 1663–1688. https://doi.org/10.1111/raq.12403

275. Mishra, A., A. Alnahit, and B. Campbell, 2021: Impact of land uses, drought, flood, wildfire, and cascading events on water quality and microbial communities: A review and analysis. *Journal of Hydrology*, **596**, 125707. https://doi.org/10.1016/j.jhydrol.2020.125707

276. Parasiewicz, P., E.L. King, J.A. Webb, M. Piniewski, C. Comoglio, C. Wolter, A.D. Buijse, D. Bjerklie, P. Vezza, and A. Melcher, 2019: The role of floods and droughts on riverine ecosystems under a changing climate. *Fisheries Management and Ecology*, **26** (6), 461–473. https://doi.org/10.1111/fme.12388

277. Foss, A.J., E.J. Phlips, M. Yilmaz, and A. Chapman, 2012: Characterization of paralytic shellfish toxins from *Lyngbya wollei* dominated mats collected from two Florida springs. *Harmful Algae*, **16**, 98–107. https://doi.org/10.1016/j.hal.2012.02.004

278. Reis Costa, P., 2016: Impact and effects of paralytic shellfish poisoning toxins derived from harmful algal blooms to marine fish. *Fish and Fisheries*, **17** (1), 226–248. https://doi.org/10.1111/faf.12105

279. Alkishe, A., R.K. Raghavan, and A.T. Peterson, 2021: Likely geographic distributional shifts among medically important tick species and tick-associated diseases under climate change in North America: A review. *Insects*, **12** (3), 225. https://doi.org/10.3390/insects12030225

280. Couper, L.I., A.J. MacDonald, and E.A. Mordecai, 2021: Impact of prior and projected climate change on US Lyme disease incidence. *Global Change Biology*, **27** (4), 738–754. https://doi.org/10.1111/gcb.15435

281. Lantos, P.M., J. Tsao, M. Janko, A. Arab, M.E. Fricken, P.G. Auwaerter, L.E. Nigrovic, V. Fowler, F. Ruffin, D. Gaines, J. Broyhill, and J. Swenson, 2021: Environmental correlates of Lyme disease emergence in southwest Virginia, 2005–2014. *Journal of Medical Entomology*, **58** (4), 1680–1685. https://doi.org/10.1093/jme/tjab038

282. Seukep, S.E., K.N. Kolivras, Y. Hong, J. Li, S.P. Prisley, J.B. Campbell, D.N. Gaines, and R.L. Dymond, 2015: An examination of the demographic and environmental variables correlated with Lyme disease emergence in Virginia. *EcoHealth*, **12** (4), 634–644. https://doi.org/10.1007/s10393-015-1034-3

283. Stevens, L.K., K.N. Kolivras, Y. Hong, V.A. Thomas, J.B. Campbell, and S.P. Prisley, 2019: Future Lyme disease risk in the south-eastern United States based on projected land cover. *Geospatial Health*, **14** (1). https://doi.org/10.4081/gh.2019.751

284. Morse, W., K. Izenour, B. McKenzie, S. Lessard, and S. Zohdy, 2019: Perceptions and practices of mosquito-borne diseases in Alabama – Is concern where it should be? *BMC Public Health*, **19** (1), 987. https://doi.org/10.1186/s12889-019-7308-x

285. Kollars, T.M., 2017: Identifying health disparities of mosquito-borne diseases in low and medium income communities in Savannah, Georgia, USA. *Annals of Community Medicine and Practice*, **3** (2), 1025. https://www.jscimedcentral.com/public/assets/articles/communitymedicine-3-1024.pdf

286. Kollars, T.M., 2017: Identifying high risk areas of West Nile Virus in minority and low-income neighborhoods. *Clinical Microbiology and Infectious Diseases*, **2** (1), 1–3. https://doi.org/10.15761/cmid.1000123

287. Mental Health America, 2020: 2020 Prevalence Data. Mental Health America. https://www.nssbehavioralhealth.com/blog-nss-the-state-of-mental-health-in-america-2020-adult-prevalence-and-access-to-care/

288. Mental Health America, 2020: 2020 Access to Care Data. Mental Health America. https://www.nssbehavioralhealth.com/blog-nss-the-state-of-mental-health-in-america-2020-adult-prevalence-and-access-to-care/

289. Sugg, M., J. Runkle, R. Leeper, H. Bagli, A. Golden, L.H. Handwerger, T. Magee, C. Moreno, R. Reed-Kelly, M. Taylor, and S. Woolard, 2020: A scoping review of drought impacts on health and society in North America. *Climatic Change*, **162** (3), 1177–1195. https://doi.org/10.1007/s10584-020-02848-6

290. Palinkas, L.A. and M. Wong, 2020: Global climate change and mental health. *Current Opinion in Psychology*, **32**, 12–16. https://doi.org/10.1016/j.copsyc.2019.06.023

291. Clayton, S., 2020: Climate anxiety: Psychological responses to climate change. *Journal of Anxiety Disorders*, **74**, 102263. https://doi.org/10.1016/j.janxdis.2020.102263

292. Panu, P., 2020: Anxiety and the ecological crisis: An analysis of eco-anxiety and climate anxiety. *Sustainability*, **12** (19), 7836. https://doi.org/10.3390/su12197836

293. Espinel, Z., J.P. Kossin, S. Galea, A.S. Richardson, and J.M. Shultz, 2019: Forecast: Increasing mental health consequences from Atlantic hurricanes throughout the 21st century. *Psychiatric Services*, **70** (12), 1165–1167. https://doi.org/10.1176/appi.ps.201900273

294. Orengo-Aguayo, R., R.W. Stewart, M.A. Arellano, J.L. Suárez-Kindy, and J. Young, 2019: Disaster exposure and mental health among Puerto Rican youths after Hurricane Maria. *JAMA Network Open*, **2** (4), 192619. https://doi.org/10.1001/jamanetworkopen.2019.2619

295. Scaramutti, C., C.P. Salas-Wright, S.R. Vos, and S.J. Schwartz, 2019: The mental health impact of Hurricane Maria on Puerto Ricans in Puerto Rico and Florida. *Disaster Medicine and Public Health Preparedness*, **13** (1), 24–27. https://doi.org/10.1017/dmp.2018.151

296. Kunreuther, H.C., E.O. Michel-Kerjan, N.A. Doherty, M.F. Grace, R.W. Klein, and M.V. Pauly, 2009: *At War with the Weather: Managing Large-Scale Risks in a New Era of Catastrophes*. The MIT Press, 440 pp. http://www.jstor.org/stable/j.ctt5hhn3h

297. Mileti, D., 1999: *Disasters by Design: A Reassessment of Natural Hazards in the United States*. Joseph Henry Press, Washington, DC, 371 pp. https://doi.org/10.17226/5782

298. Martinich, J. and A. Crimmins, 2019: Climate damages and adaptation potential across diverse sectors of the United States. *Nature Climate Change*, **9** (5), 397–404. https://doi.org/10.1038/s41558-019-0444-6

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

300. Hsiang, S., R. Kopp, A. Jina, J. Rising, M. Delgado, S. Mohan, D.J. Rasmussen, R. Muir-Wood, P. Wilson, M. Oppenheimer, K. Larsen, and T. Houser, 2017: Estimating economic damage from climate change in the United States. *Science*, **356** (6345), 1362–1369. https://doi.org/10.1126/science.aal4369

301. Bhattachan, A., M.D. Jurjonas, P.R. Morris, P.J. Taillie, L.S. Smart, R.E. Emanuel, and E.L. Seekamp, 2019: Linking residential saltwater intrusion risk perceptions to physical exposure of climate change impacts in rural coastal communities of North Carolina. *Natural Hazards*, **97** (3), 1277–1295. https://doi.org/10.1007/s11069-019-03706-0

302. Colburn, L.L., M. Jepson, C. Weng, T. Seara, J. Weiss, and J.A. Hare, 2016: Indicators of climate change and social vulnerability in fishing dependent communities along the Eastern and Gulf Coasts of the United States. *Marine Policy*, **74**, 323–333. https://doi.org/10.1016/j.marpol.2016.04.030

303. Seara, T., M. Jepson, and M. McPherson, 2022: Community Climate Change Vulnerability in the South Atlantic, Florida Keys and Gulf of Mexico. NOAA Technical Memorandum NMFS-SEFSC-754. National Oceanic and Atmospheric Administration, National Marine Fisheries Service, Miami, FL, 40 pp. https://doi.org/10.25923/0wqe-3511

304. Pederson, N., A.R. Bell, T.A. Knight, C. Leland, N. Malcomb, K.J. Anchukaitis, K. Tackett, J. Scheff, A. Brice, B. Catron, W. Blozan, and J. Riddle, 2012: A long-term perspective on a modern drought in the American Southeast. *Environmental Research Letters*, **7** (1), 014034. https://doi.org/10.1088/1748-9326/7/1/014034

305. Raczynski, K. and J. Dyer, 2022: Variability of annual and monthly streamflow droughts over the southeastern United States. *Water*, **14** (23). https://doi.org/10.3390/w14233848

306. Sohn, J., 2011: Watering cities: Spatial analysis of urban water use in the southeastern United States. *Journal of Environmental Planning and Management*, **54** (10), 1351–1371. https://doi.org/10.1080/09640568.2011.575188

307. Sun, G., S.G. McNulty, J.A. Moore Myers, and E.C. Cohen, 2008: Impacts of multiple stresses on water demand and supply across the southeastern United States. *JAWRA Journal of the American Water Resources Association*, **44** (6), 1441–1457. https://doi.org/10.1111/j.1752-1688.2008.00250.x

308. Bolinger, B., 2019: How Drought Prone Is Your State? A Look at the Top States and Counties in Drought over the Last Two Decades. National Oceanic and Atmospheric Administration, National Integrated Drought Information System. https://www.drought.gov/news/how-drought-prone-your-state-look-top-states-and-counties-drought-over-last-two-decades

309. Engström, J., K. Jafarzadegan, and H. Moradkhani, 2020: Drought vulnerability in the United States: An integrated assessment. *Water*, **12** (7), 2033. https://doi.org/10.3390/w12072033

310. Alexandrov, V.A. and G. Hoogenboom, 2000: Vulnerability and adaptation assessments of agricultural crops under climate change in the southeastern USA. *Theoretical and Applied Climatology*, **67** (1), 45–63. https://doi.org/10.1007/s007040070015

311. Shortridge, J., 2019: Observed trends in daily rainfall variability result in more severe climate change impacts to agriculture. *Climatic Change*, **157** (3), 429–444. https://doi.org/10.1007/s10584-019-02555-x

312. Castillo, F., A.M. Mora, G.L. Kayser, J. Vanos, C. Hyland, A.R. Yang, and B. Eskenazi, 2021: Environmental health threats to Latino migrant farmworkers. *Annual Review of Public Health*, **42** (1), 257–276. https://doi.org/10.1146/annurev-publhealth-012420-105014

313. Zhang, Y. and D.T. Shindell, 2021: Costs from labor losses due to extreme heat in the USA attributable to climate change. *Climatic Change*, **164** (3), 35. https://doi.org/10.1007/s10584-021-03014-2

314. DOT, 2021: Climate Action Plan: Revitalizing Efforts to Bolster Adaptation & Increase Resilience. U.S. Department of Transportation, Office of the Secretary of Transportation, Washington, DC. https://rosap.ntl.bts.gov/view/dot/66379

315. Burton, M., J. Camp, C. Philip, and L. Bray, 2017: The Impacts of Unscheduled Lock Outages. National Waterways Foundation and U.S. Maritime Administration. https://www.nationalwaterwaysfoundation.org/file/2/low%20res%20lock%20outage%20nwf_final_report%202017.pdf

316. Pinkley, S.G.N., K.M. Sullivan, B.R. Runkle, H.T. Bui, J. Khatamov, J. Camp, K. Turner, and N. Laning, 2021: Informing Post-Disaster Restoration Through Modeling Interdependent Agriculture and Transportation Networks. Maritime Transportation Research and Education Center. https://rosap.ntl.bts.gov/view/dot/61007

317. Neumann, J.E., P. Chinowsky, J. Helman, M. Black, C. Fant, K. Strzepek, and J. Martinich, 2021: Climate effects on US infrastructure: The economics of adaptation for rail, roads, and coastal development. *Climatic Change*, **167** (3), 44. https://doi.org/10.1007/s10584-021-03179-w

318. Ghadge, A., H. Wurtmann, and S. Seuring, 2020: Managing climate change risks in global supply chains: A review and research agenda. *International Journal of Production Research*, **58** (1), 44–64. https://doi.org/10.1080/00207543.2019.1629670

319. Camp, J., M. Abkowitz, G. Hornberger, L. Benneyworth, and J.C. Banks, 2013: Climate change and freight-transportation infrastructure: Current challenges for adaptation. *Journal of Infrastructure Systems*, **19** (4), 363–370. https://doi.org/10.1061/(asce)is.1943-555x.0000151

320. Fant, C., B. Boehlert, K. Strzepek, P. Larsen, A. White, S. Gulati, Y. Li, and J. Martinich, 2020: Climate change impacts and costs to U.S. electricity transmission and distribution infrastructure. *Energy*, **195**, 116899. https://doi.org/10.1016/j.energy.2020.116899

321. Larsen, P.H., B. Boehlert, J. Eto, K. Hamachi-LaCommare, J. Martinich, and L. Rennels, 2018: Projecting future costs to U.S. electric utility customers from power interruptions. *Energy*, **147**, 1256–1277. https://doi.org/10.1016/j.energy.2017.12.081

322. Polansek, T., 2021: US Coast Guard shuts part of lower Mississippi River as bridge cracks. *Reuters*, May 12, 2021. https://www.reuters.com/world/us/coast-guard-shuts-portion-lower-mississippi-river-due-bridge-crack-2021-05-12/

323. Prida, A., 2021: How Does Climate Change Affect Inland Waterway Transport in the Mississippi river? AXA Climate. https://www.climate.axa/articles/how-does-climate-change-affect-inland-waterway-transport-in-the-mississippi-river

324. Nakano, K., 2021: Risk assessment for adaptation to climate change in the international supply chain. *Journal of Cleaner Production*, **319**, 128785. https://doi.org/10.1016/j.jclepro.2021.128785

325. Godde, C.M., D. Mason-D'Croz, D.E. Mayberry, P.K. Thornton, and M. Herrero, 2021: Impacts of climate change on the livestock food supply chain; a review of the evidence. *Global Food Security*, **28**, 100488. https://doi.org/10.1016/j.gfs.2020.100488

326. BTS, 2022: Low Water on the Mississippi Slows Critical Freight Flows. U.S. Department of Transportation, Bureau of Transportation Statistics, accessed April 27, 2023. https://www.bts.gov/data-spotlight/low-water-mississippi-slows-critical-freight-flows

327. CoFiRES, 2023: Characterizing and Managing the Financial Risks of Drought Along the Mississippi River. University of North Carolina, Gillings School of Global Public Health, Center on Financial Risk in Environmental Systems, accessed May 18, 2023. https://sph.unc.edu/cfres/mississippi-river/

328. Neidell, M., J.G. Zivin, M. Sheahan, J. Willwerth, C. Fant, M. Sarofim, and J. Martinich, 2021: Temperature and work: Time allocated to work under varying climate and labor market conditions. *PLoS ONE*, **16** (8), 0254224. https://doi.org/10.1371/journal.pone.0254224

329. Rode, A., R.E. Baker, T. Carleton, A. D'Agostino, M. Delgado, T. Foreman, D.R. Gergel, M. Greenstone, T. Houser, S. Hsiang, A. Hultgren, A. Jina, R.E. Kopp, S.B. Malevich, K.E. McCusker, I. Nath, M. Pecenco, J. Rising, and J. Yuan, 2022: Labor Disutility in a Warmer World: The Impact of Climate Change on the Global Workforce. Social Science Research Network, 96 pp. https://doi.org/10.2139/ssrn.4221478

330. Karthick, S., S. Kermanshachi, B. Rouhanizadeh, and M. Namian, 2021: Short- and long-term health challenges of transportation workforce due to extreme weather conditions. In: *Tran-SET 2021*. American Society of Civil Engineers, 39–51. https://doi.org/10.1061/9780784483787.005

331. EIA, 2022: Gulf of Mexico Fact Sheet. U.S. Energy Information Administration, Washington, DC. http://www.eia.gov/special/gulf_of_mexico/

332. Burkett, V., 2011: Global climate change implications for coastal and offshore oil and gas development. *Energy Policy*, **39** (12), 7719–7725. https://doi.org/10.1016/j.enpol.2011.09.016

333. Cruz, A.M. and E. Krausmann, 2008: Damage to offshore oil and gas facilities following Hurricanes Katrina and Rita: An overview. *Journal of Loss Prevention in the Process Industries*, **21** (6), 620–626. https://doi.org/10.1016/j.jlp.2008.04.008

334. Coleman, N., A. Esmalian, and A. Mostafavi, 2020: Equitable resilience in infrastructure systems: Empirical assessment of disparities in hardship experiences of vulnerable populations during service disruptions. *Natural Hazards Review*, **21** (4), 04020034. https://doi.org/10.1061/(asce)nh.1527-6996.0000401

335. Sussman, F.G. and J.R. Freed, 2008: Adapting to Climate Change: A Business Approach. Pew Center on Global Climate Change, Arlington, VA. https://www.pewtrusts.org/~/media/legacy/uploadedfiles/wwwpewtrustsorg/reports/global_warming/businessadaptationpdf.pdf

336. Louie, E.P. and J.M. Pearce, 2016: Retraining investment for U.S. transition from coal to solar photovoltaic employment. *Energy Economics*, **57**, 295–302. https://doi.org/10.1016/j.eneco.2016.05.016

337. Carley, S. and D.M. Konisky, 2020: The justice and equity implications of the clean energy transition. *Nature Energy*, **5** (8), 569–577. https://doi.org/10.1038/s41560-020-0641-6

338. Tomer, A., J. Kane, and C. George, 2021: How Renewable Energy Jobs Can Uplift Fossil Fuel Communities and Remake Climate Politics. The Brookings Institution. https://www.brookings.edu/research/how-renewable-energy-jobs-can-uplift-fossil-fuel-communities-and-remake-climate-politics/

339. Abraham, J., 2017: Just transitions for the miners: Labor environmentalism in the Ruhr and Appalachian coalfields. *New Political Science*, **39** (2), 218–240. https://doi.org/10.1080/07393148.2017.1301313

340. Chesmore, G., R. Starr, R. Van Hoeck, and M. Ward, 2021: The crisis of US coal communities: Strategies for a just transition to renewable energy. *Journal of Science Policy & Governance*, **18** (2). https://doi.org/10.38126/jspg180202

341. Becker, W.S. and B. McKibben, 2021: *The Creeks Will Rise: People Coexisting with Floods*. Chicago Review Press, 368 pp. https://www.chicagoreviewpress.com/creeks-will-rise--the-products-9781682752753.php

342. ERS, 2022: Ag and Food Sectors and the Economy. U.S. Department of Agriculture, Economic Research Service. https://www.ers.usda.gov/data-products/ag-and-food-statistics-charting-the-essentials/ag-and-food-sectors-and-the-economy/

343. NASS, 2019: 2017 Census of Agriculture: United States Summary and State Data. AC-17-A-51. U.S. Department of Agriculture, National Agricultural Statistics Service. https://www.nass.usda.gov/publications/agcensus/2017/index.php

344. Karakoc, D.B., J. Wang, and M. Konar, 2022: Food flows between counties in the United States from 2007 to 2017. *Environmental Research Letters*, **17** (3), 034035. https://doi.org/10.1088/1748-9326/ac5270

345. Walker, R.E., C.R. Keane, and J.G. Burke, 2010: Disparities and access to healthy food in the United States: A review of food deserts literature. *Health & Place*, **16** (5), 876–884. https://doi.org/10.1016/j.healthplace.2010.04.013

346. DeGaetano, A.T. and R.J. Allen, 2002: Trends in twentieth-century temperature extremes across the United States. *Journal of Climate*, **15** (22), 3188–3205. DOI:10.1175/1520-0442(2002)015<3188:titcte>2.0.co;2. https://journals.ametsoc.org/view/journals/clim/15/22/1520-0442_2002_015_3188_titcte_2.0.co_2.xml

347. Bernabucci, U., 2019: Climate change: Impact on livestock and how can we adapt. *Animal Frontiers: The Review Magazine of Animal Agriculture*, **9** (1), 3–5. https://doi.org/10.1093/af/vfy039

348. Parker, L.E. and J.T. Abatzoglou, 2019: Warming winters reduce chill accumulation for peach production in the southeastern United States. *Climate*, **7** (8), 94. https://doi.org/10.3390/cli7080094

349. EPA, 2016: Climate Change Indicators: Length of Growing Season. U.S. Environmental Protection Agency. https://www.epa.gov/climate-indicators/climate-change-indicators-length-growing-season

350. Schaarschmidt, S., L.M.F. Lawas, J. Kopka, S.V.K. Jagadish, and E. Zuther, 2021: Physiological and molecular attributes contribute to high night temperature tolerance in cereals. *Plant, Cell & Environment*, **44** (7), 2034–2048. https://doi.org/10.1111/pce.14055

351. Apurv, T. and X. Cai, 2021: Regional drought risk in the contiguous United States. *Geophysical Research Letters*, **48** (5), 2020GL092200. https://doi.org/10.1029/2020gl092200

352. Ficklin, D.L., J.T. Maxwell, S.L. Letsinger, and H. Gholizadeh, 2015: A climatic deconstruction of recent drought trends in the United States. *Environmental Research Letters*, **10** (4), 044009. https://doi.org/10.1088/1748-9326/10/4/044009

353. Rind, D., R. Goldberg, J. Hansen, C. Rosenzweig, and R. Ruedy, 1990: Potential evapotranspiration and the likelihood of future drought. *Journal of Geophysical Research: Atmospheres*, **95** (D7), 9983–10004. https://doi.org/10.1029/jd095id07p09983

354. Leeper, R.D., R. Bilotta, B. Petersen, C.J. Stiles, R. Heim, B. Fuchs, O.P. Prat, M. Palecki, and S. Ansari, 2022: Characterizing U.S. drought over the past 20 years using the U.S. Drought Monitor. *International Journal of Climatology*, **42** (12), 6616–6630. https://doi.org/10.1002/joc.7653

355. Apurv, T., X. Cai, and X. Yuan, 2019: Influence of internal variability and global warming on multidecadal changes in regional drought severity over the continental United States. *Journal of Hydrometeorology*, **20** (3), 411–429. https://doi.org/10.1175/jhm-d-18-0167.1

356. Crystal-Ornelas, R., E.J. Hudgins, R.N. Cuthbert, P.J. Haubrock, J. Fantle-Lepczyk, E. Angulo, A.M. Kramer, L. Ballesteros-Mejia, B. Leroy, B. Leung, E. López-López, C. Diagne, and F. Courchamp, 2021: Economic costs of biological invasions within North America. *NeoBiota*, **67**, 485–510. https://doi.org/10.3897/neobiota.67.58038

357. Paini, D.R., A.W. Sheppard, D.C. Cook, P.J. De Barro, S.P. Worner, and M.B. Thomas, 2016: Global threat to agriculture from invasive species. *Proceedings of the National Academy of Sciences of the United States of America*, **113** (27), 7575–7579. https://doi.org/10.1073/pnas.1602205113

358. Armal, S., N. Devineni, and R. Khanbilvardi, 2018: Trends in extreme rainfall frequency in the contiguous United States: Attribution to climate change and climate variability modes. *Journal of Climate*, **31** (1), 369–385. https://doi.org/10.1175/jcli-d-17-0106.1

359. Bartels, R.J., A.W. Black, and B.D. Keim, 2020: Trends in precipitation days in the United States. *International Journal of Climatology*, **40** (2), 1038–1048. https://doi.org/10.1002/joc.6254

360. Brown, V.M., B.D. Keim, and A.W. Black, 2019: Climatology and trends in hourly precipitation for the southeast United States. *Journal of Hydrometeorology*, **20** (8), 1737–1755. https://doi.org/10.1175/jhm-d-19-0004.1

361. Brown, V.M., B.D. Keim, and A.W. Black, 2020: Trend analysis of multiple extreme hourly precipitation time series in the southeastern United States. *Journal of Applied Meteorology and Climatology*, **59** (3), 427–442. https://doi.org/10.1175/jamc-d-19-0119.1

362. Kossin, J.P., 2018: A global slowdown of tropical-cyclone translation speed. *Nature*, **558** (7708), 104–107. https://doi.org/10.1038/s41586-018-0158-3

363. Harris, A.R., E.N. Fidan, N.G. Nelson, R.E. Emanuel, T. Jass, S. Kathariou, J. Niedermeyer, M. Sharara, F.L. de los Reyes, D.A. Riveros-Iregui, and J.R. Stewart, 2021: Microbial contamination in environmental waters of rural and agriculturally-dominated landscapes following Hurricane Florence. *ACS ES&T Water*, **1** (9), 2012–2019. https://doi.org/10.1021/acsestwater.1c00103

364. Paul, M.J., R. Coffey, J. Stamp, and T. Johnson, 2019: A review of water quality responses to air temperature and precipitation changes 1: Flow, water temperature, saltwater intrusion. *JAWRA Journal of the American Water Resources Association*, **55** (4), 824–843. https://doi.org/10.1111/1752-1688.12710

365. Izaguirre, C., I.J. Losada, P. Camus, J.L. Vigh, and V. Stenek, 2021: Climate change risk to global port operations. *Nature Climate Change*, **11** (1), 14–20. https://doi.org/10.1038/s41558-020-00937-z

366. Markolf, S.A., C. Hoehne, A. Fraser, M.V. Chester, and B.S. Underwood, 2019: Transportation resilience to climate change and extreme weather events—Beyond risk and robustness. *Transport Policy*, **74**, 174–186. https://doi.org/10.1016/j.tranpol.2018.11.003

367. Verschuur, J., E.E. Koks, and J.W. Hall, 2020: Port disruptions due to natural disasters: Insights into port and logistics resilience. *Transportation Research Part D: Transport and Environment*, **85**, 102393. https://doi.org/10.1016/j.trd.2020.102393

368. Benevolenza, M.A. and L. DeRigne, 2019: The impact of climate change and natural disasters on vulnerable populations: A systematic review of literature. *Journal of Human Behavior in the Social Environment*, **29** (2), 266–281. https://doi.org/10.1080/10911359.2018.1527739

369. Craig, C.A., S. Feng, and S. Gilbertz, 2019: Water crisis, drought, and climate change in the southeast United States. *Land Use Policy*, **88**, 104110. https://doi.org/10.1016/j.landusepol.2019.104110

370. Harris, G., 2020: Beginning, minority, and other underserved farmers and ranchers in the 2017 Census of Agriculture. *Agricultural Outlook Forum*. U.S. Department of Agriculture. https://doi.org/10.22004/ag.econ.320929

371. Furman, C., C. Roncoli, W. Bartels, M. Boudreau, H. Crockett, H. Gray, and G. Hoogenboom, 2014: Social justice in climate services: Engaging African American farmers in the American South. *Climate Risk Management*, **2**, 11–25. https://doi.org/10.1016/j.crm.2014.02.002

372. Ali, C., 2021: *Farm Fresh Broadband: The Politics of Rural Connectivity*. MIT Press, 306 pp. https://mitpress.mit.edu/9780262543064/farm-fresh-broadband/

373. Lal, P., J.R.R. Alavalapati, and E.D. Mercer, 2011: Socio-economic impacts of climate change on rural United States. *Mitigation and Adaptation Strategies for Global Change*, **16** (7), 819–844. https://doi.org/10.1007/s11027-011-9295-9

374. Leslie, I.S. and M.M. White, 2018: Ch. 19. Race and Food: Agricultural resistance in U.S. history. In: *Handbook of the Sociology of Racial and Ethnic Relations*. Batur, P. and J.R. Feagin, Eds. Springer, Cham, Switzerland, 347–364. https://doi.org/10.1007/978-3-319-76757-4_19

375. Quaye, F., D. Nadolnyak, and V. Hartarska, 2018: Climate change impacts on farmland values in the southeast United States. *Sustainability*, **10** (10), 3426. https://doi.org/10.3390/su10103426

376. Holka, M., J. Kowalska, and M. Jakubowska, 2022: Reducing carbon footprint of agriculture—Can organic farming help to mitigate climate change? *Agriculture*, **12** (9). https://doi.org/10.3390/agriculture12091383

377. Jouzi, Z., H. Azadi, F. Taheri, K. Zarafshani, K. Gebrehiwot, S. Van Passel, and P. Lebailly, 2017: Organic farming and small-scale farmers: Main opportunities and challenges. *Ecological Economics*, **132**, 144–154. https://doi.org/10.1016/j.ecolecon.2016.10.016

378. Flörke, M., C. Schneider, and R.I. McDonald, 2018: Water competition between cities and agriculture driven by climate change and urban growth. *Nature Sustainability*, **1** (1), 51–58. https://doi.org/10.1038/s41893-017-0006-8

379. Schlef, K.E., S. Steinschneider, and C.M. Brown, 2018: Spatiotemporal impacts of climate and demand on water supply in the Apalachicola-Chattahoochee-Flint Basin. *Journal of Water Resources Planning and Management*, **144** (2), 05017020. https://doi.org/10.1061/(ASCE)WR.1943-5452.0000865

380. Krayenhoff, E.S., M. Moustaoui, A.M. Broadbent, V. Gupta, and M. Georgescu, 2018: Diurnal interaction between urban expansion, climate change and adaptation in US cities. *Nature Climate Change*, **8** (12), 1097–1103. https://doi.org/10.1038/s41558-018-0320-9

381. Napton, D.E., R.F. Auch, R. Headley, and J.L. Taylor, 2010: Land changes and their driving forces in the southeastern United States. *Regional Environmental Change*, **10** (1), 37–53. https://doi.org/10.1007/s10113-009-0084-x

382. Changnon, S.A., 1989: The 1988 drought, barges, and diversion. *Bulletin of the American Meteorological Society*, **70** (9), 1092–1104. DOI:10.1175/1520-0477(1989)070<1092:tdbad>2.0.co;2. https://journals.ametsoc.org/view/journals/bams/70/9/1520-0477_1989_070_1092_tdbad_2_0_co_2.xml

383. Kemp, G.P., C.S. Willson, J.D. Rogers, K.A. Westphal, and S.A. Binselam, 2014: Adapting to change in the lowermost Mississippi River: Implications for navigation, flood control and restoration of the delta ecosystem. In: *Perspectives on the Restoration of the Mississippi Delta: The Once and Future Delta.* Day, J.W., G.P. Kemp, A.M. Freeman, and D.P. Muth, Eds. Springer, Dordrecht, Netherlands, 51–84. https://doi.org/10.1007/978-94-017-8733-8_5

384. Balbus, J.M. and C. Malina, 2009: Identifying vulnerable subpopulations for climate change health effects in the United States. *Journal of Occupational and Environmental Medicine*, **51** (1), 33–37. https://doi.org/10.1097/jom.0b013e318193e12e

385. Porfirio, L.L., D. Newth, J.J. Finnigan, and Y. Cai, 2018: Economic shifts in agricultural production and trade due to climate change. *Palgrave Communications*, **4** (1), 1–9. https://doi.org/10.1057/s41599-018-0164-y

386. Balafoutis, A., B. Beck, S. Fountas, J. Vangeyte, T. Van der Wal, I. Soto, M. Gómez-Barbero, A. Barnes, and V. Eory, 2017: Precision agriculture technologies positively contributing to GHG emissions mitigation, farm productivity and economics. *Sustainability*, **9** (8), 1339. https://doi.org/10.3390/su9081339

387. Kaye, J.P. and M. Quemada, 2017: Using cover crops to mitigate and adapt to climate change. A review. *Agronomy for Sustainable Development*, **37** (1), 1–17. https://doi.org/10.1007/s13593-016-0410-x

388. Kladivko, E.J., T.C. Kaspar, D.B. Jaynes, R.W. Malone, J. Singer, X.K. Morin, and T. Searchinger, 2014: Cover crops in the upper midwestern United States: Potential adoption and reduction of nitrate leaching in the Mississippi River Basin. *Journal of Soil and Water Conservation*, **69** (4), 279–291. https://doi.org/10.2489/jswc.69.4.279

389. Sarrantonio, M. and E. Gallandt, 2003: The role of cover crops in North American cropping systems. *Journal of Crop Production*, **8** (1–2), 53–74. https://doi.org/10.1300/j144v08n01_04

390. Grey, T.L., K. Rucker, T.M. Webster, and X. Luo, 2016: High-density plantings of olive trees are tolerant to repeated applications of indaziflam. *Weed Science*, **64** (4), 766–771. https://doi.org/10.1614/ws-d-16-00025.1

391. Hanly, M. and S. Davis, 2010: History of Olive Growing in Georgia: The Past and Future of Olive Tree Production in Georgia. Georgia Olive Growers Association. http://georgiaolivegrowers.com/resources-research/history/

392. Jacobs, J. and G. Krewer, 2009: An Early Look at Olives in Georgia. The University of Georgia. https://extension.uga.edu/about/our-impact/impact-stories/impact-statement/2393/an-early-look-at-olives-in-georgia.html

393. Nesbitt, M.L., R.C. Ebel, and W.A. Dozier Jr., 2008: Production practices for satsuma mandarins in the southeastern United States. *HortScience*, **43** (2), 290–292. https://doi.org/10.21273/hortsci.43.2.290

394. Davis, M., 2020: U.S. Fish and Wildlife Service Programmatic Environmental Assessment for Use of Genetically Engineered Agricultural Crops for Natural Resource Management on National Wildlife Refuges in the Southeastern United States. U.S. Department of Interior, U.S. Fish and Wildlife Service, Atlanta, GA. https://ecos.fws.gov/servcat/downloadfile/171732

395. Kovak, E., D. Blaustein-Rejto, and M. Qaim, 2022: Genetically modified crops support climate change mitigation. *Trends in Plant Science*, **27** (7), 627–629. https://doi.org/10.1016/j.tplants.2022.01.004

396. Lesk, C., E. Coffel, J. Winter, D. Ray, J. Zscheischler, S.I. Seneviratne, and R. Horton, 2021: Stronger temperature–moisture couplings exacerbate the impact of climate warming on global crop yields. *Nature Food*, **2** (9), 683–691. https://doi.org/10.1038/s43016-021-00341-6

397. Seifert, C.A. and D.B. Lobell, 2015: Response of double cropping suitability to climate change in the United States. *Environmental Research Letters*, **10** (2), 024002. https://doi.org/10.1088/1748-9326/10/2/024002

398. Nabhan, G.P. and J.L. Carr, Eds., 1994: *Ironwood: An Ecological and Cultural Keystone of the Sonoran Desert.* University of Chicago Press, 92 pp. https://press.uchicago.edu/ucp/books/book/distributed/I/bo3634046.html

399. Noss, R.F., E.T. LaRoe III, and J.M. Scott, 1995: Endangered Ecosystems of the United States: A Preliminary Assessment of Loss and Degradation. Biological Report 28. U.S. Department of the Interior, National Biological Service, Washington, DC. https://ecos.fws.gov/servcat/downloadfile/101448?reference=61075

400. Anderson, M.K. and T. Oakes, 2011: Plant Guide for Giant Cane *Arundinaria gigantea*. U.S. Department of Agriculture, Natural Resources Conservation Service, National Plant Data Team, Greensboro, NC. https://plants.sc.egov.usda.gov/documentlibrary/plantguide/pdf/cs_argi.pdf

401. McKenzie, E.R., 2021: Indigenous Approaches to Rivercane Restoration Workshop. U.S Army Corps of Engineers, 38 pp. https://www.spa.usace.army.mil/portals/16/docs/tntcx/misc/feb_2022_rr%20workshop%20report_final.pdf?ver=8b900adld-cpycs2bh4x_q%3d%3d

402. Michaux, F.A. and B. Lambert, 1805: *Travels to the Westward of the Allegany Mountains, in the States of Ohio, Kentucky, and Tennessee, and Return to Charlestown, Through the Upper Carolinas; Containing Details on the Present State of Agriculture and the Natural Production of These Countries; As Well as Information Relative to the Commercial Connections of These States with Those Situated to the Eastward of the Mountains and with Lower Louisiana. Undertaken in the Year X, 1802, Under the Auspices of His Excellency M. Chaptal, Minister of the Interior. With a Very Correct Map of the States in the Centre, West and South of the United States*. Mawman, J., Ed., London, UK, 350 pp. [Print].

403. Aranzazu Lascurain (Author), September 8, 2022: Oral communication/email communication with Mitzi Reed, Mississippi Band of Choctaw Indians.

404. Platt, S.G., C.G. Brantley, and T.R. Rainwater, 2001: Canebrake fauna: Wildlife diversity in a critically endangered ecosystem. *Journal of the Elisha Mitchell Scientific Society*, **117** (1), 1–19. http://www.jstor.org/stable/24335363

405. Schoonover, J.E., K.W.J. Williard, J.J. Zaczek, J.C. Mangun, and A.D. Carver, 2006: Agricultural sediment reduction by giant cane and forest riparian buffers. *Water, Air, and Soil Pollution*, **169** (1), 303–315. https://doi.org/10.1007/s11270-006-3111-2

406. Adam Griffith (Technical Contributor), May 24, 2022: Oral communication/email communication with Mary W. Thompson, Eastern Band of Cherokee Indians.

407. Schramm, P.J., C.L. Brown, S. Saha, K.C. Conlon, A.P. Manangan, J.E. Bell, and J.J. Hess, 2021: A systematic review of the effects of temperature and precipitation on pollen concentrations and season timing, and implications for human health. *International Journal of Biometeorology*, **65** (10), 1615–1628. https://doi.org/10.1007/s00484-021-02128-7

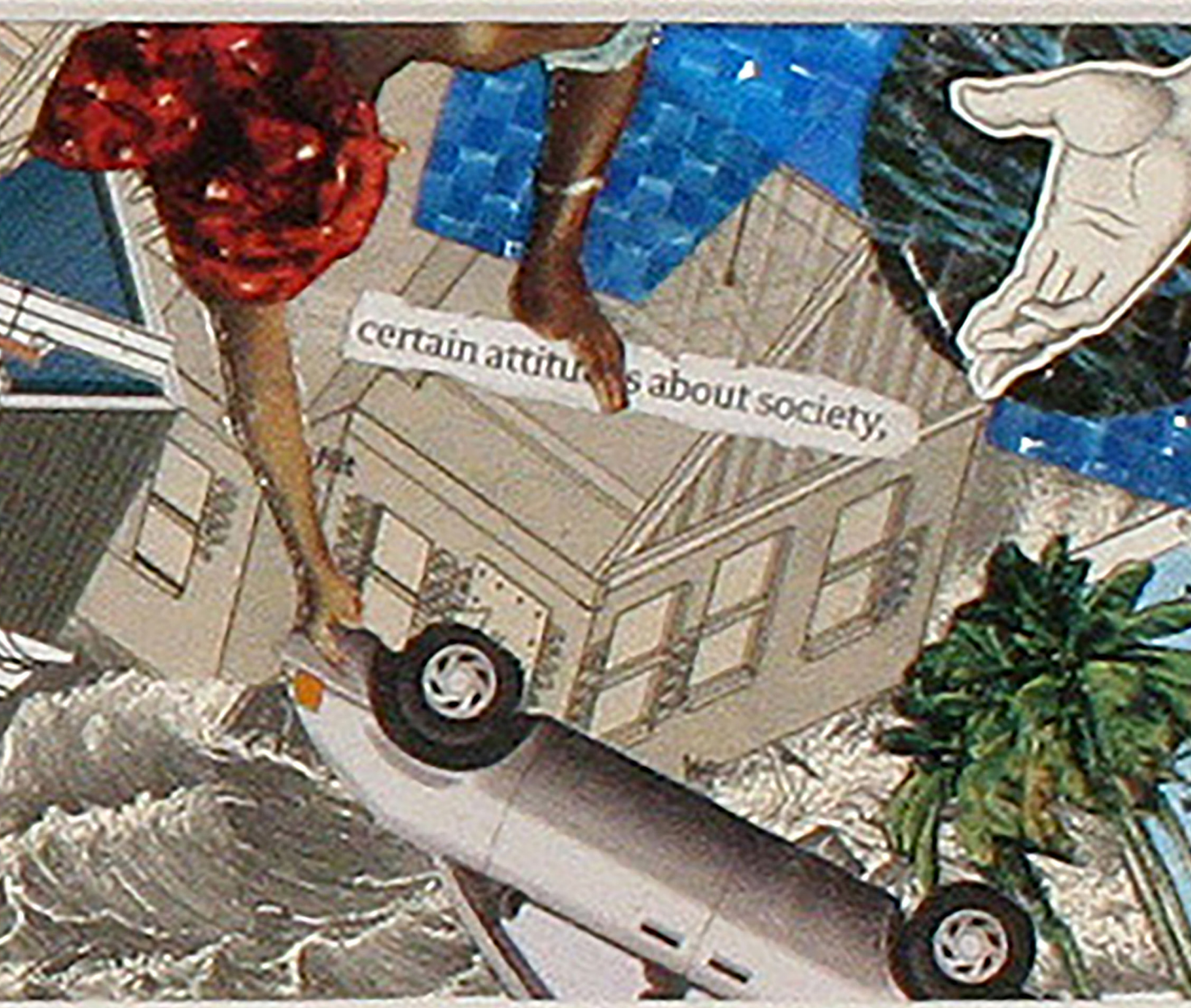
408. Eck, M.A., A.R. Murray, A.R. Ward, and C.E. Konrad, 2020: Influence of growing season temperature and precipitation anomalies on crop yield in the southeastern United States. *Agricultural and Forest Meteorology*, **291**, 108053. https://doi.org/10.1016/j.agrformet.2020.108053

409. Gordemer, B., 2021: Rising sea levels threaten the lives and livelihood of those on a fragile U.S. coast. NPR, November 7, 2021. https://www.npr.org/2021/11/07/1051529051/rising-sea-levels-climate-change-south-carolina-coast

410. Crespi, J., C. Hart, C. Pudenz, L. Schulz, O. Wongpiyabovorn, and W. Zhang, 2022: An Examination of Recent Fertilizer Price Changes. Staff Report 22-SR 117. Iowa State University, Center for Agricultural and Rural Development, Ames, IA. https://doi.org/10.13140/rg.2.2.24806.70720

Fifth National Climate Assessment: Chapter 23

US Caribbean



Chapter 23. US Caribbean

Authors and Contributors

Federal Coordinating Lead Author

Lisamarie Carrubba, NOAA Fisheries, Office of Protected Resources

Chapter Lead Authors

Pablo A. Méndez-Lazaro, University of Puerto Rico (June 2021–September 2022, April 2023 onward)

Patricia Chardón-Maldonado, Caribbean Coastal Ocean Observing System (September 2022–April 2023)

Chapter Authors

Nora Álvarez-Berríos, USDA Forest Service, International Institute of Tropical Forestry

Maritza Barreto, University of Puerto Rico Rio Piedras Campus, Graduate School of Planning

Jared H. Bowden, North Carolina State University

Patricia Chardón-Maldonado, Caribbean Coastal Ocean Observing System

Wanda I. Crespo-Acevedo, NOAA Climate Adaptation Partnerships Program–Puerto Rico/Lynker

Ernesto L. Diaz, Tetra Tech Inc.

Lloyd S. Gardner, Foundation for Development Planning Inc.

Grizelle Gonzalez, USDA Forest Service, International Institute of Tropical Forestry

Gregory Guannel, University of the Virgin Islands

Zack Guido, University of Arizona, Arizona Institute for Resilience

Eric W. Harmsen, University of Puerto Rico, Department of Agricultural and Biosystems Engineering

Amanda J. Leinberger, University of Arizona, Center for Climate Adaptation Science and Solutions

Kathleen McGinley, USDA Forest Service, International Institute of Tropical Forestry

Pablo A. Méndez-Lazaro, University of Puerto Rico

Ana P. Ortiz, University of Puerto Rico Comprehensive Cancer Center

Roger S. Pulwarty, National Oceanic and Atmospheric Administration

LaVerne E. Ragster, University of the Virgin Islands

Isabel C. Rivera-Collazo, University of California, San Diego

Ruth Santiago, Lawyer

Carlos Santos-Burgoa, George Washington University

Ingrid M. Vila-Biaggi, CAMBIO

Technical Contributors

Odalys Martínez-Sánchez, NOAA National Weather Service

Melissa Meléndez, University of Hawai'i at Mānoa, School of Ocean and Earth Science and Technology

Kim Waddell, University of the Virgin Islands

Review Editor

Edna L. Negrón-Martínez, University of Puerto Rico, Medical Sciences Campus

Cover Art

Melanie Mills

Recommended Citation

Méndez-Lazaro, P.A., P. Chardón-Maldonado, L. Carrubba, N. Álvarez-Berríos, M. Barreto, J.H. Bowden, W.I. Crespo-Acevedo, E.L. Diaz, L.S. Gardner, G. Gonzalez, G. Guannel, Z. Guido, E.W. Harmsen, A.J. Leinberger, K. McGinley, P.A. Méndez-Lazaro, A.P. Ortiz, R.S. Pulwarty, L.E. Ragster, I.C. Rivera-ColWWlazo, R. Santiago, C. Santos-Burgoa, and I.M. Vila-Biaggi, 2023: Ch. 23. US Caribbean. In: *Fifth National Climate Assessment*. Crimmins, A.R., C.W. Avery, D.R. Easterling, K.E. Kunkel, B.C. Stewart, and T.K. Maycock, Eds. U.S. Global Change Research Program, Washington, DC, USA. https://doi.org/10.7930/NCA5.2023.CH23

Table of Contents

Introduction 6

Box 23.1. Differential Vulnerabilities in the US Caribbean 8
Observed and Projected Climate Change for the US Caribbean 9
Box 23.2. Missing Data in the US Caribbean and the Pacific Islands 12

Key Message 23.1
Climate-Driven Extreme Events Exacerbate Inequities and Impact Human Health and Well-Being 12

Community Identity and Heritage Are Necessary for Resilience and Post-disaster Recovery 13
Impacts of Extreme Events on Health and Essential Services 15
Noncommunicable Diseases 15
Climate-Driven Vector-Borne Diseases 15
Climate Impacts on Human Zoonotic Diseases 15
Excessive Heat and Differential Social Burden of Climate Impacts 16
Human Health and Natural Sources of Air Pollution 16
Sargassum and Health Intersections 16
Water Resources and Human Health Interactions 17
Underestimation of Mortality 17

Key Message 23.2
Ecology and Biodiversity Are Unique and Vulnerable 18

Impacts of a Changing Climate on Ecosystem and Biodiversity Goods and Services 19
Emerging Issues and Future Directions 20

Key Message 23.3
Climate Change Threatens Water and Food Security 22

Characteristics of the Island Food Systems 22
Characteristics of the Island Water Systems 22
Climate Stressors on Food and Water System Components 23
Social Protection 26
Emerging Issues 26

Key Message 23.4
Infrastructure and Energy Are Vulnerable, but Decentralization Could Improve Resilience 27

Key Message 23.5
Adaptation Effectiveness Increases When Coupled with Strategic Governance and Planning 30

Challenges and Opportunities 31

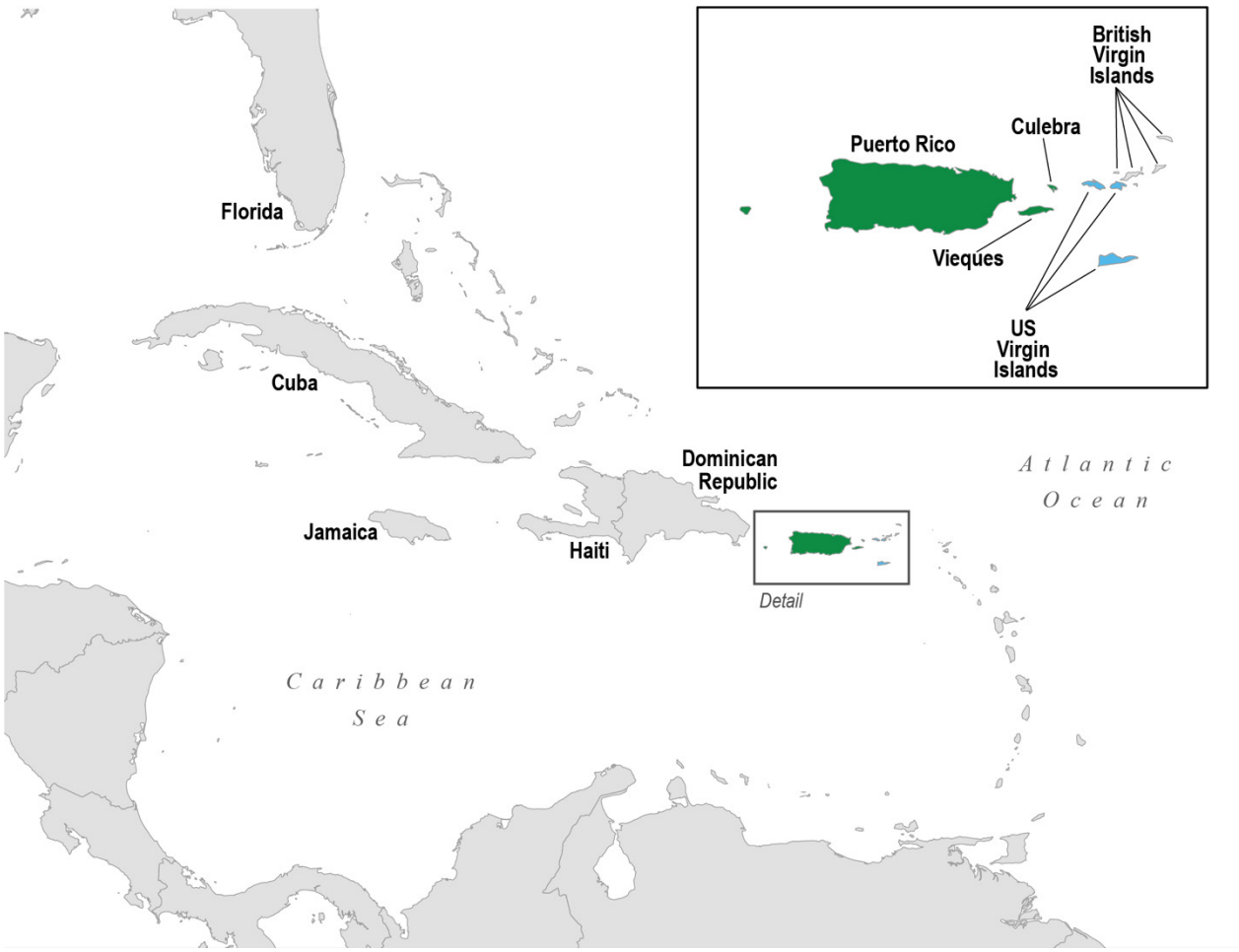
Traceable Accounts 33
Process Description 33
Key Message 23.1 33
Key Message 23.2 35
Key Message 23.3 36
Key Message 23.4 37
Key Message 23.5 38

References 39

Introduction

The US Caribbean comprises Puerto Rico (PR) and the US Virgin Islands (USVI; Figure 23.1). Both are US territories, and people born there acquire US citizenship by birth. The USVI is home to about 87,000 US citizens (Table 23.1).[1] The USVI has a majority Black population and a mix of English-, Spanish-, and Creole-speaking communities. Puerto Rico (which includes the inhabited islands of Vieques and Culebra) has a population of around 3 million US citizens who are predominantly Hispanic- or Latino-Spanish speakers. Communities in both territories are now the source of significant migration to the US mainland.[2,3,4,5,6]

The US Caribbean



The US Caribbean region in the Fifth National Climate Assessment consists of Puerto Rico and the US Virgin Islands.

Figure 23.1. The map shows the location of Puerto Rico and the US Virgin Islands in the Caribbean Basin. The inset shows the main island of Puerto Rico (green; the two municipal islands of Vieques and Culebra are shown to the east and Mona Island to the west) and the US Virgin Islands (yellow; St. Thomas and St. John to the north and St. Croix to the south). Figure credit: University of Puerto Rico, NOAA NCEI, and CISESS NC.

The USVI and PR share a geographic region. Both are populated by groups that the US government considers minorities, and both face enormous socioeconomic challenges. At the same time, they have different socioeconomic, geopolitical, and climate realities. They are also quite different in scale, governance, and demographics (Table 23.1). Island residents have learned to cope with adversity due to centuries of unfavorable social inequality, colonial policies, and extreme climate events.[7]

Table 23.1. Geography of US Caribbean Territories

The sociodemographic profiles of Puerto Rico and the US Virgin Islands are grounded in long histories of colonization, systemic inequality, and parallel historical backgrounds with deeply rooted Indigenous traditions. These territories are facing similar climate-related hazards that are compounded by shrinking economies, aging populations, and ineffective government structures. Sources: Median household income from US Department of Housing and Urban Development;[8] other data from US Census Bureau.[6]

Category	Puerto Rico	US Virgin Islands
Population Living Below Poverty Level (US average: 11.4%)	43.5%	18.4%
Main Island(s) Surface Area	3,515 square miles	St. Thomas: 32 square miles St. John: 20 square miles St. Croix: 81 square miles
Total Population	3,075,000*	St. Thomas: 42,261 St. John: 3,881 St. Croix: 41,004 Total: 87,146
Principal Language	Spanish	English
Urban Population	93%	96.3%
Rural Population	7%	3.7%
Race and Ethnicity	98.7% Hispanic or Latino** (US: 18.5% Hispanic or Latino)	76% Black (Afro-Caribbean) (US: 13.4% Black or African American)
Median Household Income (in 2020 dollars; US average $67,521)	$20,539	$37,254
Population Change 2010–2020	–17.4%	–18.1%
Government	1 governor 27 senators 51 representatives 78 mayors/municipalities 1 non-voting member of the US House of Representatives	1 governor 15 senators (7 each district, 1 at-large) No representatives No mayors 1 non-voting member of the US House of Representatives

*2020 Post-Enumeration Surveys.[9] **Although "Hispanic or Latino" is the official US Census category, it does not capture the racial and ethnic diversity of PR, the Caribbean, or Latin America. The official US Census definition for "Hispanic or Latino" refers to a person of Cuban, Mexican, Puerto Rican, South or Central American, or other Spanish cultural origin regardless of race. This definition is meant to cover all Spanish-speaking cultures.

These islands are particularly vulnerable to extreme weather events that are being exacerbated by human-driven climate change, and there is increased potential for impacts because people, cities, and critical infrastructure are often located in the most vulnerable locations.[10,11,12] Extreme weather is triggering cascading, ongoing crises and highlighting political divides, which shape response and recovery efforts. At the same time, these events are revealing grassroots organizational capacities typically ignored by national- or regional-scale discourses regarding vulnerability and resilience.[13,14] A changing climate in the Caribbean highlights the interdependencies of critical infrastructure systems. In addition, climate change threatens

the preservation of heritage, particularly tangible heritage both on land and underwater.[15] In addition to catastrophic failures caused by powerful hurricanes, the impacts of extreme events in many places in the Caribbean are exacerbated by intangible factors that undermine the foundations of strong communities and functional ecosystems. Post-disaster recovery is particularly complex in the US Caribbean because of diverse cultural practices, complicated governance structures, and uneven access to information and resources, sometimes referred to as differential social vulnerability (Box 23.1).

The absence of adequate governmental response to climate change and extreme events, coupled with a long history of political marginalization, has catalyzed the rise of community-based organizations that are pursuing sustainable development efforts on their own.[13]

Box 23.1. Differential Vulnerabilities in the US Caribbean

Impacts of climate change on US Caribbean societies must be understood in the context of the social and historical processes that shape identity and exposure (see Chapter 20 for a detailed explanation of these concepts and the links to justice). Not everyone is equally impacted by climate change. Social vulnerability is a multidimensional process affected by social, political, and economic forces interacting from local to international scales.[16] In the US Caribbean, social vulnerability and social determinants of health are best viewed within a systemic risk framework and are at least partially influenced by the following:

- *Culture*: Broad ethnic diversity, different economic backgrounds, and deep historical traumas linked to colonization and struggle characterize the US Caribbean. These backgrounds shape locally relevant worldviews, risk-perception, decision-making, and adaptation and mitigation strategies. Perception of and response to climate risks include local and Traditional Ecological Knowledge and long-term memory of disasters that might or might not be transferable within or between islands (Ch. 20).

- *Access to resources*: High poverty indices and sharp social stratification, together with growing gentrification, migration, displacement, accumulated impacts from past disasters, and concerns linked to human health, influence access to resources—from economic to material objects—that could be used to lessen risks and prepare for adaptation. Aside from economic resources, access to natural resources is affected by the cumulative effects of human activities over time. In the Caribbean, for example, years of Indigenous agricultural practices, colonial plantation systems, and industrialization have contributed to reduced biodiversity, loss of forest cover, soil depletion, unstable slopes, and degraded marine ecosystems, which converge to heighten the severity of risks (Chs. 17, 18).

- *Access to information*: Climate data are often available only on scales that are too large for the needs of relatively small islands with very wide microclimatic diversity. Other barriers to accessing information include language (Spanish and English are the principal languages of PR and the USVI, respectively), educational barriers, poverty, growing indices of illiteracy, and distrust in official entities.

- *Governance*: The political relationship between the US Caribbean territories and the Federal Government affects the ability and capacity for local action. Other formal and informal systems of local governance also affect action, including grassroots leadership, local nongovernmental organizations, and religious organizations.

- *Puerto Rico's fiscal and economic situation:* The prolonged and deep contraction of Puerto Rico's economy since 2006, coupled with the fiscal crisis and the Puerto Rico government's bankruptcy, resulted in significant cutbacks in government institutions, social services, and infrastructure improvements and maintenance.[17,18,19] Such austerity measures, intensified by the escalating intervention of the federally controlled Fiscal Management Board, influence Puerto Rico's ability to address the underlying causes of vulnerability and hinder its capacity to recover and adapt.[20]

Observed and Projected Climate Change for the US Caribbean

The assessment of observed and projected climate-related trends provides information for evaluating climatic and environmental consequences of future climate changes, risks, and impacts. The following assessment builds on the most recent findings.[1,12,20,21,22,23,24,25]

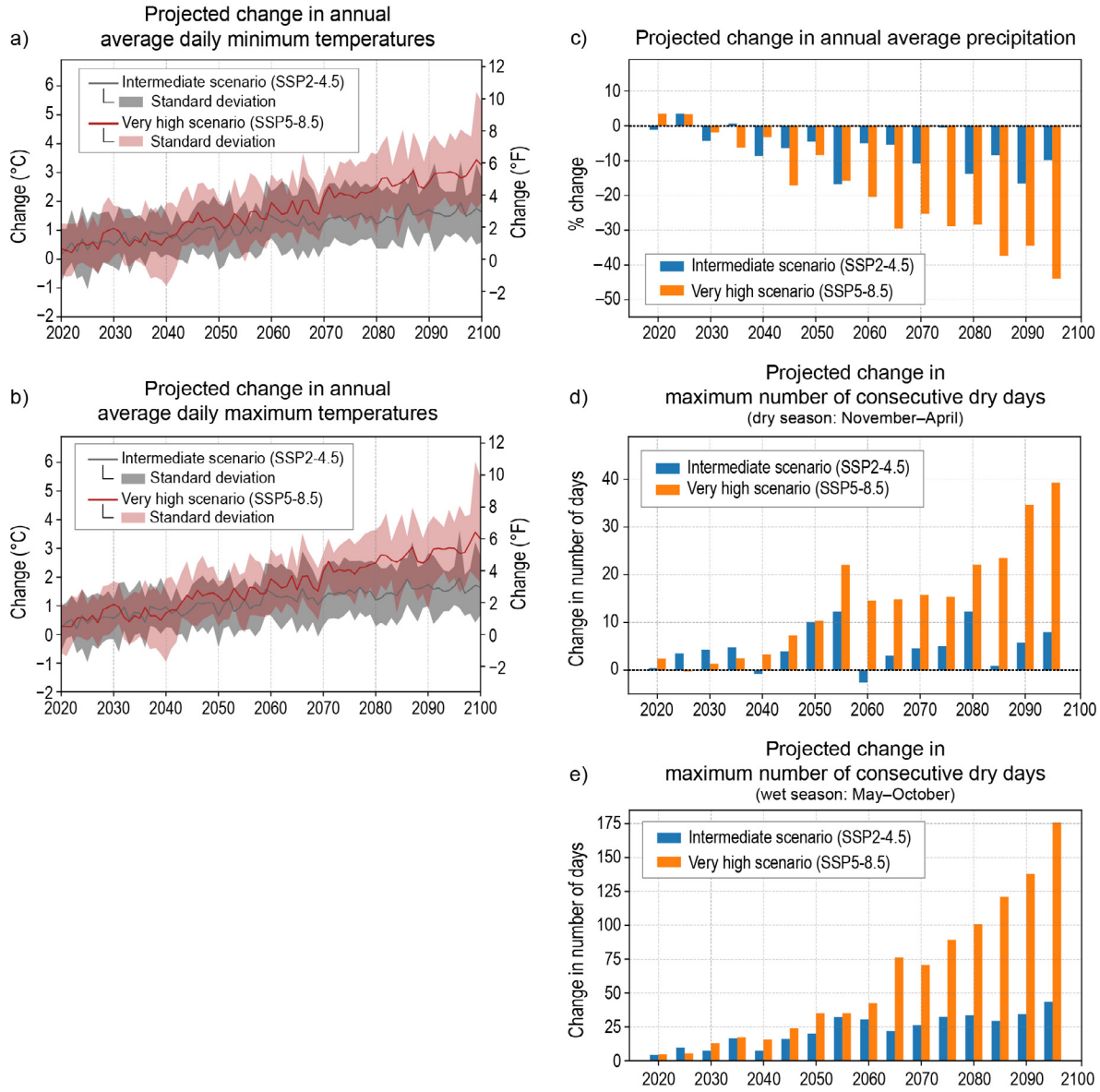
- Natural climate variability (Table 23.2), including the El Niño–Southern Oscillation (ENSO), North Atlantic Oscillation (NAO), and Saharan dust events, has an important role in the subseasonal to interannual (year-to-year) climate within the US Caribbean.
- Daily average temperatures in PR have increased by 2°F since 1950. Minimum temperatures are increasing faster than daily average temperatures, with the largest increase for minimum temperatures at lower elevations. Projections for end-of-century temperatures show additional warming, from as low as 1.1°F under an intermediate scenario (SSP2-4.5) to as high as 7°F under a very high scenario (SSP5-8.5; Figure 23.2).
- No clear long-term trend is detected in seasonal or annual average rainfall over PR, although Figure 2.4 does show a small increase (less than 5%) in Puerto Rico in 2002–2021 compared to the 1901–1960 average. However, climate models project a significant reduction in annual average rainfall by end-century with reductions of 10% for SSP2-4.5 and 33% for SSP5-8.5. The rainfall reductions for SSP5-8.5 compared to SSP2-4.5 become increasingly larger after midcentury. The consequence of reductions in annual average rainfall is a large increase in the number of consecutive dry days, especially for the wet season (Figure 23.2).
- Within the Atlantic basin, the tropical cyclone rain rate is projected to increase by about 15% and the average storm wind intensity around 3% for a global average temperature increase of 3.6°F (2°C) above present-day levels. The number of intense tropical cyclones (Categories 4 and 5) are projected to increase as well (KM 2.2). There is some indication within Puerto Rico that tropical cyclone rainfall rates are increasing over the climatological record, increasing the likelihood of extreme events like Hurricane Maria's rainfall. Sea surface temperatures have warmed, and oceans are becoming more acidic, absorbing increased concentrations of atmospheric carbon dioxide (CO_2).
- Sea level is rising and is expected to continue to rise for centuries (KM 9.1). Long-range sea level scenarios indicate an additional rise of approximately 0.6 feet (0.2 m; Low scenario) to 1.4 feet (0.4 m; High scenario) by 2050 and 1.9 feet (0.4 m; Low scenario) to 6.8 feet (2.1 m; High scenario) by 2100;[25] for connections to Shared Socioeconomic Pathways [SSPs], see the Guide to the Report). The trajectory from tide-gauge observations from within the US Caribbean archipelago from 1970–2020 aligns with the Intermediate scenario out to 2050.

Table 23.2. Large-Scale Circulation and Climate Variability

Changes in the global (large-scale) circulation affect climate variability in the US Caribbean. El Niño–Southern Oscillation (ENSO) is the strongest source of year-to-year climate variability across the globe. An ENSO warm phase is referred to as El Niño and is associated with the warmer water in the eastern equatorial Pacific. The cool phase is referred to as La Niña and is associated with cooler water in that region. These warmer and cooler waters affect the atmosphere and worldwide weather patterns. The different phases of ENSO typically last between 6 and 18 months and recur every 2 to 7 years.[26,27,28] The North Atlantic Oscillation (NAO) is an oscillation in the sea level pressure between the Icelandic Low and North Atlantic Subtropical High.[29,30,31,32] A positive NAO occurs when both the Icelandic low and the Azores high are stronger than average, which creates strong atmospheric pressure differences within the North Atlantic. A negative NAO is associated with a weak Icelandic low and Azores high and weakened pressure differences within the North Atlantic. Saharan dust (consisting of particles containing minerals, organic matter, marine salts, viruses and bacteria, quartz, calcite, hematite, sulfates, and other materials) reaches the Americas from Africa (mainly from the Sahara and the Sahel). Dust season in the Caribbean occurs between May and September (summer), with maximum peaks from June to August.[31,32]

Climate Variability	El Niño	La Niña	North Atlantic Oscillation (positive)	North Atlantic Oscillation (negative)	Saharan Dust
North Atlantic Tropical Cyclone Activity	Suppress activity	Increase activity	Suppress activity	Increase activity	Suppress activity
US Caribbean Rainfall	Weak to negligible impact	Weak to negligible impact	Suppress rainfall	Increase rainfall	Suppress rainfall

Temperature and Rainfall in Puerto Rico



Puerto Rico is projected to become warmer and drier, with increasing uncertainty in the magnitude of change beyond midcentury; just how warm and dry depends on the scenario followed.

Figure 23.2. Projected temperature and precipitation changes for Puerto Rico are shown for an intermediate scenario (SSP2-4.5) and a very high scenario (SSP5-8.5) to demonstrate the range of plausible future changes in the climate. Climate change projections are shown for annual average daily minimum (**a**) and maximum (**b**) temperatures, annual average precipitation (**c**), and maximum number of consecutive dry days during the dry season (**d**) and wet season (**e**). Both scenarios indicate a warmer and drier climate for Puerto Rico, but the magnitude of change for the very high scenario is alarming, especially when considering the availability of fresh water. The average maximum temperature increases for the end of the century (2071–2100) range from 2.8°F (1.5° C) for the intermediate scenario to 4.8°F (2.7° C) for the very high scenario. The increased temperatures, coupled with reductions in annual average precipitation at the end of the century of approximately 10% (intermediate scenario) to greater than 30% (very high scenario), are both indications of a significantly drier climate, with very large impacts anticipated for the very high scenario. A particular concern is the precipitation reduction during the wet season and the large increase in the number of consecutive days without rain, exceeding an increase of 115 days, on average, by the end of the century for the very high scenario. The bar plots in panels (c–e) are averages over five-year periods. All plots are differences relative to the entire period (2021–2100). Figure credit: NOAA NCEI and CISESS NC.

Box 23.2. Missing Data in the US Caribbean and the Pacific Islands

The US Caribbean and Pacific Islands continue to face similar challenges related to climate change (Ch. 30), including geographic constraints (e.g., limited land area, variable topography), reliance on imports, critical dependence on local natural resources (fresh water, fisheries), and differential vulnerabilities to drought, sea level rise, and natural disasters. These territories are home to underserved and underrepresented communities that are systemically excluded from data collection efforts due to administrative structures that are rooted in colonialism.[33,34] These structures, combined with the lack of data, have resulted in capacity issues that continue to promote discrimination, inequity, and inequality in a wide range of sectors (e.g., health, natural resources, education, agriculture, food security, imports, and housing).[35,36,37,38]

Data for the US Caribbean are missing for metrics such as carbon dioxide sources and carbon sinks, municipality-level population projections, and locally relevant downscaled projections for both the changes in average conditions (e.g., temperature, precipitation) and extreme events (e.g., heatwaves, hurricanes, droughts, marine heatwaves, winter storms, dust storms). Even in cases where downscaled data are available for the US Caribbean region, they are not at a fine-enough resolution to distinguish small islands such as the US Virgin Islands, Culebra, and Vieques. Furthermore, Caribbean Traditional Knowledge systems and stewardship have been foundational in responding to climate change, but generations of knowledge have been undervalued, suppressed, and ignored by Western science and have only recently been recognized as valid knowledge sources at the federal level.[39,40] By identifying and addressing the underlying causes for missing information in the US Caribbean, scientific institutions will be able to more equitably develop future research and climate assessments. Doing so would better serve evidence-based decision-making throughout the Caribbean region.

Key Message 23.1

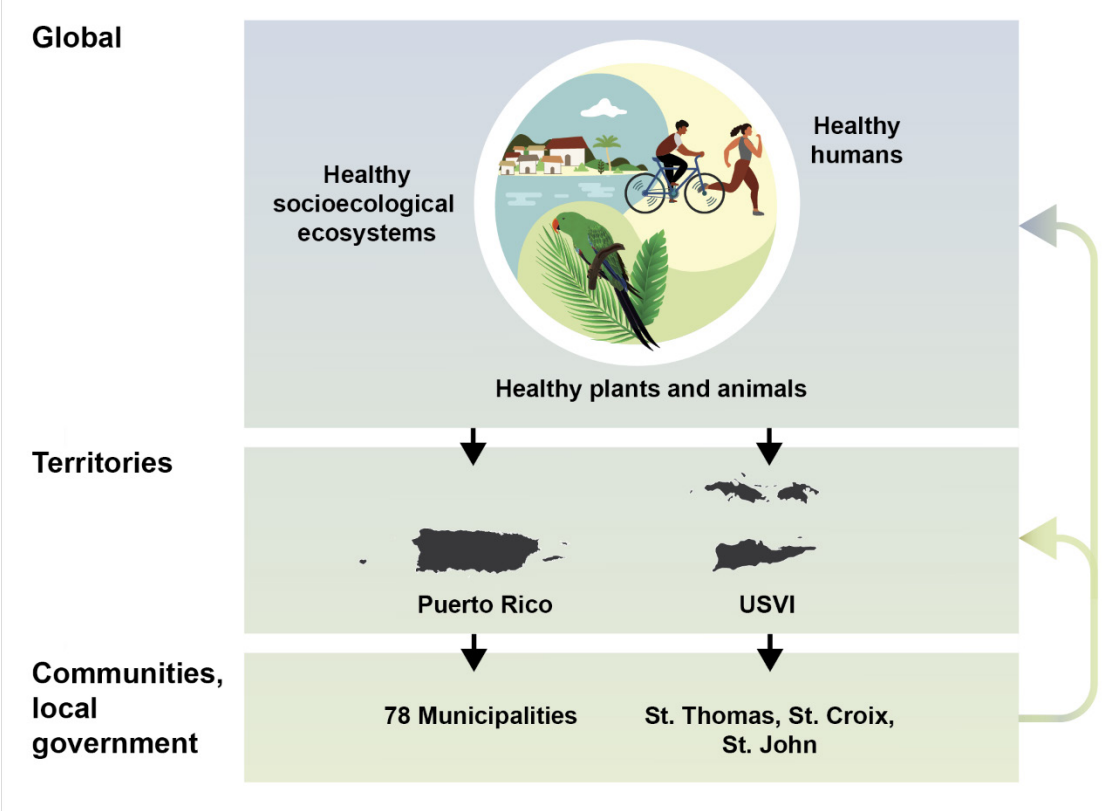
Climate-Driven Extreme Events Exacerbate Inequities and Impact Human Health and Well-Being

Traditionally underserved and disadvantaged communities suffer disproportionate impacts from climate change because they have been systematically excluded from social services, secure livelihoods, quality education, and other social benefits that help sustain health and well-being (*high confidence*). Hurricanes and other climate-related extreme events have been associated with higher rates of disease, mental illness, and overall mortality, as well as loss of cultural heritage that is central to community identity (*high confidence*). As extreme weather events become more intense and more frequent, residents will continue experiencing increasing levels of noncommunicable diseases, excess mortality, behavioral health challenges, and loss of quality of life (*high confidence*). The frequency of heat episodes and the severity of hurricanes are both expected to increase in the region due to human-induced climate change, which will affect public health unless adaptation measures are taken (*high confidence*).

Long histories of colonization and systemic inequality shape the ability of the US Caribbean peoples to maintain health, quality of life, and overall individual and social well-being. Evidence from both PR and the USVI suggests risks from climate impacts to multiple elements of human health, including vector-borne and noncommunicable diseases, mental health, and overall quality of life (Ch. 15).[41] US Caribbean societies, with their multiethnic and multiracial makeup of high proportions of people of African and Indigenous descent, are more vulnerable to climate-related risks due to economic policies and social systems, varying levels of educational attainment, unemployment, poverty, out-migration, older-age demographics, food insecurity, colonialism, and unjust historical treatment.[42] As an effort to address these circumstances and the threat of more frequent extreme events, the One Health approach, similar to the community health concept

described in Chapter 15, mobilizes collaborative work among communities, stakeholders, practitioners, sectors, and disciplines to tackle climate change while improving well-being and quality of life for all living organisms (Figure 23.3).

The One Health Approach



In the face of climate change, the health of Caribbean people, plants, animals, and ecosystems depends on coordination across multiple scales and boundaries.

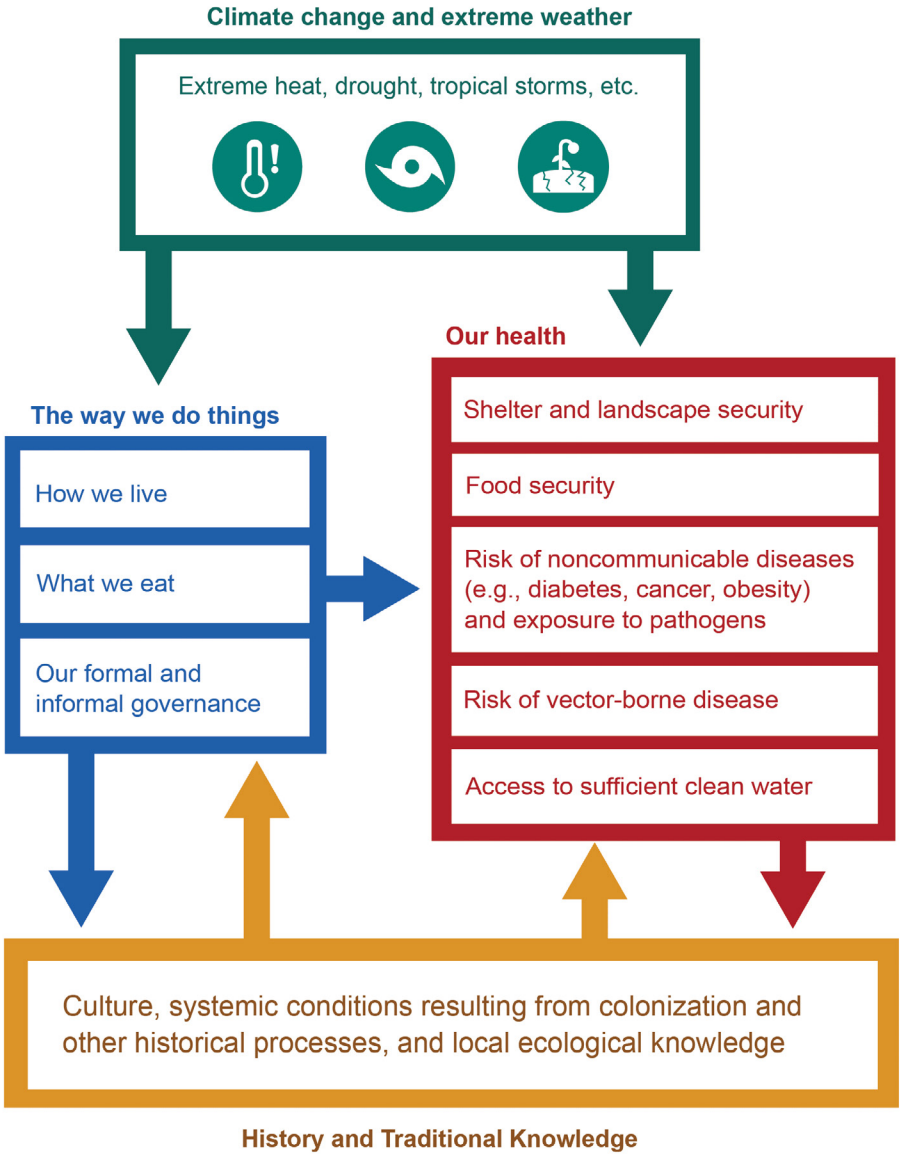
Figure 23.3. In the US Caribbean, climate change is interacting with the institutional and environmental context of the islands and the social determinants of health. Extreme weather events (e.g., powerful hurricanes, extreme heat, and droughts) are threatening access to clean air, safe drinking water, nutritious food, and safe settlements, as well as damaging infrastructure, reducing tourism, displacing vulnerable communities, promoting migration among islanders, disrupting ecosystem services, and endangering animals. The One Health approach illustrated here promotes collaborative work at local, regional, and global levels to achieve health for humans, ecosystems, and animals alike. Adapted from World Health Organization 2021[43] [CC BY-NC-SA 3.0 IGO].

Community Identity and Heritage Are Necessary for Resilience and Post-disaster Recovery

US Caribbean cultural heritage is under threat due to changing climate conditions (Figure 23.4). Cultural heritage includes tangible elements (such as buildings, artifacts, monuments, and archaeological sites on land and underwater) and intangible elements (such as practices, ideas, representations, knowledge, music, songs, and ceremonies) that are recognizable components of community identity.[15,44] Research from recent hurricane events suggests that the magnitude of loss of heritage is severely underestimated[45,46] and that measures to mitigate climate impacts greatly threaten the preservation of cultural heritage and identity. For example, the traditional ways of life in the US Caribbean placed communities next to riverbanks for thousands of years. Archaeological sites associated with such communities, however, are under threat

from flood-control projects,[15] which entail channelizing, dredging, or covering rivers (e.g., USACE 2022[47]). These flood-control projects not only impact archaeological sites but also transform landscapes that are integral to the identity, recreation, and overall well-being of local residents.[15,48] Climate impacts also increase out-migration, which can lead to disintegration of traditional communities and loss of Indigenous and Traditional Knowledge (KM 30.2).[49]

Climate Change and Public Health



Public health is shaped by sociocultural factors and further affected by climate change.

Figure 23.4. The impacts of climate change on human health in the US Caribbean must be considered in the context of the social, cultural, and historical realities of the islands. Shelter and food security, access to clean water, and communicable and noncommunicable diseases are certainly affected by climate, but they are also conditioned by culture, tradition, and historical and colonization processes. Figure credit: University of California, San Diego; University of the Virgin Islands; NOAA NCEI; and CISESS NC.

Impacts of Extreme Events on Health and Essential Services

Extreme events, combined with deteriorating infrastructure and unequal distribution of social determinants of health, are expected to continue to cause interruptions in and insufficient access to healthcare services, as documented after Hurricanes Irma and Maria (KM. 15.2).[14,50,51,52] PR and the USVI have contaminated sites where hazardous waste has been discarded and, in some cases, improperly managed. Some of these sites—26 in PR and 2 in the USVI—are designated as EPA Superfund sites.[53] Extreme flooding has the potential to impact Superfund sites, spreading large amounts of contaminants and carcinogens into the surrounding environment.[54]

In the aftermath of Hurricane Maria, many older adults in PR experienced unmet needs that contributed to declining physical and emotional health, inadequate management of noncommunicable disease (NCD), social isolation, financial strain, environmental health issues, and excess mortality.[14,55,56] High levels of post-traumatic stress disorder (PTSD), depressive symptoms, and disaster-related stressors were also evident (KM 30.2).[42,57] Many hospitals suffered significant damages in both territories.[58] Various healthcare services were greatly affected, including vaccinations, cervical cancer screenings, surgeries, oncologic treatments, and dialysis.[59,60,61,62,63,64] Experts recommend that further disease-specific planning be delineated within the emergency response of each jurisdiction and in collaboration with disease-specific plans for relevant organizations.[65] For instance, region-specific and federal health plans, such as the CDC's comprehensive cancer control plans, would mitigate the impact of extreme weather on specific populations and maintain adequate cancer prevention and treatment care during and after disasters.

Noncommunicable Diseases

The US Caribbean territories have high rates of NCDs, as well as increasing rates of impaired mental health.[42,66] After Hurricane Maria, there were obstacles to providing nutritious, affordable, and culturally acceptable food appropriate for people with NCDs.[42] In PR and the USVI, 67.5% and 65.2% of the population, respectively, are overweight, and 31.4% and 32.5% live with obesity;[67] these conditions are considered predictors of early mortality.[68] Surveys in PR in 2017 and 2019, pre- and post-Hurricane Maria, show an increase over that time span in the prevalence of NCDs and depression in adults.[69] In March 2018, an online survey identified PTSD in 44% of respondents in PR and 66% of those displaced from PR to Florida.[70,71]

Climate-Driven Vector-Borne Diseases

Vector-borne diseases (VBD) in the Caribbean, such as dengue, Zika, and chikungunya, are mostly transmitted by the *Aedes aegypti*, *Aedes albopictus*, and *Culex* mosquitoes (KM 15.1). The abundance of *Ae. aegypti* and *Ae. albopictus* are influenced by temperature and precipitation, and both species have excellent adaptation skills under extreme temperature and precipitation conditions.[72,73,74,75,76] Factors in the US Caribbean that favor VBD outbreaks include climate change, inequality, poverty, serotype profile (virus variation), immunity, deficient water and waste management, and lack of community awareness.[75]

Climate Impacts on Human Zoonotic Diseases

Human leptospirosis is an important zoonotic disease—that is, a disease that transmits from animals to humans—with worldwide distribution. It was first reported in PR in 1942, while the first cases of leptospirosis in the USVI were reported in the aftermaths of Hurricanes Irma and Maria. Recent evidence suggests an excess risk in PR of leptospirosis associated with flood-prone areas, heavy rainfall, and higher temperatures.[77] Extreme weather events such as tropical storms, heavy rainfall, and floods are expected to result in an upsurge in the number and magnitude of leptospirosis outbreaks.[78] Under the above-mentioned climate scenarios, outbreaks in both US territories are *very likely* to occur following extreme weather events.

Excessive Heat and Differential Social Burden of Climate Impacts

Heatwaves are increasing the risk for heat-related illness and death (KMs 6.2, 15.1; Figure 15.1). Conditions of extreme heat in the Caribbean have intensified since 1980. Recent research suggests an increasing trend in the number of days with heat stress (days above 39.9°C [103.8°F]) for the Caribbean region since 1980.[79] Several factors contribute to heat vulnerability and sensitivity, including:

- Populations at the extremities of age (e.g., newborns, children, elders)
- Pregnant women/people
- Individuals who are
  - living in single-person households
  - living below the poverty line
  - working in confined spaces with poor ventilation
  - working outdoors and exposed to risk factors such as direct sunlight or high humidity combined with extremely high air temperature
  - living with disabilities
  - living with chronic health conditions (e.g., obesity, hypertension, diabetes, cardiovascular disease, respiratory illness)
  - without health insurance coverage

With rapid urbanization in the USVI and PR and past population growth, urban heat island effects have become stronger (KM 12.2). San Juan, PR, is already showing evidence of these effects;[80] extreme heat episodes there have been associated with a significant increase in mortality and an increased relative risk for stroke and cardiovascular diseases.[81] Cooling indoor environments help lessen the impact of heatwaves, but energy demands on a crumbling power infrastructure, as well as rising costs of living, create climate risks associated with inequality, as only a section of the society will be able to afford cooling equipment.[82]

Human Health and Natural Sources of Air Pollution

Recent studies suggest that global warming will make dust storms more severe in the Mediterranean and the Atlantic (KM 14.1).[83] In the US Caribbean, dust particles carried across the Atlantic from the Sahara, mostly during summer, affect climate, weather, and ecosystems, including coral reefs, forests, and human populations.[84,85,86,87,88,89,90,91,92] Saharan dust provides nutrients to terrestrial and marine ecosystems. However, in PR, Saharan dust has been associated with increased cardiovascular and respiratory risks;[93] it has also been linked to increased risk of emergency room visits and hospitalizations related to asthma in children in Trinidad and Tobago,[94] Guadeloupe,[95] and Grenada.[96] As humidity and temperatures rise, the abundance of mold and spores in the air also impacts air quality and thus respiratory NCDs.

Sargassum and Health Intersections

Sargassum is a brown seaweed that floats in the Atlantic Ocean and provides an important habitat for migratory organisms that have adapted specifically to it. These algal mats are sometimes pushed by wind and currents into the Caribbean Sea and are frequently reaching the coasts of the region's islands. Evidence suggests that these events threaten coastal ecosystems and social and cultural activities (e.g., fisheries), with negative economic impacts (e.g., reduced tourism and degraded infrastructure; Ch.10; KM 1.2) and adverse human health effects (e.g., heart palpitations, shortness of breath, and skin rashes) due to hydrogen sulfide from decomposing sargassum in the air and direct exposure to algae.[97,98,99,100,101,102,103] While sargassum mats can be harvested for beneficial uses such as fertilizer and animal feed and as an energy source, its use as a fertilizer could transfer heavy metals to crops.[104,105,106] While the impact of this phenomenon has not yet been assessed for the US Caribbean, these conditions are expected to worsen as climate change intensifies.

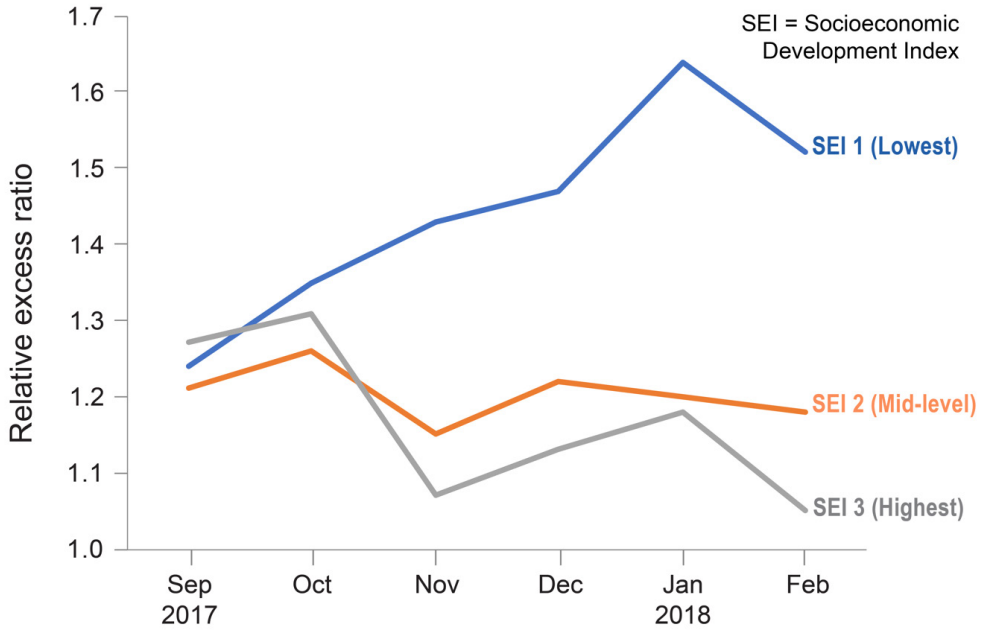
Water Resources and Human Health Interactions

Factors related to environmental health and changing climate (e.g., sea level rise, saltwater intrusion, and pollution) impact water security. Inefficient water management and climate change, including the increasing intensity of storms, have led to growing concerns about water scarcity and water insecurity for both territories.[107] While Traditional Knowledge has been shown to mitigate water scarcity during emergencies—such as individuals and communities activating historic or abandoned water sources during recent disasters[44,108]—these responses might not be enough, as Traditional Knowledge is also threatened, cultural heritage is being lost, and the magnitude of impacts exceeds previous experience (KM 30.1). Older traditional farmers in Puerto Rico have recorded a reduction in freshwater availability in streams and springs that impacts their traditional access to fresh water and their food production, which they consider a heightened risk for their health.[15] Reports on communities in both PR and the USVI that are systematically excluded from welfare, education, and other social services and benefits link inequity to poverty levels and the impact of status on the development and interpretation of laws and programs that address these issues (KM 15.2). Studies after hurricanes in PR and the USVI have shown water pollution, disease vectors, and bacteria in the drinking water supply, all of which are expected to worsen with expected impacts of climate change, thus affecting livelihood security.[109,110,111]

Underestimation of Mortality

Total excess mortality identifies how many more observed deaths happen after a specific event in comparison to the baseline historical trend of expected deaths had the natural event not occurred. After Hurricane Maria in PR, a large excess mortality was noticed by many people but not identified by the official certification of 64 deaths. Six months after Maria, a commissioned independent study identified 21% more deaths in males than expected and a total excess mortality estimate of 2,975 (Figure 23.5),[56] including both direct (related to hurricane injuries) and indirect (related to lack of access to effective care after the storm) deaths. These deaths mostly affected the most vulnerable populations, including those at lower socioeconomic levels.[56] The distribution of causes of excess mortality is predominantly driven by chronic noncommunicable diseases.[112] Further analysis estimated 514 excess deaths in the Puerto Rican population displaced to the US mainland.[113] Evidence shows that considering only direct hurricane injuries greatly underestimates the overall impact on excess mortality. After Hurricane Fiona in 2022, the mortality in Puerto Rico was 1.15 times higher in adults older than 75 years of age, who experienced 226 excess deaths.[114]

Excess Mortality from Hurricane Maria in Puerto Rico



Excess mortality from Hurricane Maria was most common among Puerto Rico's most impoverished residents.

Figure 23.5. Between September 2017 and February 2018, 2,975 excess deaths—that is, above what the mortality rate would have been if the storm had not occurred—were estimated in Puerto Rico due to Hurricane Maria. Mortality was higher for individuals living in low-income municipalities, for those with the lowest scores on the Municipal Socioeconomic Development Index (SEI)—a multidimensional index of poverty developed by the Government of Puerto Rico—and for men aged 65 years or older. These results are useful to health officers, emergency preparedness personnel, and residents, as they help to prepare for and to mitigate the potential effects of hurricanes. Adapted from Santos-Burgoa et al. 2018.[115]

Key Message 23.2

Ecology and Biodiversity Are Unique and Vulnerable

Coastal and terrestrial ecosystems provide a large number of goods and services that are vital to the islands' economies and to the health and well-being of their residents (*high confidence*). These essential systems are degraded by human actions and climate change, thereby reducing the benefits they provide to people, as well as their functionality as habitats for protecting biological diversity (*high confidence*). Climate change is expected to exacerbate the degradation of ecosystems (*very likely*, *high confidence*). The success of climate adaptation strategies will depend on reducing all sources of stress on ecological systems (*medium confidence*).

PR and the USVI are home to diverse aquatic and terrestrial ecosystems and are rich in natural resources and cultural heritage. Residents depend on the region's natural resources and ecosystem services for their well-being and livelihoods. These important ecosystems are being degraded by economic activity, habitat destruction, land conversion, pollution impacts, and overfishing.[116] Climate change impacts on land will have environmental consequences along the coast and beyond. Impacts and consequences will vary by territory, species, and ecosystem type.

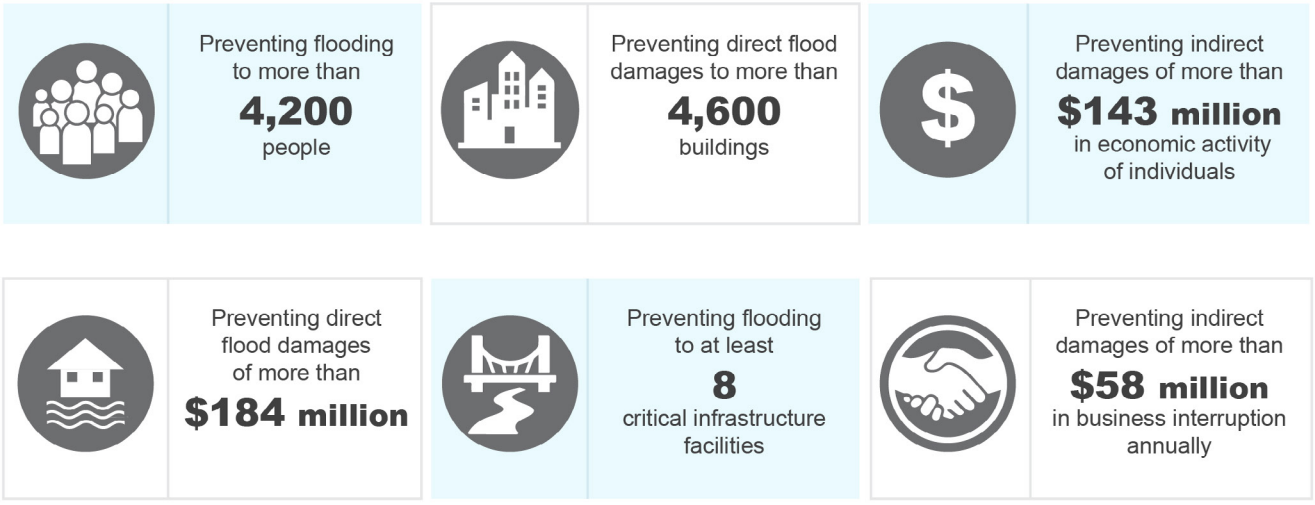
Impacts of a Changing Climate on Ecosystem and Biodiversity Goods and Services

Climate stressors (e.g., extreme precipitation, droughts, frequent and intense tropical cyclones, and steady increases in surface temperatures) and non-climate stressors (e.g., pollution and deforestation) interact to impact ecosystems and the services they provide to people (Ch. 9). Ecosystem services include provisioning services such as food, feed, and fiber; regulating services such as climate regulation, flood control, and air and water purification; cultural services such as recreation and spiritual and aesthetic benefits; and supporting services such as nutrient cycling, primary production, and soil formation.[117] Climate change is increasingly compromising ecosystem goods and services (Ch. 8).

Coastal zones—often highly valued and the focal point for cultural activities, Traditional Knowledge, tourism, and industries essential for economic and social vitality—are at risk from climate change (KM 9.2).[118,119,120] The US Caribbean coastline is roughly 876 miles (1,410 km) in length (PR, 700 miles [1,127 km]; USVI, 175 miles [282 km])[121] and is composed of nested coastal ecosystems such as sandy dunes, beaches, mangroves, salt flats, coral reefs, and seagrass beds. The high population density, concentrated development, and critical infrastructure located within 0.6 miles (1 km) of the coastline are highly vulnerable to coastal hazards and climate stressors.[20] The combined destructive power of wave action and intense rainfall from Hurricanes Irma and Maria alone damaged over 12% of coral reefs,[122,123,124] caused beach loss of 1.2–3.1 miles (2–5 km),[119,125,126] eroded dunes,[118,127] and devastated almost 33% of mangroves.[128] These impacts added to the degradation of ecosystems caused by other climate stressors (KM 8.2).

The loss of recreational benefits from the degradation of coastal reefs is expected to reach $172 billion (in 2022 dollars) by 2100 under a very high scenario (RCP8.5).[129,130,131] In 2019, an assessment quantified the annual coastal flood risk-reduction benefits provided by all US coral reefs, including those in PR and the USVI, as illustrated in Figure 23.6.

Annual Expected Benefits from Coral Reefs in the US Caribbean



Coral reefs provide substantial coastal protection benefits to the US Caribbean each year.

Figure 23.6. Coral reefs are a major component for recreational and commercial fisheries, coastal protection, and the tourism economy. Acting as a natural defense, coral reefs dissipate incident wave energy and protect coasts from erosion and flooding. Arguably, they are one of the most economically valuable ecosystems.[130] Economic estimates are in 2010 dollars. Figure credit: Caribbean Coastal Ocean Observing System.

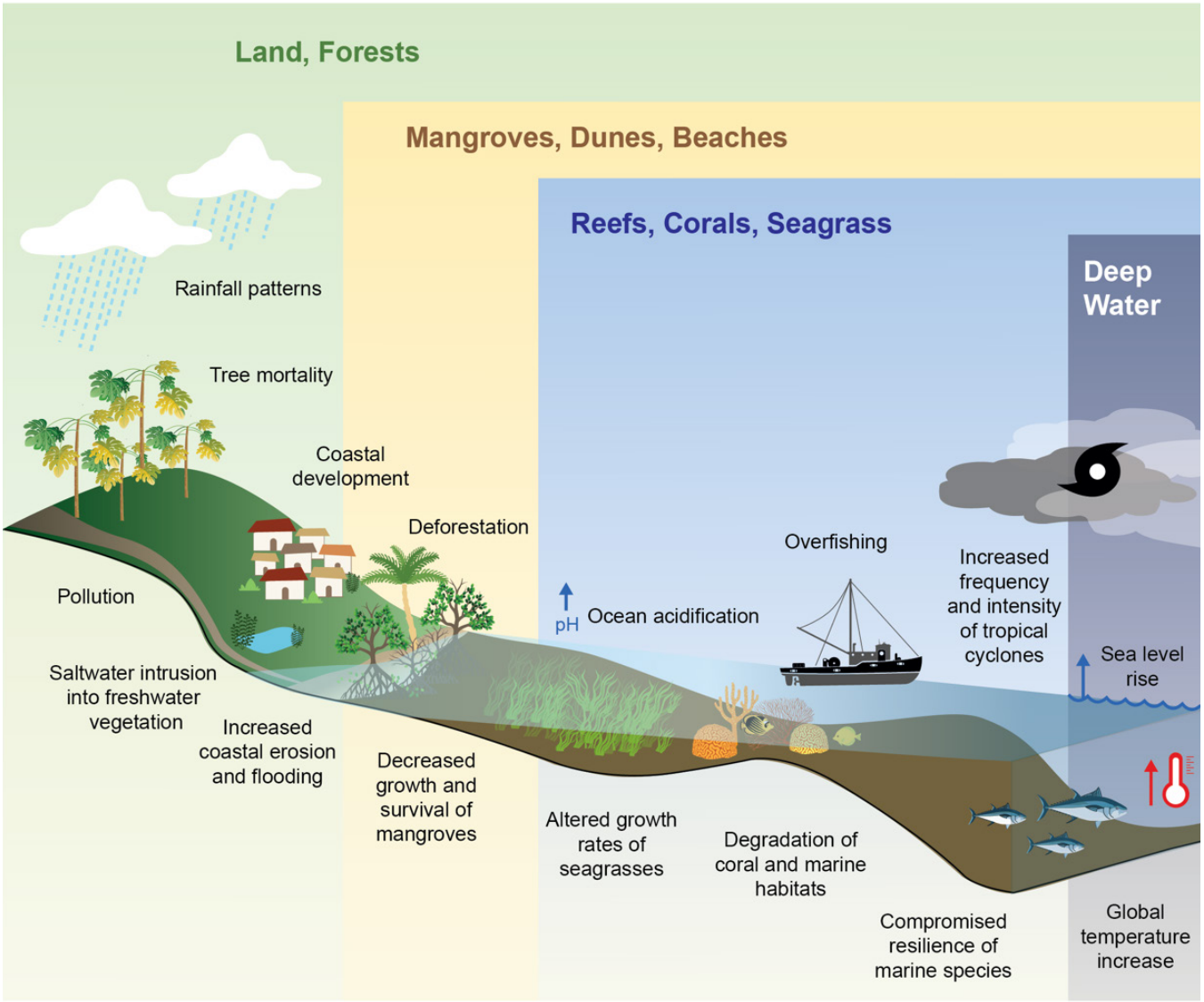
Sediment and contaminant runoff derived from various land-based activities also threaten coastal ecosystems.[125,132] Runoff of land-derived sediment could directly impact coral regeneration capacity, growth, and mortality, as well as the ecosystem services they provide.[93] Cross-jurisdictional strategies and ecosystem-based management principles must be adopted to significantly reduce the adverse impacts of anthropogenic/land-derived pressures on coastal ecosystems.[133] In PR's Guánica Bay watershed, for example, a watershed management plan is being implemented to restore the health of coral reefs damaged by sediment and nutrient runoff.[134]

Caribbean forests are highly diverse, ranging from coastal mangroves to dry forests. These ecosystems provide many services, including habitat, recreation, coastal protection, and improved air and water quality.[135] Although forests are adapted to withstand frequent natural disturbances, projected changes in temperature and rainfall are expected to impact the amount of fruiting and flowering, tree productivity, and nutrient cycling, as well as increase the likelihood of tree mortality, among other impacts (KM 7.2). Furthermore, they can alter the forest ecosystem's biogeochemical processes and affect their composition, structure, and functioning.[136] For example, trees within northeastern PR are already operating above their optimum temperature for photosynthesis; thus, increasing temperatures (which are projected) will lead to the release of more carbon dioxide (a major driver of climate change) into the atmosphere.[137,138,139] Meanwhile, research on tropical forestry, ecology, and conservation in the Luquillo Mountains in PR has reversed the paradigm that tropical ecosystems are fragile, demonstrating instead that they exhibit remarkable resilience to many forms of disturbance.[140]

Emerging Issues and Future Directions

Ecosystems that are already degraded or stressed may have lower adaptive capacity and resilience. Increased stress from climate change may drive ecosystems to tipping points,[141] with potentially irreversible socioeconomic consequences for coastal socioecological systems and community livelihoods.[141] Maintaining, enhancing, and/or restoring ecological connectivity and corridors as conservation strategies are key to helping ecosystems adapt to climate change (Figure 23.7; Ch.1; KM 3.6).

Ecosystem Stressors



Both climate and non-climate stressors affect aquatic and terrestrial ecosystems and biodiversity in the US Caribbean.

Figure 23.7. The cumulative effects of these stressors could result in the degradation of aquatic habitats, increases in coastal erosion and flooding, tree mortality, alterations in the growth of mangroves and seagrasses, and diminishment of resilience and adaptive capacity. Adapted with permission from Fitzpatrick and Giovas 2021.[142]

Key Message 23.3

Climate Change Threatens Water and Food Security

US Caribbean food and water systems are becoming increasingly vulnerable to the escalation of climate change, including stronger hurricanes, more severe drought, warmer air temperatures, and other extreme weather (*likely*, *high confidence*). Because the territories are heavily reliant on imported foods, they are affected by climate changes occurring both within and outside of the region (*high confidence*). Reductions in average annual rainfall, increasing air temperatures, and rising sea levels will adversely affect freshwater availability in the future (*medium confidence*). Improved adaptation efforts would benefit from a better understanding of the ways food and water systems interrelate and of the cascading impacts generated by climate change (*medium confidence*).

Food and water security are important for well-being and emerge from complex social and environmental interactions across groups and regions in the Caribbean. About one-third of Puerto Rican adult residents in 2015 lacked consistent access to adequate food, higher than the rate on the US mainland (12%).[143,144,145] Low-income households were more than three times as likely to experience food insecurity as households with higher income.[145] These numbers are influenced by lower governmental expenditures for key economic security programs relative to other US states or territories.[146]

Within this context, climate change can deepen food and water insecurity in the region.

Characteristics of the Island Food Systems

More than 80% of the food consumed in PR comes from the US mainland[147,148,149] on US-flagged ships, as required by law.[150] Most of the food imported by PR arrives at a single port of entry and is transported by only a few maritime companies.[151] In PR, food imports have been increasing since the 1950s.[151,152]

The agricultural sector represents an important source of employment and food security, although production accounts for less than 1% of the GDP in Puerto Rico.[153] Between 2012 and 2018, the total number of Puerto Rican farms declined by 37%, with farms less than 10 acres in size declining by about 57%.[154] The main classes of production are plantains and bananas, coffee, root crops and tubers, fruits and vegetables, nursery crops, and grasses.[154] Cattle and dairy production generate more than 25,000 jobs on the island and occupy more than 50,000 acres.[155,156]

The USVI imports more than 90% of its food, with importation of most food categories increasing over time.[157,158] The main crops grown and sold on the islands are vegetables, nursery crops, and tree crops. Between 2007 and 2018, the sale of these main crops increased by 1.1%, but they still represent less than 1% of GDP.[159,160]

Characteristics of the Island Water Systems

In PR, approximately 82% of water used is derived from surface water sources (reservoirs and streams), with the remaining 18% extracted from groundwater sources.[161] The total storage capacity in reservoirs is decreasing due to sedimentation.[162] Rain harvesting and desalination plants are also sources of potable water, primarily in the USVI. There is a tension between water for consumption and agricultural uses. PR has four irrigation districts around the main island that draw on a network of reservoirs to provide water to farmers for crops via irrigation canals. The Puerto Rico Aqueduct and Sewer Authority (PRASA) also purchases rights to the water in the districts. Water from PRASA is expensive and cannot be used for

agriculture.[149] Due to faulty infrastructure, mismanagement, evaporation, and theft, approximately 50% of water purchased by PRASA from the irrigation districts is lost before reaching the public.

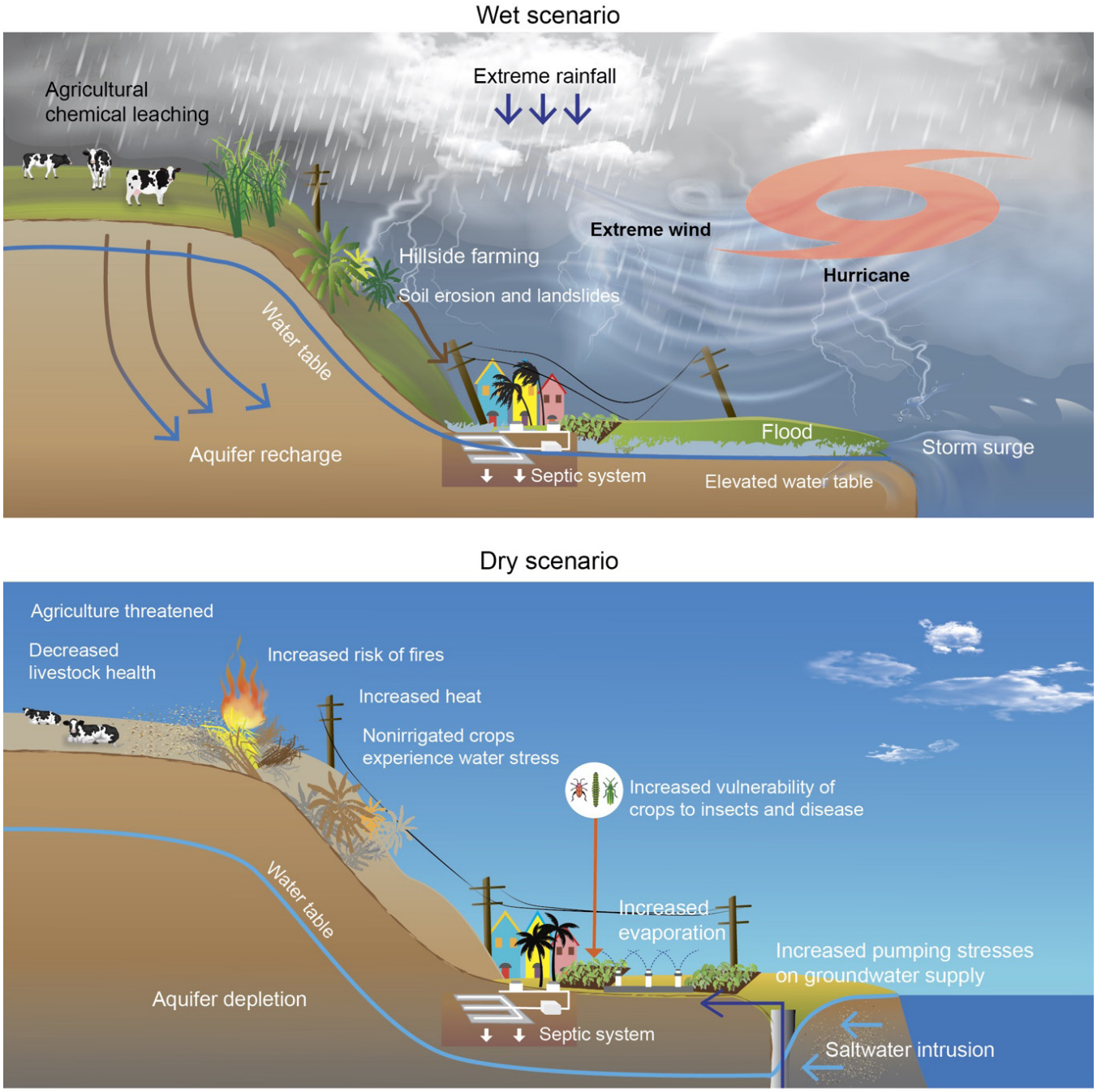
Outside of these four irrigation districts, surface runoff is stored in ponds or pumped from aquifers. The South Coast aquifer (SCA) has declining water levels due to over-pumping, which in some cases has lowered the water levels below sea level, leading to salinification.[163,164,165] The cost of water to farmers is low,[149] which may discourage them from using water efficiently. Irrigation scheduling can be used to optimize irrigation water use;[166] however, limited data exist on the irrigation scheduling methods used by farmers in PR and the USVI. About 10%–20% of the water introduced into the irrigation canals is lost by leakage.[161]

In the USVI, farmers access water from surface ponds and aquifers and from stored rainwater in cisterns. On St. Thomas, the majority of the farming occurs in the drier Estate Bordeaux.[167] Farmers there depend mostly on private and public cisterns and ponds or on wells that are privately managed. On St. Croix, most farmers depend on groundwater from deep wells or water from private cisterns or ponds they own or that are managed by the USVI Department of Agriculture. On St. John, farmers capture water in privately owned ponds. Few farmers depend on the public water system.

Climate Stressors on Food and Water System Components

Climate change is affecting and will continue to affect the region's food and water systems (Figures 23.8, 23.9).[147] In the past, strong winds and heavy rain have destroyed crops and caused livestock mortality. They have also led to landslides, soil erosion and degradation, flooding, and sediment contamination of water.[168] Between 1995 and 2017, agricultural losses attributed to hurricanes in PR accounted for 3%–26% of the total estimated economic damages. Hurricane Maria in 2017 alone caused more than $2.3 billion (in 2022 dollars) in losses and damages to crops and infrastructure,[169] which represented a reduction of about 80% of the main island's total agricultural value.[170] Beyond these direct impacts, a substantial portion of agricultural losses were caused by indirect effects of tropical cyclones, including energy outages, disrupted telecommunication and water supplies, and damaged roads and irrigation systems.[152,168,171] With a projected increase in the intensity of major tropical cyclones, these impacts are expected to worsen without investments to make food and water systems more resilient (KMs 8.3, 11.3, 30.1).

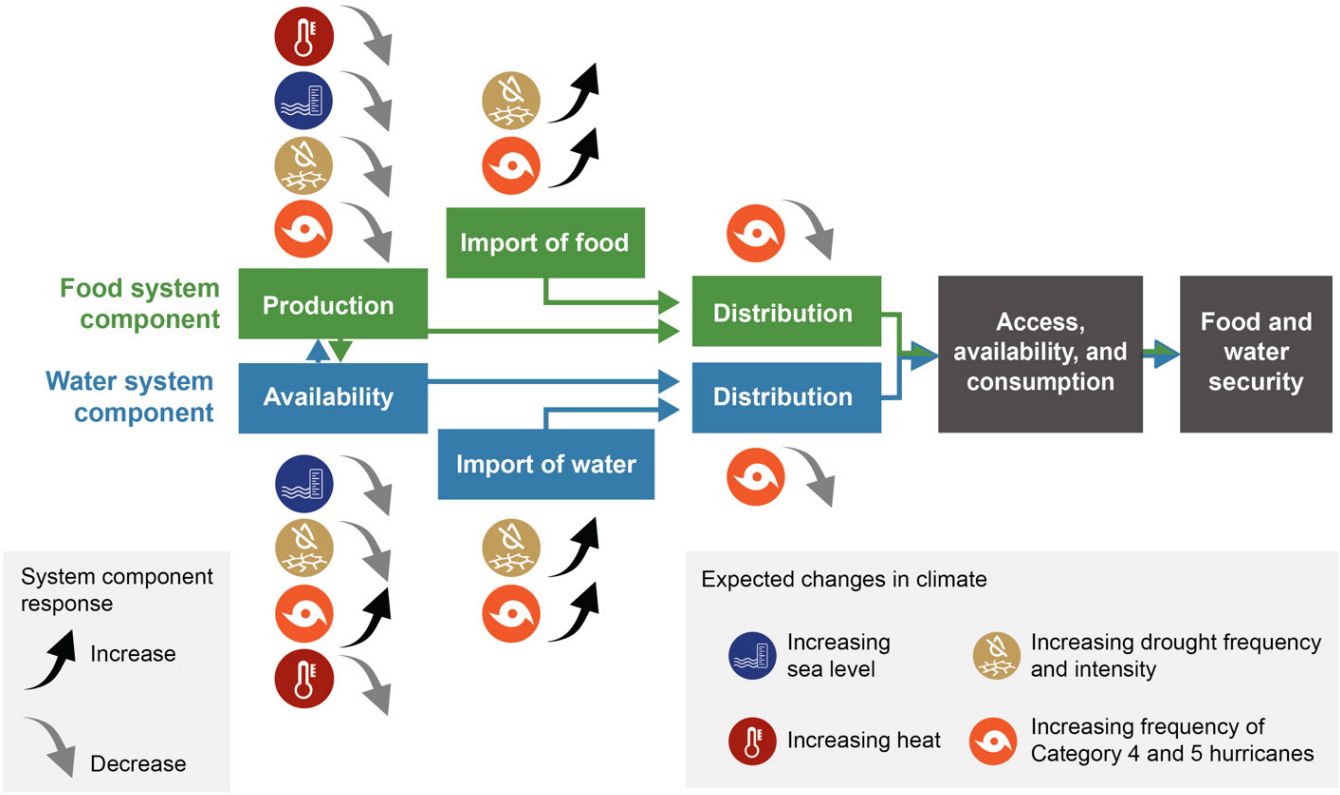
Climate Impacts on Food and Water Systems from Ridge to Reef



Risks to food and water systems differ under wet and dry scenarios.

Figure 23.8. (**top**) In periods of wet conditions, saturated soils coupled with heavy rainfall from hurricanes and storms can lead to flooding and, in turn, soil erosion and vegetation and crop destruction. Strong winds and floods can also damage infrastructure needed for food and water distribution. Excessive rain combined with higher sea levels affects water quality through the leaching of agricultural chemicals and wastewater from septic systems. (**bottom**) Dry conditions, on the other hand, increase groundwater pumping for irrigation. When combined with sea level rise, these conditions can also lead to saltwater intrusion into coastal aquifers. Figure credit: University of Puerto Rico, North Carolina State University, USDA Forest Service, University of Arizona, and University of the Virgin Islands.

Food and Water Systems



Cascading impacts of climate change affect food and water systems and security.

Figure 23.9. The figure displays the effects of the main climate changes that directly affect the islands on each of the system's components. The up and down arrows show the increasing or decreasing effect of a given climate change stressor on the food or water system components. For example, the increasing frequency of Category 4 and 5 hurricanes will cause a decrease in the distribution of food and water. The effects of climate changes are moderated by external influences such as socioeconomic changes that precondition the islands to be more or less susceptible to climate changes. Figure credit: University of Puerto Rico, USDA Forest Service, University of Arizona, North Carolina State University, and University of the Virgin Islands.

Drought has been common to PR and the USVI. Between 1950 and 2016, periods of severe drought occurred across the Caribbean (1974–77, 1997–98, 2009–10, and 2013–16). Regions of PR in 2020 and the USVI in 2021–2022 were declared by the USDA to be natural disaster areas because of drought conditions. The 2014–2016 drought was characterized as the most severe on record.[172] Livestock losses in 2015 accounted for about 62% of all reported economic losses, and plantain losses accounted for 22%. The combination of periodically dry conditions with a warming trend leads to aridification and compounding impacts (KM 4.1).[173] Aridification leads to increased demand for irrigation. Higher demand for irrigation, coupled with salinification of aquifers from sea level rise, suggests that groundwater aquifers like the SCA will be under increasing pressure in the future. Following 2015, the government of Puerto Rico created the Scientific Drought Committee. The USDA Caribbean Climate Hub created the Caribbean Drought Learning Network in 2021 to integrate drought-related information, initiatives, and programs in PR and the USVI.[174] These initiatives can help preparation and response to future droughts.

Increasing average and intermittent extreme temperatures are expected to reduce crop yields,[175] especially in tropical regions.[176] Expected impacts on crops include reduced seed yield,[177] reduced pollen production, and increased rate of senescence (i.e., shortening of a crop's life cycle).[178] The negative effects of increasing

temperature worsen under water deficit conditions.[178] Higher temperatures also increase the potential for wildfires;[179] can affect the range of weeds, diseases, and insects;[180] and can cause heat stress in farmworkers (KM 4.2).[181] Increased atmospheric CO_2 levels may counteract the negative impacts of higher temperatures; however, adequate water is required to take advantage of CO_2 fertilization.[182] Crop water use may increase[183,184,185] or decrease[186] under climate change conditions, depending on site-specific changes in the meteorological parameters.

Both drought and elevated temperature have negatively impacted livestock producers in PR and the USVI.[152,156] High temperatures lead to heat stress, which reduces animal productivity, increases the proliferation and survival of parasites and disease pathogens, reduces the ability of dairy cattle to produce milk and gain weight, and lowers conception rates. Furthermore, bovine breeds in PR and the USVI are more susceptible to heat because they were largely introduced from temperate regions, such as from within the US mainland.[155,156]

Soil health has direct effects on the ability to maintain agricultural production in the future and to adapt to climate change. Soil organic carbon is affected by increasing temperatures. Both mineralization and the loss of organic carbon and nitrogen increase under elevated temperatures.[187] Extreme variation in rainfall can promote carbon loss via soil drying and soil erosion. Certain conservation practices—such as no-till farming and the use of cover crops—can promote soil health and enable the sequestration of larger amounts of carbon in the soil.[187,188,189] The USDA Natural Resources Conservation Service is promoting methods to increase soil health in PR and the USVI.[190]

Social Protection

Crop insurance plays an important role in reducing climate impacts. In PR, about 50% of farmers participate in the Puerto Rico Crop Insurance Corporation (PRCIC; a similar program is currently unavailable in the USVI). Between 2010 and 2019, the PRCIC paid compensation for agricultural losses for 25 events, all but one—a wildfire—related to rainfall (hurricanes, tropical storms, tropical depression floods, and extreme rains). Ninety-eight percent of the total insurance payouts for the 2010–2019 period was for losses caused by hurricanes. The insurance program, however, does not cover drought.[152]

Emerging Issues

Areas receiving increased attention essential to managing extreme weather include plant and animal breeding,[156,191] crop production within controlled environments,[192] precision agriculture,[193] irrigation scheduling,[194,195] and flood and drought early warning systems.[196,197] Increased local food production and the need to balance water use among sectors will become increasingly important issues.[149] In the USVI, the lack of information to quantify economic losses associated with climate impacts, such as the effects of drought on food and agriculture, is also an issue. Superimposing climate change on top of other compounding issues (internal and external) will create additional stressors and have cascading impacts on food and water systems within the region. Understanding the complexity of the islands and their food and water systems will aid in the creation of contingency planning for problems that may arise.

Key Message 23.4

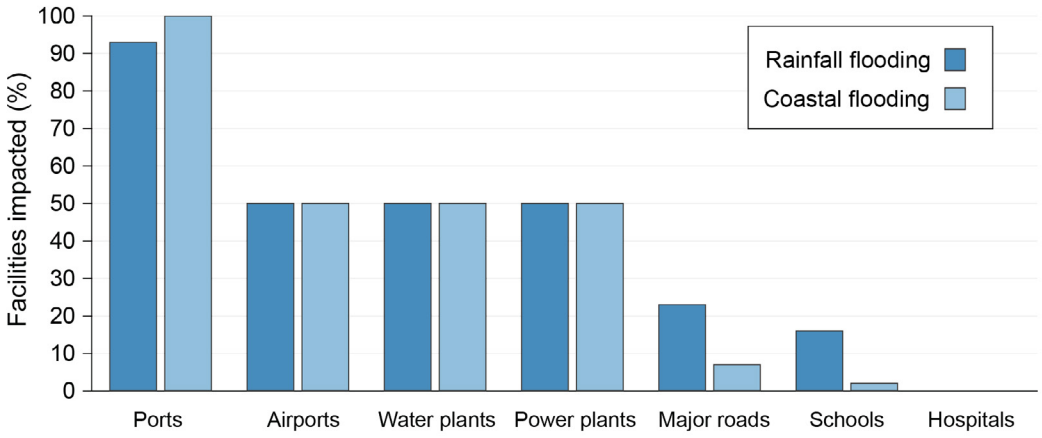
Infrastructure and Energy Are Vulnerable, but Decentralization Could Improve Resilience

Climate change has created profound risks for the US Caribbean's critical infrastructure, already weakened from years of disinvestment and deferred maintenance (*high confidence*). Increasingly powerful storms, along with rising sea levels, are severely impairing infrastructure systems, with increasing damage projected in future years (*likely*, *high confidence*). Dependence on fossil fuel imports increases energy insecurity (*high confidence*). Infrastructure improvements, coupled with a new paradigm focused on decentralization, adoption of distributed solar, and shared governance, could help limit residents' vulnerability to health and other risks associated with loss of essential services (*likely*, *medium confidence*).

The 2017 and 2022 hurricane seasons in the Caribbean demonstrated the vulnerability of critical infrastructure (e.g., energy, water, healthcare, transportation, telecommunications, wastewater, stormwater, and solid waste) in Puerto Rico and the USVI to natural hazards.[23,24,198] This vulnerability is mainly caused by years of deferred maintenance, the recurrence of powerful tropical storms,[199,200] and a centralized mode of production and governance that limits redundancy, flexibility, and, therefore, the ability to anticipate and adapt to future scenarios that climate change will create.[201,202,203,204,205]

Powerful tropical storm impacts are exacerbated by higher sea levels, which increase storm surge and prevent proper drainage of higher stormwater volumes.[12,21,25,206,207,208,209] As a consequence, critical infrastructure systems, which tend to be concentrated near the coasts and floodplains, will experience compounded effects of different hazards and disrupt the movement of people, goods, and services (Figure 23.10; KM 9.2).[204,210] Climate change is also causing higher temperatures and drier conditions,[12,21,211] thereby reducing water availability, increasing water demand, and intensifying saltwater intrusion into aquifers.[212,213] And, because infrastructure systems are interconnected and interdependent, the disruption of any single system will affect the operation of other systems. Currently, even outside of droughts, water for human needs competes against demand for power production (KMs 4.2, 5.1).[214] Similarly, even without hurricanes, sea level rise affects the operation of marine, air, and surface transportation systems,[204] and stormwater flows overwhelm wastewater systems.[200,204]

Infrastructure at Risk of Flooding in the US Virgin Islands



Many types of facilities in the US Virgin Islands and Puerto Rico are threatened by storm-induced flooding.

Figure 23.10. The figure shows the percentage of critical infrastructure currently located in flood zones (rainfall flooding caused by rainstorms and coastal flooding caused by storm surges and waves) in the US Virgin Islands. Many similar facilities are at risk in Puerto Rico,[215,216] but data are missing to represent the information in this report. Facilities at risk of flooding or that are flooded might not be able to provide critical services to communities when flooded, and there might not be another alternative available. The figure shows vulnerabilities under current climate conditions; additional flooding caused by sea level rise or potential future increases in intensity and duration of rainstorms is not included. Figure credit: University of the Virgin Islands, NOAA NCEI, and CISESS NC.

Increasing temperature and heatwaves will drive power and water demand, and wetter storms will increase demand on wastewater and stormwater pumps.[217,218] Damage from increased rainfall rates from hurricanes and increased hurricane intensities are projected to increase solid-waste flows, and response and recovery activities may intensify the use of single-use items such as utensils or water bottles.[24,219,220] Demand for healthcare is also expected to increase as communities experience higher temperatures or greater exposure to stormwater or wastewater and associated waterborne pathogens.[221]

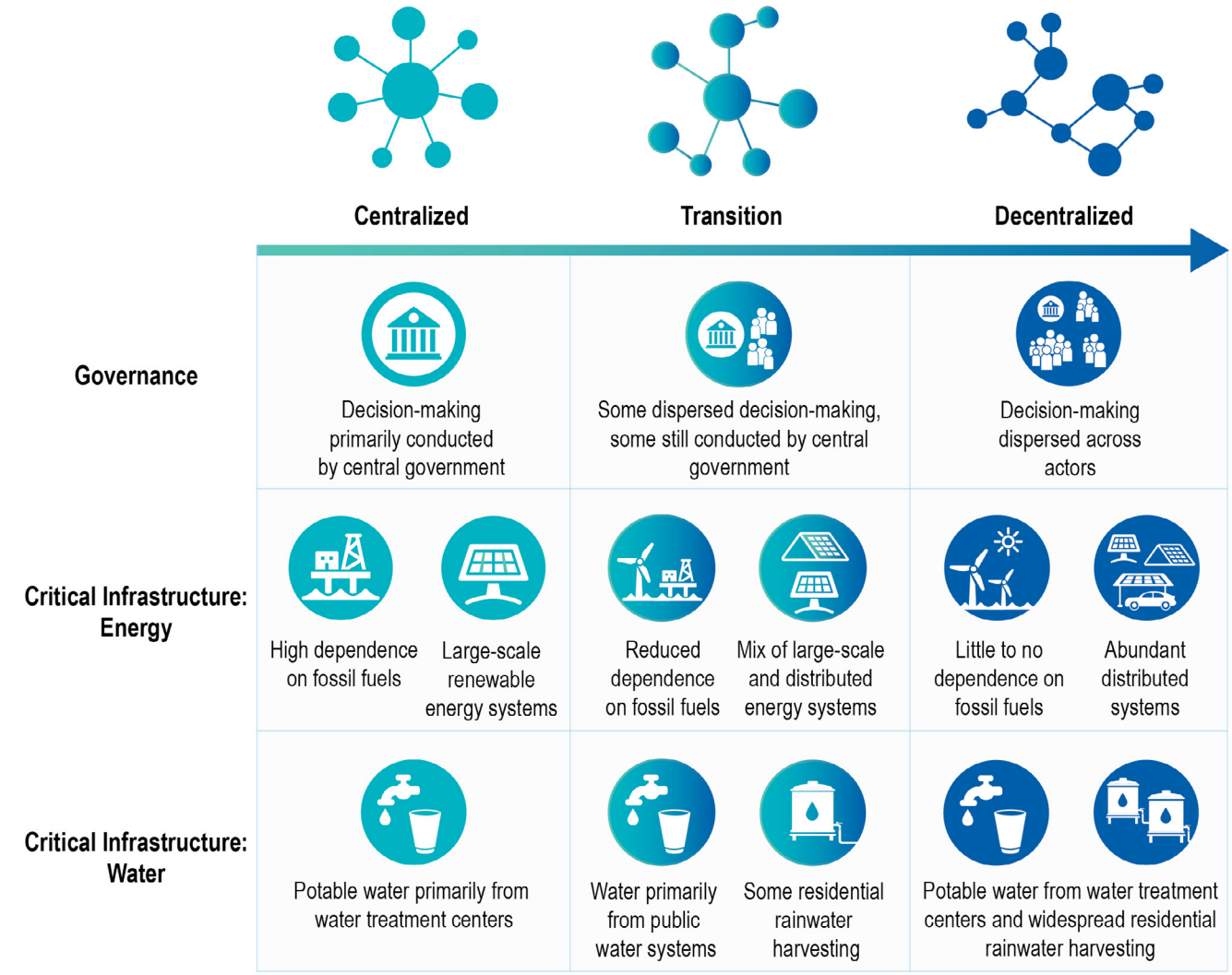
The effects of climate change on infrastructure systems are compounded by human impacts on ecosystems. Ecosystem degradation (e.g., beach erosion, loss of coral reefs or mangroves) is also increasing hazard impacts on infrastructure.[222,223,224,225] Similarly, increased sargassum seaweed[226] can impair infrastructure and render it inoperative, as well as affect the health of the people operating these systems.[227,228,229]

Finally, climate change compounds the stress on already-strained infrastructure systems. Legacy challenges, including systemic lack of investment, mismanagement, and fiscal limitations, undermine the capacity to invest in adaptation activities or to maintain a competitive edge in retaining talent and updating technical capacity.[199,230,231]

Dealing with climate hazards while mitigating other risks will require new thinking about the pitfalls of existing approaches and the potential for a path that allows for better management of resources and service delivery. Highly interdependent infrastructure systems with centralized operation and management structures might be unable to anticipate and adapt to disruptions caused by future climate conditions.[202,232,233] Successful infrastructure adaptation strategies may require restoring natural infrastructure systems (e.g., aquifers, mangrove wetlands, nearshore coral reefs, etc.) for provision of services.[234,235,236] It also may require the adoption of a new paradigm, such as more decentralized infrastructure systems and different models of governance (KM 18.4). For example, household rainwater harvesting protects against prolonged public water system interruptions;[237] sustainable material management reduces pressure on landfills;[238] and microgrids and community solar and household solar systems provide power during inter-

ruptions from the centralized utility (Figure 23.11). These types of decentralized systems can help achieve mitigation targets[239,240,241,242] while also reducing negative health impacts of fossil fuel plants.[243] However, it is important to consider whether or how the adoption of these new systems could exacerbate existing inequities of access to services or to these technologies,[203,244,245] or compete against other land-use opportunities such as farming and housing.[246]

Decentralizing Infrastructure and Governance



Strengthening the resilience of infrastructure will require a transition to decentralized systems as well as decentralized modes of governance.

Figure 23.11. For power systems, decentralization means not only investing in more renewable energy systems managed by utilities but also increasing investments in systems managed by communities and households. For water systems, decentralization means increasing investments in water harvesting infrastructure to serve as an alternative. The improvement of governance models, by decentralizing decision-making and resource allocation, will better address climate change threats and current system frailties and problems. Figure credit: University of the Virgin Islands, NOAA NCEI, and CISESS NC.

Infrastructure systems in the Caribbean are at risk of future climate events, but current operation and management approaches increase their vulnerability.[199,200,230] Further research on infrastructure systems, including community-based solutions to climate challenges, could help identify appropriate paths for adaptation.

Key Message 23.5

Adaptation Effectiveness Increases When Coupled with Strategic Governance and Planning

Climate adaptation in the US Caribbean is challenging because of multiple interacting factors, including high risk exposure, limited or misaligned funding, insufficient institutional and organizational capacity, and siloed approaches to risk reduction and resilience (*high confidence*). Effective adaptation to support resilience in the US Caribbean could be enhanced through co-development and integration of robust global, regional, and local climate science and risk-based knowledge into planning and implementation, as well as improved governance arrangements (*high confidence*). US Caribbean capabilities in planning and adaptation could be enhanced by strengthening partnerships across the wider Caribbean region and the US mainland (*medium confidence*).

Small islands provide a special case for development and adaptation due to their geographic isolation, complex geographies, diverse cultures, and unique natural resources, compounded by challenges such as their small economies, limited human resources, and costs of utility provision and services.[247,248] Sound policies and institutional capacity are fundamental to effective risk-reduction and disaster response and recovery, as well as the ability to seize current and emerging opportunities for adaptation planning and implementation.

For PR and the USVI, significant financial resources could be made accessible for climate adaptation and comprehensive disaster management, such as through disaster recovery funds, the Community Development Block Grant Mitigation (CDBG-MIT) program, and other federal and nongovernmental organization donors. However, effective adaptation planning is impeded by limited uptake of climate change information in decision-making,[249] weak linkages between programs,[250,251] and insufficient institutional capacity for prioritizing initiatives and designing linked operational systems across multiple organizations.[168,252,253] In addition, adaptation and recovery could be made more efficient and effective by allocating funds that account for social vulnerability metrics.[254]

Policy for climate change planning and adaptation in the US Caribbean has advanced slowly in recent years, as evidenced by the Puerto Rico Climate Change Mitigation, Adaptation, and Resilience Act[255] and Executive Order No. 474-2015: Preparing the Virgin Islands of the United States for Adapting to the Impacts of Climate Change.[256] The Puerto Rico law that created the Expert Advisory Committee on Climate Change mandates that the government allocate funds for its operation and develop a climate change mitigation, adaptation, and resilience plan. Many community-based organizations have also taken action to advance social transformation, climate adaptation, and sustainable development.[257,258,259,260] Organizations in PR include Casa Pueblo (energy); Vieques Love (disaster preparedness, resilience, and capacity building); Mujeres de Islas (sustainable development); Vida Marina (dune restoration); Protectores de Cuenca (watershed restoration); Corporación de Servicios de Salud Primaria y Desarrollo Socioeconómico El Otoao (socioeconomic development and public health); and El Josco Bravo (agriculture). Organizations in the USVI that have taken action on climate change include the University of the Virgin Islands Caribbean Exploratory Research Center (climate change and health), St. Thomas East End Medical Center Corporation (education program on climate change and health), and Foundation for Development Planning Inc. (advocacy on climate change and disaster risk-reduction and participation in public policy process on climate change). Self-organization has also enhanced community trust and cohesiveness.[13]

In the USVI, the US Department of the Interior funded a climate change initiative in 2016 that produced a vulnerability and risk assessment report.[261] The Caribbean Climate Hub and a limited number of civil society organizations supported the initiative. However, there is currently no climate change adaptation program in the USVI, and the inadequate uptake of climate change information for decision-making identified in 2016[249] is still reflected in current public sector policies and programs in both the USVI and PR.[262]

Challenges and Opportunities

Advances in climate adaptation planning and implementation by individuals, communities, and public, private, and civil society organizations are constrained by shifts in demographics, fiscal and socioeconomic conditions and capacities, and high levels of risk exposure in the region (KM 31.2).

In PR and the USVI, vulnerable populations are located in sites exposed to high climatic risk.[20,263] Social determinants of vulnerability include economic instability and limited access to education and healthcare services.[254,264,265,266] This vulnerability amplifies the effects of disasters and undermines the ability to prepare, respond, recover, and adapt.[168,254,267,268]

Between 2000 and 2019, PR was among the territories and countries most affected by extreme weather–related events, and between 2010 and 2020, it registered the highest number of new displacements in the Caribbean,[269,270] largely because its residents are US citizens and can move to the continental US without restrictions.[271]

The US Caribbean experiences both in- and out-migration, which should be considered in planning and adaptation, as migrants require permanent or temporary shelter and essential services.[272] Progress in policy, programs, and implementation has been made, but the dynamics of intraregional migration are not fully understood or addressed.[270]

Decision-making processes and program delivery mechanisms typically involve multiple institutions, including civil society organizations. However, these public and private organizations often work in silos or with limited coordination or collaboration. The effectiveness of these mixed-delivery systems would be significantly improved through enhancements to coordination mechanisms, improved institutional processes, and increased investment in human resources to understand and manage the connected processes and systems (Ch. 31).[42,251,262,273,274] Similarly, overcoming the limitations in the institutional capacity to develop and manage federal grants will help advance adaptation actions in PR and the USVI.[275]

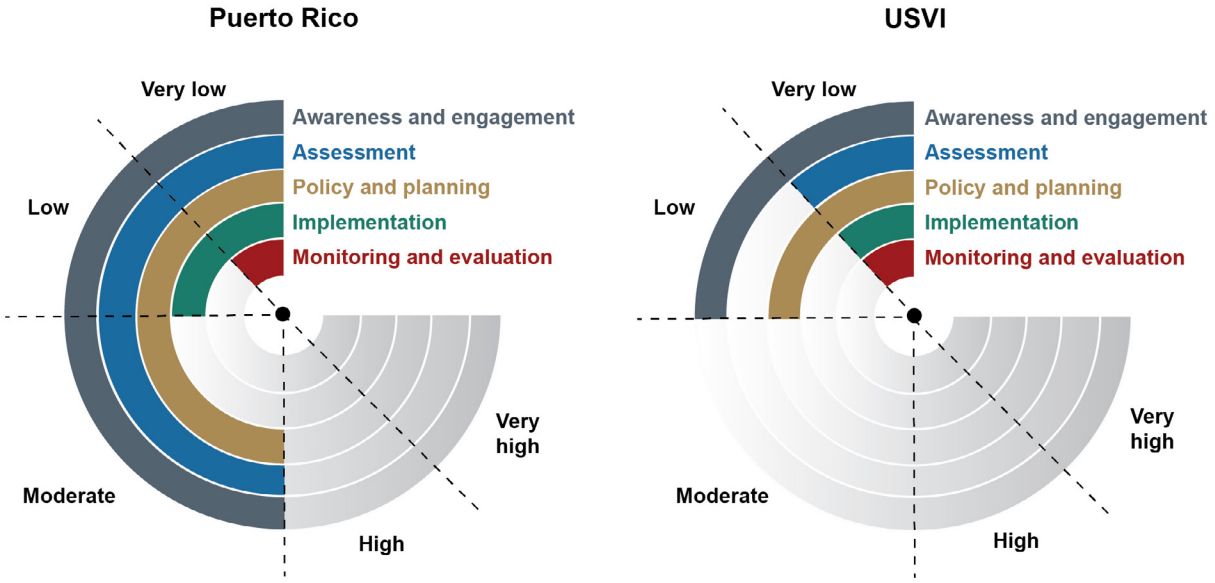
The physical separation of the US Caribbean from the mainland makes disaster response more complex and difficult.[253] Recent reports on the response to Hurricanes Irma and Maria highlight the need for improved planning processes and delivery systems in the relevant federal agencies.[276,277] Ensuring that federal policies and programs are appropriate to local physical conditions and institutional environments and include flexibility to account for future shocks and disturbances could improve disaster response and recovery, as well as climate adaptation action. Policies and program designs that incorporate sustainable land management approaches could reduce vulnerabilities associated with the location of infrastructure and housing in coastal areas and flood zones, water and food insecurity, and degradation of ecological systems. Enhanced alignment of federal and local programs could improve project, program, and development outcomes in the two territories. The government has a fundamental role in creating an appropriate enabling environment for sustainable development—that is, the social ecosystem created by the interplay of policies, laws, institutions, and processes that influence the development of a country. Therefore, ongoing investment in the capacity of government could help ensure that it has the competence to formulate and deliver public policy, maintain significant decision-making capabilities, maintain appropriate and effective governing systems, and develop resilience to shocks.[199,252,278,279,280,281,282]

Current risk-mitigation and emergency response programs focus predominantly on preparedness, response, and recovery—only three of the four phases of a comprehensive disaster management program. The fourth phase is prevention and mitigation, and it is in this phase that economic, legal, sociopolitical, institutional, and other measures are integrated to reduce vulnerability and strengthen resilience.[283,284] In this context, building resilience to disasters and climate change could be enhanced by improving institutional capacity for risk assessment and management.

Both PR Act 33-2019 and USVI Executive Order 474-2015 provide governance frameworks that facilitate coordinated planning and participatory decision-making that involve the public, private, and civil society sectors and the general public. Current federal funding streams available to the territories under the CDBG-MIT program also present an opportunity to advance disaster risk-reduction strategies by focusing more on mitigation and prevention. Modification of the current plans for the USVI and Puerto Rico would make better use of this opportunity.[285]

In the USVI and PR, varying levels of progress have been made across the key elements of climate adaptation (Figure 23.12). This progress reflects the reality that adaptation is an ongoing process that requires evolving governance arrangements to facilitate engagement by all of society.

Status of Adaptation Action



Adaptation action in Puerto Rico and the US Virgin Islands reflects different starting times and available capacity.

Figure 23.12. The figure illustrates progress in adaptation action in Puerto Rico and the US Virgin Islands. The colored bars in the charts show the level of progress for each key element of climate adaptation. Adaptation is presented as a continuous process in which multiple elements may overlap or advance simultaneously. Accelerating adaptation action in both territories would reduce risk and enhance resilience. Figure credit: NOAA/Lynker and Foundation for Development Planning Inc. See figure metadata for additional contributors.

Monitoring, research, and action on regional changes to weather systems, ocean health, and terrestrial and coastal ecosystems may be beyond the financial means of individual island states and territories, underscoring the need for pooling of resources and experiences across the region. Many formal and nonformal relationships exist between institutions, governments, and professional associations in the US Caribbean and other Caribbean countries, which provide opportunities for improving climate adaptation actions through stronger regional collaboration.

Traceable Accounts

Process Description

This chapter was written by a multidisciplinary team of 22 authors that was built in August and September 2021 according to inclusive criteria that sought a diversity of voices by gender, ethnicity, discipline, career stage, knowledge, and geography. Approximately half of the authors work mainly in Puerto Rico (PR), 35% in both US territories, and 15% in the US Virgin Islands (USVI). Sixty percent of authors represent academia, followed by the public sector (about 20%), nongovernmental organizations, and the private sector. The authors are Hispanic- or Latino-Spanish speakers, Afro-Caribbean Black English speakers, and White alone or combined with other races.

Starting in September 2021, the team held weekly all-author meetings to build relationships and capacity. The authors worked in distributed writing teams, each responsible for leading the narrative in each topic and providing evidence supported with literature. On January 19, 2022, the Caribbean chapter hosted a public engagement workshop with 90 participants. Since January 2022, the team continued holding weekly meetings where programmatic and technical issues were discussed. Each Key Message writing team and the chapter lead held weekly meetings to discuss thematic issues, figure development, and more in-depth discussions related to each Key Message.

Key Message 23.1

Climate-Driven Extreme Events Exacerbate Inequities and Impact Human Health and Well-Being

Description of Evidence Base

This topic combines the most recent peer-reviewed information and gray literature on assessment of climate change impacts on the health of people in the US Caribbean. The peer-reviewed literature came from a range of sources.[14,42,50,52,56,59,60,61,62,63,64,80,81,210] The gray literature and reports sourced information from local databases in US Caribbean government agencies and surveys, as well as from databases and other reports.[53,54,67,286] US Census reports lay the foundation for the challenges with descriptions of high levels of poverty and incomes below the US median in both Puerto Rico and the USVI. The literature describing the background information regarding the history of US Caribbean populations being disadvantaged and underserved is documented for the USVI in the needs assessment conducted by Michael et al. (2019)[42] following the 2017 hurricanes; it also provides a combination of local and federal data and information indicating challenges with access to and the extent of services to significant portions of the population before and after the hurricanes. Similar assessments for Puerto Rico have been done by Maldonado et al. (2021)[287] (residential security and community relocation), Seara et al. (2020)[288] (fishing community perception of climate impacts), and Boger et al. (2019)[44] (cultural heritage and traditional knowledge). The relevance of the links between cultural and traditional resources and well-being of people are reported in Boger et al. (2019);[44] Dawson (2013);[289] Finneran (2017);[290] Kohler and Rockman (2020);[291] Perdikaris et al. (2021);[292] and Rockman and Hritz (2020).[293]

There is strong evidence[23,81] in Puerto Rico that extreme heat episodes and extreme rainfall events are increasing in frequency, intensity, and duration, posing the threat of increased incidence of heat-related illness and death, but such evidence is more limited for the USVI at this time. Data on underestimation of

mortality was presented for Puerto Rico specifically in Santos-Burgoa et al. (2018)[56] and in NCHS (2019)[294] in the context of the COVID-19 pandemic. The quantification for USVI is not available for the period after Hurricane Maria.

Major Uncertainties and Research Gaps

Post-disaster settings present opportunities for researchers and for developers, often to the detriment of local or impacted communities.[292,295] Louis-Charles et al. (2020)[36] call for the need to pay closer attention to the ethics of engagement between, on the one hand, external researchers, agencies, and investment interests, and, on the other, local communities in the Caribbean. Although there have been popular claims calling out the damages of post-disaster gentrification in the media, social media, and popular music, not much research has been conducted on how disaster capitalism exacerbates injustices and cultural erasure in Puerto Rico and the USVI. Elders and Traditional Knowledge highlight concerns with rates of migration of youth and disarticulation of traditional communities that still would benefit from further research.[296]

While research on aerosol and aeroallergen distribution and health impacts has been conducted in Puerto Rico, this association has not yet been quantified in the USVI.

Reports[42,51] and peer-reviewed literature describe impacts of extreme weather and the efforts or needs to mitigate or adapt activities in both Puerto Rico and the USVI.[297] Strengthened education and adaptation outreach efforts could help address issues with behavioral health, noncommunicable disease burdens, and other challenges.

The impact of sargassum algal mats reaching the coasts of the US territories is uncertain. Evidence from other Caribbean islands suggests that this phenomenon will contribute to worsening air quality, ecosystem health, and public health in coastal areas. There are some initial initiatives on an early warning system for Saharan dust, extreme heat, and public health, yet preparedness of the public health sector to mitigate illnesses is still low (and lower in the USVI than in PR). There are uncertainties related to Saharan dust clouds and how climate change will affect seasonality, patterns, concentration, and dust distribution. There are still uncertainties as to why excess mortality happens for extended periods after a natural event; the understanding of these mechanisms requires the identification of the cause-specific mortality and the different conditions leading to death, including infrastructure, critical building capacity, housing, and living conditions. Such an approach is currently being advanced in a project led by the National Institute of Standards and Technology.[298]

Description of Confidence and Likelihood

There is *high confidence* that climate-related extreme weather events contribute to loss of quality of life and well-being in the US Caribbean. Long histories of colonization, generational trauma, and systemic inequality shape the ability of the US Caribbean peoples to maintain health, quality of life, and overall individual and social well-being (*high confidence*). The level of local and federal research and reports following Hurricanes Irma and Maria in 2017 included information on trends and also identified significant changes and challenges with general health, support services, mental health and well-being in general. In addition, it was noted that the conditions that supported the poor outcomes are major challenges for communities in both PR and the USVI. More frequent heat episodes and powerful hurricanes are expected to increase in the region due to human-induced climate change, affecting public health unless clear and urgent adaptation measures take place (*high confidence*). Climate conditions are favorable for vector-borne diseases (e.g., dengue, Zika, and chikungunya) and human zoonotic diseases (e.g., leptospirosis) in the US Caribbean (*high confidence*). However, many behavioral factors play a confounding and important role (e.g., life-concurrent events, social distancing, age, exposure) in the spread of these diseases. There is *high confidence* in the data and methods in the estimation of the excess mortality in Puerto Rico from Hurricane Maria, and such estimates are now in the official NOAA reports.[299]

Key Message 23.2

Ecology and Biodiversity Are Unique and Vulnerable

Description of Evidence Base

This topic reviews and synthesizes the most up-to-date assessments of climate change impacts on biodiversity, ecosystems, and ecosystem services in the US Caribbean region. The review included gray literature alongside peer-reviewed literature. The peer-reviewed literature considered strong resources from academic and scholarly journals such as the *Journal of Ecology*; *Biological Conservation*; *American Journal of Marine Science*; *Sustainability Science*; *Ecological Indicators*; *Estuarine, Coastal and Shelf Science*; and *Ecosystem Consequences of Soil Warming*. The gray literature included reports, documents, and white papers from federal and local agencies (USDA, USGS, FEMA, US Global Change Research Program, Puerto Rico Department of Natural and Environmental Resources), government entities (Puerto Rico and US Virgin Islands Taskforce), academia (University of Puerto Rico, University of the Virgin Islands), and nonprofit organizations.

The preliminary literature review established and confirmed the observed ecosystem- and biodiversity-level changes in response to climate change due to direct impacts from climate drivers[20,118,123,125,130,136] and the lack of effective adaptation strategies, policies, and measures.[141] Most of the comprehensive assessments reviewed illustrated the rapid changes of habitats, species, and abundance.[131]

Major Uncertainties and Research Gaps

Both territories experience weather- and climate change–related hazards such as drought, sea level rise, coastal flooding, and erosion. However, the amount of climate research, observations, assessments, and modeling (prediction) are greater in PR than in the USVI. It would be necessary to gather knowledge and information from local agencies, institutions, community-based organizations, and even unpublished information to address existing and pressing gaps in the understanding of climate impacts on biodiversity and ecosystems in the USVI.

Description of Confidence and Likelihood

There is *high confidence* that the synergistic effects of climate and non-climate stressors are impacting ecosystem goods and services, given the expanding literature with regional examples of these changes. As documented in federal, regional, and local climate change assessment reports, climate and non-climate stressors are *very likely* to persist and become more severe, further accelerating ecosystem degradation and aggravating their service efficiency. These assessment reports also highlight the dependence of the US Caribbean residents on ecosystem services for their well-being and livelihood (*high confidence*), hence the need to safeguard these services. Based on a broad range of evidence, there is *high confidence* that maintaining ecosystem functionality will require integrating effective local-level adaptation and mitigation strategies. However, given the lack of literature on implemented adaptation strategies, there is *medium confidence* that local-level adaptation and mitigation strategies could reduce and manage the risks of climate change on coastal and terrestrial ecosystems.

Key Message 23.3

Climate Change Threatens Water and Food Security

Description of Evidence Base

The discussion of the vulnerability of the US Caribbean food and water systems to climate change is based on observations within the islands and projected changes in the regional and global climate.[10,12,20,21,23,24,25] Localized threats to water and food security include changes in drought intensity, frequency, or duration[20,21] and tropical cyclone rainfall rates and intensity.[24] There is mounting evidence of the impact of climate-related extreme events on the food and water system based on measurements, local knowledge, and published and gray literature.[149,152,168,200,300] There is strong evidence that both hurricanes and drought are major issues for island food and water systems, as illustrated by the impacts of Hurricanes Irma, Maria, and Fiona[168] and the 2014–2016 drought.[300] The direct and cascading impacts of these climate stressors with additional compounding problems, especially sea level rise, are a concern for food and water systems.[165] The literature on direct climate impacts to certain sectors such as crops and livestock is widely available[156,185] for Puerto Rico but is limited for the USVI. The evidence is limited when specifically considering island freshwater and food availability and is mostly available through evidence captured by the drought information system reports.[301] There are no systematic studies that quantify the cascading and compounding impacts of these hazards.

Major Uncertainties and Research Gaps

The lack of availability of high-resolution climate change projections that better resolve the island climates is a major research gap for understanding plausible future changes in the island climates. Major uncertainties exist with respect to the role of the island terrain and land-use and land-cover change as the climate warms.[21] This research gap is larger for the USVI than for PR. Another modeling challenge and research gap is how future tropical cyclones may interact with small islands like PR and the USVI, especially as rainfall intensity increases in a warmer climate, with cascading impacts on food and water systems. The association between natural hazards and decreased food security or diet diversity in PR and the USVI is another research gap.[302] For the USVI, there is a noted gap of statistics and scientific impact studies on food production and water use. An area of research not discussed is the impact of climate change and major storms on Puerto Rico and the USVI. While there are some reports that document the impact of climate change on fisheries within the Caribbean basin, there are fewer studies that assess the impacts for Puerto Rico and the USVI.[303,304] The role of community-based efforts for mitigating food and water insecurity, as well as the importance of local and Indigenous knowledge to these ends (KMs 30.1, 30.5), has been poorly researched in the US Caribbean and deserves further attention. More information is needed to better assess the impact and response to extreme climate events.[305] Finally, there are research gaps in the compounding and cascading impacts generated by climate change in both Puerto Rico and the USVI.[168]

Description of Confidence and Likelihood

In the first statement of the Key Message, there is *high confidence* that the US Caribbean food and water systems will become more vulnerable as the climate warms, in part because extreme meteorological events like hurricanes and droughts are *likely* to become stronger and more severe in the future. There is *high confidence* that climate change at both global and regional scales is important because the islands are heavily reliant on imported foods. However, climate change projections at the scale of the islands are limited to a few studies, allowing *medium confidence* in predictions of local direct impacts of climate change on freshwater availability for the region. While improved knowledge will enhance adaptation, the authors have *medium confidence* because the adaptation process also relies on social and economic changes. The evidence base was not sufficient to determine quantitative probabilities for the second through the fourth statements in this Key Message; thus, no likelihood is specified.

Key Message 23.4

Infrastructure and Energy Are Vulnerable, but Decentralization Could Improve Resilience

Description of Evidence Base

The vulnerability of US Caribbean infrastructure systems to climate change is based on observations of impacts of recent climatic events within the islands and projected changes in the regional and global climate. The evidence to support current vulnerability of systems and future climate vulnerability is mostly based on documents from the gray literature, including reports from federal agencies and/or sponsored by federal or territorial agencies[199,200,204,230] following Hurricanes Irma and Maria. The published literature and reports are not as rich as for locations in the continental US. The description of the need for a paradigm change in the governance of infrastructure systems is based on a number of peer-reviewed journal articles describing observations of the limits of current governance systems, as well as more academic journal articles addressing best practices for building resilient infrastructure systems. There is very little published literature on the effects of governance on the ability to adapt, especially in the US Caribbean.

Major Uncertainties and Research Gaps

The availability of more structural and system operation assessments of the vulnerability of infrastructure systems to flood and wind events is a major research gap, because most assessments are made by looking at the presence or absence of a system component in a flood zone. Often it is unclear whether the system component can be accessed or operated, or even whether it may have been rendered unsafe by previous mitigation activities that took place. Another gap is the lack of availability of public geodatabases of infrastructure systems. The region is also missing flood maps that take into account future climates. Furthermore, understanding the effectiveness and feasibility of decentralized governance systems for critical infrastructure is a major research gap and need, as much of the current literature demonstrates the limits of centralized systems in the Caribbean. Finally, the lack of easily accessible data on water and power consumption, traffic patterns, and other ways that humans use infrastructure systems is a major data gap that needs to be filled so that adaptation strategies can be developed to mitigate against any disruption in the delivery of services.

Description of Confidence and Likelihood

Based on the level of damage incurred during Hurricanes Irma and Maria (2017) and Hurricane Fiona (2022), as well as the post-2017 hurricane reports published by the government and federal agencies, there is *high confidence* that infrastructure systems in the US Caribbean are suffering from a lack of maintenance and investment and that climate change has created profound risks for the US Caribbean's critical infrastructure, especially as extreme meteorological events become more *likely* in the future. There is *high confidence* that dependence on fossil fuel imports increases energy insecurity, based on numerous reports from the gray literature and the recent fiscal difficulties experienced by the public utilities in both Puerto Rico and the USVI.

Given the lack of stability of the public utilities, as described in government and federal agency reports, and given the relative lack of long-term data on the effectiveness of solar electric systems as an alternative to centralized systems to provide power to communities during and outside of disasters, there is *medium confidence* that decentralization of system production and distribution, and *medium confidence* that decarbonization and shared governance, will *likely* help limit residents' vulnerability to health and other risks associated with the loss of essential services programs.

Key Message 23.5

Adaptation Effectiveness Increases When Coupled with Strategic Governance and Planning

Description of Evidence Base

The evidence to support the Key Message consists of articles in peer-reviewed journals, research publications by universities, technical papers, assessment reports produced by or on behalf of the federal and territorial governments, executive orders and legislation passed by the territorial governments, and technical reports by Caribbean and global intergovernmental organizations.

The peer-reviewed journals were classified with impact factors that range from 3.20 to 9.5, indicating that the journals are trustworthy. The documents prepared or funded by federal and territorial governments underpin the conclusions regarding challenges of various levels of government for effective planning and adaptation.[148,249,252,253,276,277,279] Literature that supports the conclusions regarding effective adaptation action through improved governance arrangements and coproduction with community organizations includes McGinley et al (2022),[168] Filantropia Puerto Rico Inc. (2022),[258] and Towe et al. (2020).[262] The gray literature also includes publications by research institutions such as the National Institute of Building Sciences, the International Council for Local Environmental Initiatives–Local Governments for Sustainability USA, the University of the Virgin Islands, and the University of Colorado.

Since the publication of the Fourth National Climate Assessment in 2018, climate adaptation action is increasingly being informed by high-quality data, policies, laws, white papers, and technical reports prepared by the governments of the two territories, Puerto Rico's Expert Advisory Committee on Climate Change, the Puerto Rico Climate Change Council, the Governors' Institute on Community Design, academia, scientists, and community-based organizations.

Major Uncertainties and Research Gaps

A large body of literature is available globally and for the wider Caribbean on the benefits of local adaptation through coproduction. For the US Caribbean, although there are participatory efforts, mostly from the nonprofit sector and many supported by academia, the published literature is sparse. As such, additional research and evaluation on the capacity requirements and design for collective action would enhance implementation.

Description of Confidence and Likelihood

Statements about the challenges of climate adaptation in the US Caribbean due to multiple interacting factors—including high risk exposure, limited or misaligned funding, insufficient institutional and organizational capacity, and siloed approaches to risk reduction and resilience—are based on extensive analysis of peer-reviewed papers; federal, regional, and local technical reports; and the onsite experience of the multidisciplinary, multisectoral team of 22 authors of this chapter. Authors had the opportunity to deal with, study, and/or assess these diverse interacting factors that are related to climate adaptation in the US Caribbean from diverse points of view. As a result, authors have *high confidence* in the first statement of the Key Message.

On-site experience, data, and numerous studies with consistent findings support the idea that US Caribbean adaptation could be enhanced through co-development and integration of robust global, regional, and local climate science and risk-based knowledge into planning and implementation, as well as improved governance, resulting in *high confidence* in the second part of the Key Message.

Based on a smaller number of studies but further deliberation among our author team, the statements about how US Caribbean capabilities in planning and adaptation can be enhanced by strengthening partnerships across the wider Caribbean region and the US mainland is assigned *medium confidence*.

References

1. Gould, W.A., E.L. Díaz (co-leads), N.L. Álvarez-Berríos, F. Aponte-González, W. Archibald, J.H. Bowden, L. Carrubba, W. Crespo, S.J. Fain, G. González, A. Goulbourne, E. Harmsen, E. Holupchinski, A.H. Khalyani, J. Kossin, A.J. Leinberger, V.I. Marrero-Santiago, O. Martínez-Sánchez, K. McGinley, P. Méndez-Lázaro, J. Morell, M.M. Oyola, I.K. Parés-Ramos, R. Pulwarty, W.V. Sweet, A. Terando, and S. Torres-González, 2018: Ch. 20. U.S. Caribbean. In: *Impacts, Risks, and Adaptation in the United States: Fourth National Climate Assessment, Volume II*. Reidmiller, D.R., C.W. Avery, D. Easterling, K. Kunkel, K.L.M. Lewis, T.K. Maycock, and B.C. Stewart, Eds. U.S. Global Change Research Program, Washington, DC, USA, 809–871. https://doi.org/10.7930/nca4.2018.ch20

2. American Community Survey, 2015: Data Profiles. U.S. Census Bureau. https://www.census.gov/acs/www/data/data-tables-and-tools/data-profiles/2015/

3. DeWaard, J., J.E. Johnson, and S.D. Whitaker, 2020: Out-migration from and return migration to Puerto Rico after Hurricane Maria: Evidence from the consumer credit panel. *Population and Environment*, **42** (1), 28–42. https://doi.org/10.1007/s11111-020-00339-5

4. Mayol-García, Y.H., 2020: Pre-hurricane linkages between poverty, families, and migration among Puerto Rican-origin children living in Puerto Rico and the United States. *Population and Environment*, **42** (1), 57–78. https://doi.org/10.1007/s11111-020-00353-7

5. U.S. Census Bureau, 2010: QuickFacts: United States. U.S. Department of Commerce, U.S. Census Bureau. https://www.census.gov/quickfacts/fact/table/us/pst045221

6. U.S. Census Bureau, 2020: data.census.gov. U.S. Department of Commerce, U.S. Census Bureau. https://data.census.gov/table

7. Rodríguez-Díaz, C.E., 2018: Maria in Puerto Rico: Natural disaster in a colonial archipelago. *American Journal of Public Health*, **108** (1), 30–32. https://doi.org/10.2105/ajph.2017.304198

8. HUD, 2017: Office of Policy Development and Research. U.S. Department of Housing and Urban Development. https://www.hud.gov/programdescription/pdr

9. U.S. Census Bureau, 2020: Post-Enumeration Surveys. U.S. Department of Commerce, U.S. Census Bureau. https://data.census.gov/all?y=2020&d=DEC+Decennial+Post-Enumeration+Survey

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

11. McPhillips, L.E., H. Chang, M.V. Chester, Y. Depietri, E. Friedman, N.B. Grimm, J.S. Kominoski, T. McPhearson, P. Méndez-Lázaro, E.J. Rosi, and J. Shafiei Shiva, 2018: Defining extreme events: A cross-disciplinary review. *Earth's Future*, **6** (3), 441–455. https://doi.org/10.1002/2017ef000686

12. Runkle, J., K.E. Kunkel, L.E. Stevens, S.M. Champion, D.R. Easterling, A. Terando, L. Sun, B.C. Stewart, G. Landers, and S. Rayne, 2022: Puerto Rico and the U.S. Virgin Islands State Climate Summary 2022. NOAA Technical Report NESDIS 150-PR. National Oceanic and Atmospheric Administration, National Environmental Satellite, Data, and Information Service, Silver Spring, MD, 5 pp. https://statesummaries.ncics.org/chapter/pr/

13. Holladay, P., P. Méndez-Lázaro, and K. Brundiers, 2021: From hurricanes to pandemics: Community-based transformation and destination resilience in Utuado, Puerto Rico. *Journal of Sustainability and Resilience*, **1** (2), 1–6. https://digitalcommons.usf.edu/jsr/vol1/iss2/1

14. Méndez-Lázaro, P.A., Y.M. Bernhardt, W.A. Calo, A.M. Pacheco Díaz, S.I. García-Camacho, M. Rivera-Lugo, E. Acosta-Pérez, N. Pérez, and A.P. Ortiz-Martínez, 2021: Environmental stressors suffered by women with gynecological cancers in the aftermath of Hurricanes Irma and María in Puerto Rico. *International Journal of Environmental Research and Public Health*, **18** (21), 11183. https://doi.org/10.3390/ijerph182111183

15. Rivera-Collazo, I.C., 2021: Climate change and archaeological sites: A case study for partnering cultural heritage and climate action. In: *Stemming the Tide: Global Strategies for Sustaining Cultural Heritage through Climate Change*. Rushfield, R., Ed. Smithsonian Institution Scholarly Press, Washington, DC, 25–38. https://doi.org/10.5479/si.14750727

16. Thomas, K., R.D. Hardy, H. Lazrus, M. Mendez, B. Orlove, I. Rivera-Collazo, J.T. Roberts, M. Rockman, B.P. Warner, and R. Winthrop, 2019: Explaining differential vulnerability to climate change: A social science review. *WIREs Climate Change*, **10** (2), e565. https://doi.org/10.1002/wcc.565

17. FOMBPR, 2022: 2022 Fiscal Plan for Puerto Rico: Restoring Growth and Prosperity. The Financial Oversight and Management Board for Puerto Rico, 355 pp. https://oversightboard.pr.gov/fiscal-plans-2/

18. Lamba-Nieves, D., Sergio M. Marxuach, and R. Torres, 2021: PROMESA: A Failed Colonial Experiment? Center for a New Economy. https://grupocne.org/2021/06/29/promesa-a-failed-colonial-experiment/

19. U.S. Department of the Treasury, 2018: Puerto Rico's Economic and Fiscal Crisis. U.S. Department of the Treasury, 7 pp. https://www.supremecourt.gov/opinions/urls_cited/ot2019/18-1334/18-1334-1.pdf

20. Puerto Rico Climate Change Council, 2022: Puerto Rico's State of the Climate 2014–2021: Assessing Puerto Rico's Social-Ecological Vulnerabilities in a Changing Climate. Puerto Rico Coastal Zone Management Program, Department of Natural and Environmental Resources, NOAA Office of Ocean and Coastal Resource Management, San Juan, PR. https://www.drna.pr.gov/wp-content/uploads/2022/10/PR_StateOfTheClimate_2014-2021_PRCCC-09-2022.pdf

21. Bowden, J.H., A.J. Terando, V. Misra, A. Wootten, A. Bhardwaj, R. Boyles, W. Gould, J.A. Collazo, and T.L. Spero, 2021: High-resolution dynamically downscaled rainfall and temperature projections for ecological life zones within Puerto Rico and for the U.S. Virgin Islands. *International Journal of Climatology*, **41** (2), 1305–1327. https://doi.org/10.1002/joc.6810

22. Fox-Kemper, B., H.T. Hewitt, C. Xiao, G. Aðalgeirsdóttir, S.S. Drijfhout, T.L. Edwards, N.R. Golledge, M. Hemer, R.E. Kopp, G. Krinner, A. Mix, D. Notz, S. Nowicki, I.S. Nurhati, L. Ruiz, J.-B. Sallée, A.B.A. Slangen, and Y. Yu, 2021: Ch. 9. Ocean, cryosphere and sea level change. In: *Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*. Masson-Delmotte, V., P. Zhai, A. Pirani, S.L. Connors, C. Péan, S. Berger, N. Caud, Y. Chen, L. Goldfarb, M.I. Gomis, M. Huang, K. Leitzell, E. Lonnoy, J.B.R. Matthews, T.K. Maycock, T. Waterfield, O. Yelekçi, R. Yu, and B. Zhou, Eds. Cambridge University Press, Cambridge, UK and New York, NY, USA, 1211–1362. https://doi.org/10.1017/9781009157896.011

23. Keellings, D. and J.J. Hernández Ayala, 2019: Extreme rainfall associated with Hurricane Maria over Puerto Rico and its connections to climate variability and change. *Geophysical Research Letters*, **46** (5), 2964–2973. https://doi.org/10.1029/2019gl082077

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

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

26. Bell, G.D. and M. Chelliah, 2006: Leading tropical modes associated with interannual and multidecadal fluctuations in North Atlantic hurricane activity. *Journal of Climate*, **19** (4), 590–612. https://doi.org/10.1175/jcli3659.1

27. Philander, G., 1989: El Niño and La Niña. *American Scientist*, **77** (5), 451–459. http://www.jstor.org/stable/27855934

28. Torres-Valcárcel, A.R., 2018: Teleconnections between ENSO and rainfall and drought in Puerto Rico. *International Journal of Climatology*, **38** (S1), e1190–e1204. https://doi.org/10.1002/joc.5444

29. Hurrell, J.W., Y. Kushnir, G. Ottersen, and M. Visbeck, 2003: Ch. 1. An overview of the North Atlantic Oscillation. In: *The North Atlantic Oscillation: Climatic Significance and Environmental Impact*. Hurrell, J.W., Y. Kushnir, G. Ottersen, and M. Visbeck, Eds. American Geophysical Union, 1–35. https://doi.org/10.1029/134gm01

30. Martinez, C., Y. Kushnir, L. Goddard, and M. Ting, 2020: Interannual variability of the early and late-rainy seasons in the Caribbean. *Climate Dynamics*, **55** (5), 1563–1583. https://doi.org/10.1007/s00382-020-05341-z

31. Mote, T.L., C.A. Ramseyer, and P.W. Miller, 2017: The Saharan Air Layer as an early rainfall season suppressant in the Eastern Caribbean: The 2015 Puerto Rico drought. *Journal of Geophysical Research: Atmospheres*, **122** (20), 10966–10982. https://doi.org/10.1002/2017jd026911

32. Reed, K.A., J.T. Bacmeister, J.J.A. Huff, X. Wu, S.C. Bates, and N.A. Rosenbloom, 2019: Exploring the impact of dust on North Atlantic hurricanes in a high-resolution climate model. *Geophysical Research Letters*, **46** (2), 1105–1112. https://doi.org/10.1029/2018gl080642

33. Cashman, A., 2014: Water security and services in the Caribbean. *Water*, **6** (5), 1187–1203. https://doi.org/10.3390/w6051187

34. Watson, A., S. Ganapati, A. Grossman, J. Trtanj, N. Arbour, I. Torres, and A.M. Stewart-Ibarra, 2022: Not what the doctor ordered: Prioritizing transdisciplinary science on climate, environment and health in the Latin American and Caribbean region. *PLoS Climate*, **1** (4), e0000025. https://doi.org/10.1371/journal.pclm.0000025

35. Gahman, L. and G. Thongs, 2020: Development justice, a proposal: Reckoning with disaster, catastrophe, and climate change in the Caribbean. *Transactions of the Institute of British Geographers*, **45** (4), 763–778. https://doi.org/10.1111/tran.12369

36. Louis-Charles, H.M., R. Howard, L. Remy, F. Nibbs, and G. Turner, 2020: Ethical considerations for postdisaster fieldwork and data collection in the Caribbean. *American Behavioral Scientist*, **64** (8), 1129–1144. https://doi.org/10.1177/0002764220938113

37. McHarg, E., E. Mengo, L. Benson, J. Daniel, A. Joseph-Witzig, P. Posen, and T. Luisetti, 2022: Valuing the contribution of blue carbon to small island developing states' climate change commitments and COVID-19 recovery. *Environmental Science & Policy*, **132**, 13–23. https://doi.org/10.1016/j.envsci.2022.02.009

38. Winters, Z.S., T.L. Crisman, and D.T. Dumke, 2022: Sustainability of the water-energy-food nexus in Caribbean small island developing states. *Water*, **14** (3). https://doi.org/10.3390/w14030322

39. Iwama, A.Y., F. Araos, J. Anbleyth-Evans, V. Marchezini, A. Ruiz-Luna, F. Ther-Ríos, G. Bacigalupe, and P.E. Perkins, 2021: Multiple knowledge systems and participatory actions in slow-onset effects of climate change: Insights and perspectives in Latin America and the Caribbean. *Current Opinion in Environmental Sustainability*, **50**, 31–42. https://doi.org/10.1016/j.cosust.2021.01.010

40. Latulippe, N. and N. Klenk, 2020: Making room and moving over: Knowledge co-production, Indigenous knowledge sovereignty and the politics of global environmental change decision-making. *Current Opinion in Environmental Sustainability*, **42**, 7–14. https://doi.org/10.1016/j.cosust.2019.10.010

41. PAHO, 2019: Caribbean Action Plan on Health and Climate Change. Pan American Health Organization, Washington, DC. https://iris.paho.org/bitstream/handle/10665.2/38566/pahocde19007_eng.pdf?sequence=19&isallowed=y

42. Michael, N., J.M. Valmond, L.E. Ragster, D.E. Brown, and G.B. Callwood, 2019: Community Needs Assessment: Understanding the Needs of Vulnerable Children and Families in the US Virgin Islands Post Hurricanes Irma and Maria. University of the Virgin Islands, School of Nursing, Caribbean Exploratory Research Center, St. Thomas, USVI. https://cfvi.net/wp-content/uploads/2019/03/CFVI-CERC-Community-Needs-Assessment-E-Report_February-2019_Bookmarked.pdf

43. WHO, 2021: Tripartite and UNEP Support OHHLEP's Definition of "One Health". World Health Organization. https://www.who.int/news/item/01-12-2021-tripartite-and-unep-support-ohhlep-s-definition-of-one-health

44. Boger, R., S. Perdikaris, and I. Rivero-Collazo, 2019: Cultural heritage and local ecological knowledge under threat: Two Caribbean examples from Barbuda and Puerto Rico. *Journal of Anthropology and Archaeology*, **7** (2), 1–14. https://doi.org/10.15640/jaa.v7n2p1

45. Dunnavant, J.P., A.O. Flewellen, A. Jones, A. Odewale, and W. White, 2018: Assessing heritage resources in St. Croix post-Hurricanes Irma and Maria. *Transforming Anthropology*, **26** (2), 157–172. https://doi.org/10.1111/traa.12130

46. Rivera-Collazo, I.C., 2020: Severe weather and the reliability of desk-based vulnerability assessments: The impact of Hurricane Maria to Puerto Rico's coastal archaeology. *The Journal of Island and Coastal Archaeology*, **15** (2), 244–263. https://doi.org/10.1080/15564894.2019.1570987

47. USACE, 2022: Antilles Area Office. U.S. Army Corps of Engineers, Jacksonville District, accessed September 29, 2022. https://www.saj.usace.army.mil/about/divisions-offices/antilles-office/

48. Horowitz, L.S., 2022: "Conflicts of interests" within and between elite assemblages in the legal production of space: Indigenous cultural heritage preservation and the Dakota Access Pipeline. *The Geographical Journal*, **188** (1), 91–108. https://doi.org/10.1111/geoj.12421

49. Kaenzig, R. and E. Piguet, 2014: Ch. 7. Migration and climate change in Latin America and the Caribbean. In: *People on the Move in a Changing Climate: The Regional Impact of Environmental Change on Migration*. Piguet, E. and F. Laczko, Eds. Springer, Dordrecht, Netherlands, 155–176. https://doi.org/10.1007/978-94-007-6985-4_7

50. Chowdhury, M.A.B., A.J. Fiore, S.A. Cohen, C. Wheatley, B. Wheatley, M.P. Balakrishnan, M. Chami, L. Scieszka, M. Drabin, K.A. Roberts, A.C. Toben, J.A. Tyndall, L.M. Grattan, and J.G. Morris, 2019: Health impact of Hurricanes Irma and Maria on St Thomas and St John, US Virgin Islands, 2017–2018. *American Journal of Public Health*, **109** (12), 1725–1732. https://doi.org/10.2105/ajph.2019.305310

51. Guannel, G., H. Lohmann, and J. Dwyer, 2022: The Public Health Implications of Social Vulnerability in the U.S. Virgin Islands. Natural Hazards Center Public Health Grant Report Series, 23. University of Colorado Boulder, Natural Hazards Center, Boulder, CO. https://hazards.colorado.edu/public-health-disaster-research/the-public-health-implications-of-social-vulnerability-in-the-u-s-virgin-islands

52. Irvin-Barnwell, E., M. Cruz, C. Maniglier-Poulet, J. Cabrera, J.R. Diaz, R.D.L. Cruz Perez, C. Forrester, A. Shumate, J. Mutter, L. Graziano, L.R. Gonzalez, J. Malilay, and M. Raheem, 2020: Evaluating disaster damages and operational status of health-care facilities during the emergency response phase of Hurricane Maria in Puerto Rico. *Disaster Medicine and Public Health Preparedness*, **14** (1), 80–88. https://doi.org/10.1017/dmp.2019.85

53. EPA, 2022: Search for Superfund Sites Where You Live. U.S. Environmental Protection Agency. https://www.epa.gov/superfund/search-superfund-sites-where-you-live

54. EPA, 2015: National Priorities List (NPL) Sites–By State. U.S. Environmental Protection Agency. https://www.epa.gov/superfund/national-priorities-list-npl-sites-state

55. Kishore, N., D. Marqués, A. Mahmud, M.V. Kiang, I. Rodriguez, A. Fuller, P. Ebner, C. Sorensen, F. Racy, J. Lemery, L. Maas, J. Leaning, R.A. Irizarry, S. Balsari, and C.O. Buckee, 2018: Mortality in Puerto Rico after Hurricane Maria. *New England Journal of Medicine*, **379** (2), 162–170. https://doi.org/10.1056/nejmsa1803972

56. Santos-Burgoa, C., J. Sandberg, E. Suárez, A. Goldman-Hawes, S. Zeger, A. Garcia-Meza, C.M. Pérez, N. Estrada-Merly, U. Colón-Ramos, C.M. Nazario, E. Andrade, A. Roess, and L. Goldman, 2018: Differential and persistent risk of excess mortality from Hurricane Maria in Puerto Rico: A time-series analysis. *The Lancet Planetary Health*, **2** (11), 478–488. https://doi.org/10.1016/s2542-5196(18)30209-2

57. Orengo-Aguayo, R., R.W. Stewart, M.A. Arellano, J.L. Suárez-Kindy, and J. Young, 2019: Disaster exposure and mental health among Puerto Rican youths after Hurricane Maria. *JAMA Network Open*, **2** (4), 192619. https://doi.org/10.1001/jamanetworkopen.2019.2619

58. Hall, C., R. Rudowitz, S. Artiga, and B. Lyons, 2018: One Year After the Storms: Recovery and Health Care in Puerto Rico and the U.S. Virgin Islands. Kaiser Family Foundation. https://www.kff.org/medicaid/issue-brief/one-year-after-the-storms-recovery-and-health-care-in-puerto-rico-and-the-u-s-virgin-islands/

59. Calo, W.A., M. Rivera, P.A. Mendez-Lazaro, S.I. Garcia-Camacho, Y.M. Bernhardt Utz, E. Acosta-Perez, and A.P. Ortiz, 2022: Disruptions in oncology care confronted by patients with gynecologic cancer following Hurricanes Irma and Maria in Puerto Rico. *Cancer Control*, **29**, 10732748221114691. https://doi.org/10.1177/10732748221114691

60. Cruz, N.I., E. Santiago, and K. Rodríguez, 2020: The effect of Hurricane Maria on the surgical workload of the UPR-affiliated hospitals. *Puerto Rico Health Sciences Journal*, **39** (2), 195–199. https://pubmed.ncbi.nlm.nih.gov/32663917/

61. Gay, H.A., R. Santiago, B. Gil, C. Remedios, P.J. Montes, J. López-Araujo, C.M. Chévere, W.S. Imbert, J. White, D.W. Arthur, J.K. Horton, R. Jagsi, R. Rabinovich, S. Beriwal, A. Viswanathan, B.A. Erickson, R. Rengan, D. Palma, B.W. Loo, J.A. Kavanaugh, J. Bradley, S.S. Yom, P.M. Harari, and O. Lee Burnett, 2019: Lessons learned from Hurricane Maria in Puerto Rico: Practical measures to mitigate the impact of a catastrophic natural disaster on radiation oncology patients. *Practical Radiation Oncology*, **9** (5), 305–321. https://doi.org/10.1016/j.prro.2019.03.007

62. Kunos, C.A. and P. Ivy, 2019: Leveraging National Cancer Institute programmatic collaboration for uterine cervix cancer brachytherapy in Puerto Rico after Hurricane Maria. *Frontiers in Oncology*, **9**, 414. https://doi.org/10.3389/fonc.2019.00414

63. Lukowsky, L.R., A. Dobalian, K. Kalantar-Zadeh, and C. Der-Martirosian, 2023: Dialysis care for US military veterans in Puerto Rico during the 2017 Atlantic hurricane season. *Disaster Medicine and Public Health Preparedness*, **17**, 187. https://doi.org/10.1017/dmp.2022.63

64. Rodriguez-Rabassa, M., R. Hernandez, Z. Rodriguez, C.B. Colon-Echevarria, L. Maldonado, N. Tollinchi, E. Torres-Marrero, A. Mulero, D. Albors, J. Perez-Morales, I. Flores, J. Dutil, H. Jim, E.M. Castro, and G.N. Armaiz-Pena, 2020: Impact of a natural disaster on access to care and biopsychosocial outcomes among Hispanic/Latino cancer survivors. *Scientific Reports*, **10** (1), 10376. https://doi.org/10.1038/s41598-020-66628-z

65. Ortiz, A.P., W.A. Calo, P. Mendez-Lazaro, S. García-Camacho, A. Mercado-Casillas, J. Cabrera-Márquez, and G. Tortolero-Luna, 2020: Strengthening resilience and adaptive capacity to disasters in cancer control plans: Lessons learned from Puerto Rico. *Cancer Epidemiology, Biomarkers & Prevention*, **29** (7), 1290–1293. https://doi.org/10.1158/1055-9965.epi-19-1067

66. USVI DOH, 2020: 2020 United States Virgin Islands Community Health Assessment. U.S. Virgin Islands Department of Health, Christiansted, USVI. https://doh.vi.gov/community-health-assessment-report

67. NCCDPHP, 2020: Nutrition, Physical Activity, and Obesity: Data, Trends and Maps. Centers for Disease Control and Prevention, National Center for Chronic Disease Prevention and Health Promotion. https://www.cdc.gov/nccdphp/dnpao/data-trends-maps/index.html

68. CDC, 2021: Morbidity and Mortality Weekly Report. Centers for Disease Control and Prevention. https://www.cdc.gov/mmwr/index.html

69. Mattei, J., M. Tamez, J. O'Neill, S. Haneuse, S. Mendoza, J. Orozco, A. Lopez-Cepero, C.F. Ríos-Bedoya, L.M. Falcón, K.L. Tucker, and J.F. Rodríguez-Orengo, 2022: Chronic diseases and associated risk factors among adults in Puerto Rico after Hurricane Maria. *JAMA Network Open*, **5** (1), 2139986. https://doi.org/10.1001/jamanetworkopen.2021.39986

70. Ferré, I.M., S. Negrón, J.M. Shultz, S.J. Schwartz, J.P. Kossin, and H. Pantin, 2019: Hurricane Maria's impact on Punta Santiago, Puerto Rico: Community needs and mental health assessment six months postimpact. *Disaster Medicine and Public Health Preparedness*, **13** (1), 18–23. https://doi.org/10.1017/dmp.2018.103

71. Scaramutti, C., C.P. Salas-Wright, S.R. Vos, and S.J. Schwartz, 2019: The mental health impact of Hurricane Maria on Puerto Ricans in Puerto Rico and Florida. *Disaster Medicine and Public Health Preparedness*, **13** (1), 24–27. https://doi.org/10.1017/dmp.2018.151

72. de Jesús Crespo, R., P.M. Lázaro, and S.H. Yee, 2019: Linking wetland ecosystem services to vector-borne disease: Dengue fever in the San Juan Bay Estuary, Puerto Rico. *Wetlands*, **39** (6), 1281–1293. https://doi.org/10.1007/s13157-017-0990-5

73. Johansson, M.A., D.A.T. Cummings, and G.E. Glass, 2009: Multiyear climate variability and dengue—El Niño Southern Oscillation, weather, and dengue incidence in Puerto Rico, Mexico, and Thailand: A longitudinal data analysis. *PLoS Medicine*, **6** (11), 1000168. https://doi.org/10.1371/journal.pmed.1000168

74. Laureano-Rosario, A.E., Andrew P. Duncan, Pablo A. Mendez-Lazaro, Julian E. Garcia-Rejon, Salvador Gomez-Carro, Jose Farfan-Ale, Dragan A. Savic, and Frank E. Muller-Karger, 2018: Application of artificial neural networks for dengue fever outbreak predictions in the northwest coast of Yucatan, Mexico and San Juan, Puerto Rico. *Tropical Medicine and Infectious Disease*, **3** (1), 5. https://doi.org/10.3390/tropicalmed3010005

75. Méndez-Lázaro, P.A., A. Nieves-Santiango, and J. Miranda-Bermúdez, 2014: Trends in total rainfall, heavy rain events, and number of dry days in San Juan, Puerto Rico, 1955–2009. *Ecology and Society*, **19** (2), 50. https://doi.org/10.5751/es-06464-190250

76. Morin, C.W., A.J. Monaghan, M.H. Hayden, R. Barrera, and K. Ernst, 2015: Meteorologically driven simulations of dengue epidemics in San Juan, PR. *PLoS Neglected Tropical Diseases*, **9** (8), 0004002. https://doi.org/10.1371/journal.pntd.0004002

77. Pratt, N. and S. Rajeev, 2018: Leptospira seroprevalence in animals in the Caribbean region: A systematic review. *Acta Tropica*, **182**, 34–42. https://doi.org/10.1016/j.actatropica.2018.02.011

78. Lau, C.L., L.D. Smythe, S.B. Craig, and P. Weinstein, 2010: Climate change, flooding, urbanisation and leptospirosis: Fuelling the fire? *Transactions of the Royal Society of Tropical Medicine and Hygiene*, **104** (10), 631–638. https://doi.org/10.1016/j.trstmh.2010.07.002

79. Di Napoli, C., T. Allen, P.A. Méndez-Lázaro, and F. Pappenberger, 2023: Heat stress in the Caribbean: Climatology, drivers, and trends of human biometeorology indices. *International Journal of Climatology*, **43** (1), 405–425. https://doi.org/10.1002/joc.7774

80. Méndez-Lázaro, P., F.E. Muller-Karger, D. Otis, M.J. McCarthy, and E. Rodríguez, 2018: A heat vulnerability index to improve urban public health management in San Juan, Puerto Rico. *International Journal of Biometeorology*, **62** (5), 709–722. https://doi.org/10.1007/s00484-017-1319-z

81. Méndez-Lázaro, P.A., C.M. Pérez-Cardona, E. Rodríguez, O. Martínez, M. Taboas, A. Bocanegra, and R. Méndez-Tejeda, 2018: Climate change, heat, and mortality in the tropical urban area of San Juan, Puerto Rico. *International Journal of Biometeorology*, **62** (5), 699–707. https://doi.org/10.1007/s00484-016-1291-z

82. Méndez-Lázaro, P., O. Martínez-Sánchez, R. Méndez-Tejeda, E. Rodríguez, E. Morales, and N.S. Cortijo, 2015: Extreme heat events in San Juan Puerto Rico: Trends and variability of unusual hot weather and its possible effects on ecology and society. *Journal of Climatology & Weather Forecasting*, **3**, 135. https://doi.org/10.4172/2332-2594.1000135

83. Clifford, H.M., N.E. Spaulding, A.V. Kurbatov, A. More, E.V. Korotkikh, S.B. Sneed, M. Handley, K.A. Maasch, C.P. Loveluck, J. Chaplin, M. McCormick, and P.A. Mayewski, 2019: A 2000 year Saharan dust event proxy record from an ice core in the European Alps. *Journal of Geophysical Research: Atmospheres*, **124** (23), 12882–12900. https://doi.org/10.1029/2019jd030725

84. Evan, A.T., G.R. Foltz, D. Zhang, and D.J. Vimont, 2011: Influence of African dust on ocean–atmosphere variability in the tropical Atlantic. *Nature Geoscience*, **4** (11), 762–765. https://doi.org/10.1038/ngeo1276

85. Okin, G.S., A.R. Baker, I. Tegen, N.M. Mahowald, F.J. Dentener, R.A. Duce, J.N. Galloway, K. Hunter, M. Kanakidou, N. Kubilay, J.M. Prospero, M. Sarin, V. Surapipith, M. Uematsu, and T. Zhu, 2011: Impacts of atmospheric nutrient deposition on marine productivity: Roles of nitrogen, phosphorus, and iron. *Global Biogeochemical Cycles*, **25** (2). https://doi.org/10.1029/2010gb003858

86. Prospero, J.M., 1999: Long-term measurements of the transport of African mineral dust to the southeastern United States: Implications for regional air quality. *Journal of Geophysical Research: Atmospheres*, **104** (D13), 15917–15927. https://doi.org/10.1029/1999jd900072

87. Prospero, J.M., F.-X. Collard, J. Molinié, and A. Jeannot, 2014: Characterizing the annual cycle of African dust transport to the Caribbean Basin and South America and its impact on the environment and air quality. *Global Biogeochemical Cycles*, **28** (7), 757–773. https://doi.org/10.1002/2013gb004802

88. Prospero, J.M. and O.L. Mayol-Bracero, 2013: Understanding the transport and impact of African dust on the Caribbean Basin. *Bulletin of the American Meteorological Society*, **94** (9), 1329–1337. https://doi.org/10.1175/bams-d-12-00142.1

89. Tong, D.Q., T.E. Gill, W.A. Sprigg, R.S. Van Pelt, A.A. Baklanov, B.M. Barker, J.E. Bell, J. Castillo, S. Gassó, C.J. Gaston, D.W. Griffin, N. Huneeus, R.A. Kahn, A.P. Kuciauskas, L.A. Ladino, J. Li, O.L. Mayol-Bracero, O.Z. McCotter, P.A. Méndez-Lázaro, P. Mudu, S. Nickovic, D. Oyarzun, J. Prospero, G.B. Raga, A.U. Raysoni, L. Ren, N. Sarafoglou, A. Sealy, Z. Sun, and A.V. Vimic, 2023: Health and safety effects of airborne soil dust in the Americas and beyond. *Reviews of Geophysics*, **61** (2), e2021RG000763. https://doi.org/10.1029/2021rg000763

90. Twohy, C.H., S.M. Kreidenweis, T. Eidhammer, E.V. Browell, A.J. Heymsfield, A.R. Bansemer, B.E. Anderson, G. Chen, S. Ismail, P.J. DeMott, and S.C. Van Den Heever, 2009: Saharan dust particles nucleate droplets in eastern Atlantic clouds. *Geophysical Research Letters*, **36** (1). https://doi.org/10.1029/2008gl035846

91. West, J.J., A. Cohen, F. Dentener, B. Brunekreef, T. Zhu, B. Armstrong, M.L. Bell, M. Brauer, G. Carmichael, D.L. Costa, D.W. Dockery, M. Kleeman, M. Krzyzanowski, N. Künzli, C. Liousse, S.-C.C. Lung, R.V. Martin, U. Pöschl, C.A. Pope, J.M. Roberts, A.G. Russell, and C. Wiedinmyer, 2016: What we breathe impacts our health: Improving understanding of the link between air pollution and health. *Environmental Science & Technology*, **50** (10), 4895–4904. https://doi.org/10.1021/acs.est.5b03827

92. Zhang, X., L. Zhao, D.Q. Tong, G. Wu, M. Dan, and B. Teng, 2016: A systematic review of global desert dust and associated human health effects. *Atmosphere*, **7** (12), 158. https://doi.org/10.3390/atmos7120158

93. Tuttle, L.J., C. Johnson, S. Kolinski, D. Minton, and M.J. Donahue, 2020: How does sediment exposure affect corals? A systematic review protocol. *Environmental Evidence*, **9** (1), 17. https://doi.org/10.1186/s13750-020-00200-0

94. Gyan, K., W. Henry, S. Lacaille, A. Laloo, C. Lamsee-Ebanks, S. McKay, R.M. Antoine, and M.A. Monteil, 2005: African dust clouds are associated with increased paediatric asthma accident and emergency admissions on the Caribbean island of Trinidad. *International Journal of Biometeorology*, **49** (6), 371–376. https://doi.org/10.1007/s00484-005-0257-3

95. Cadelis, G., R. Tourres, and J. Molinie, 2014: Short-term effects of the particulate pollutants contained in Saharan dust on the visits of children to the emergency department due to asthmatic conditions in Guadeloupe (French archipelago of the Caribbean). *PLoS ONE*, **9** (3), e91136. https://doi.org/10.1371/journal.pone.0091136

96. Akpinar-Elci, M., F.E. Martin, J.G. Behr, and R. Diaz, 2015: Saharan dust, climate variability, and asthma in Grenada, the Caribbean. *International Journal of Biometeorology*, **59** (11), 1667–1671. https://doi.org/10.1007/s00484-015-0973-2

97. ANSES, 2017: Exposition aux Émanations des Algues Sargasses Échouées: l'Anses Réitère et Complète ses Recommandations. Agence Nationale de Sécurité Sanitaire de L'alimentation, de L'environnement et du Travail. https://www.anses.fr/fr/content/exposition-aux-%C3%A9manations-des-algues-sargasses-%C3%A9chou%C3%A9es-l%E2%80%99anses-r%C3%A9it%C3%A8re-et-compl%C3%A8te-ses

98. Fidai, Y.A., J. Dash, E.L. Tompkins, and T. Tonon, 2020: A systematic review of floating and beach landing records of Sargassum beyond the Sargasso Sea. *Environmental Research Communications*, **2** (12), 122001. https://doi.org/10.1088/2515-7620/abd109

99. Maurer, A.S., S.P. Stapleton, C.A. Layman, and M.O. Burford Reiskind, 2021: The Atlantic Sargassum invasion impedes beach access for nesting sea turtles. *Climate Change Ecology*, **2**, 100034. https://doi.org/10.1016/j.ecochg.2021.100034

100. Resiere, D., H. Mehdaoui, J. Florentin, P. Gueye, T. Lebrun, A. Blateau, J. Viguier, R. Valentino, Y. Brouste, H. Kallel, B. Megarbane, A. Cabie, R. Banydeen, and R. Neviere, 2021: Sargassum seaweed health menace in the Caribbean: Clinical characteristics of a population exposed to hydrogen sulfide during the 2018 massive stranding. *Clinical Toxicology*, **59** (3), 215–223. https://doi.org/10.1080/15563650.2020.1789162

101. Resiere, D., H. Mehdaoui, R. Névière, and B. Mégarbane, 2019: Sargassum invasion in the Caribbean: The role of medical and scientific cooperation. *Pan American Journal of Public Health*, **43**, e52. https://doi.org/10.26633/rpsp.2019.52

102. Resiere, D., R. Valentino, R. Nevière, R. Banydeen, P. Gueye, J. Florentin, A. Cabié, T. Lebrun, B. Mégarbane, G. Guerrier, and H. Mehdaoui, 2018: Sargassum seaweed on Caribbean islands: An international public health concern. *The Lancet*, **392** (10165), 2691. https://doi.org/10.1016/s0140-6736(18)32777-6

103. Rodríguez-Martínez, R.E., A.E. Medina-Valmaseda, P. Blanchon, L.V. Monroy-Velázquez, A. Almazán-Becerril, B. Delgado-Pech, L. Vásquez-Yeomans, V. Francisco, and M.C. García-Rivas, 2019: Faunal mortality associated with massive beaching and decomposition of pelagic Sargassum. *Marine Pollution Bulletin*, **146**, 201–205. https://doi.org/10.1016/j.marpolbul.2019.06.015

104. López-Sosa, L.B., J.J. Alvarado-Flores, J.C. Corral-Huacuz, A. Aguilera-Mandujano, R.E. Rodríguez-Martínez, S.J. Guevara-Martínez, J.V. Alcaraz-Vera, J.G. Rutiaga-Quiñones, J. Zárate-Medina, M.L. Ávalos-Rodríguez, and M. Morales-Máximo, 2020: A prospective study of the exploitation of pelagic Sargassum spp. as a solid biofuel energy source. *Applied Sciences*, **10** (23), 8706. https://doi.org/10.3390/app10238706

105. Tejada-Tejada, P., Y. Rodríguez-Rodríguez, L.E. Rodríguez de Francisco, O. Paino-Perdomo, and C.J. Boluda, 2021: Lead, chromium, nickel, copper and zinc levels in Sargassum species reached the coasts of the Dominican Republic during 2019: A preliminary evaluation for the use of algal biomass as fertilizer and animal feeding. *Technology And Water Sciences*, **12** (3), 124–163. https://doi.org/10.24850/j-tyca-2021-03-04

106. Thompson, T.M., B.R. Young, and S. Baroutian, 2020: Pelagic Sargassum for energy and fertiliser production in the Caribbean: A case study on Barbados. *Renewable and Sustainable Energy Reviews*, **118**, 109564. https://doi.org/10.1016/j.rser.2019.109564

107. Lloréns, H., 2021: Toxic racism in Puerto Rico's Sacrifice Zone. *NACLA Report on the Americas*, **53** (3), 275–280. https://doi.org/10.1080/10714839.2021.1961447

108. Domonoske, C., 2017: With bottles and buckets, Puerto Ricans seek the water to survive. *NPR*, September 27, 2017. https://www.npr.org/sections/thetwo-way/2017/09/27/553898689/with-bottles-and-buckets-puerto-ricans-seek-the-water-to-survive

109. Jiang, S.C., M. Han, S. Chandrasekaran, Y. Fang, and C.A. Kellogg, 2020: Assessing the water quality impacts of two Category-5 hurricanes on St. Thomas, Virgin Islands. *Water Research*, **171**, 115440. https://doi.org/10.1016/j.watres.2019.115440

110. Lin, Y., M. Sevillano-Rivera, T. Jiang, G. Li, I. Cotto, S. Vosloo, C.M.G. Carpenter, P. Larese-Casanova, R.W. Giese, D.E. Helbling, I.Y. Padilla, Z. Rosario-Pabón, C. Vélez Vega, J.F. Cordero, A.N. Alshawabkeh, A. Pinto, and A.Z. Gu, 2020: Impact of Hurricane Maria on drinking water quality in Puerto Rico. *Environmental Science & Technology*, **54** (15), 9495–9509. https://doi.org/10.1021/acs.est.0c01655

111. Schnall, A.H., J. Roth, B. Ellis, K. Seger, M. Davis, and E.M. Ellis, 2019: Addressing community needs during the hurricane response and recovery efforts through community assessments for public health emergency response (CASPER)—United States Virgin Islands, 2017–2018. *Disaster Medicine and Public Health Preparedness*, **13** (1), 53–62. https://doi.org/10.1017/dmp.2019.6

112. Cruz-Cano, R. and E.L. Mead, 2019: Causes of excess deaths in Puerto Rico after Hurricane Maria: A time-series estimation. *American Journal of Public Health*, **109** (7), 1050–1052. https://doi.org/10.2105/ajph.2019.305015

113. Marazzi, M., B. Miloucheva, and G.J. Bobon, 2021: Displacement and Mortality After a Disaster: Deaths of Puerto Ricans in the United States Post-Hurricane Maria. Working Paper 710. University of Toronto, Department of Economics. https://econpapers.repec.org/paper/tortecipa/tecipa-710.htm

114. PR DOH, 2022: Perfil Epidemiológico de la Mortalidad en Puerto Rico Años 2015–2022. Puerto Rico Department of Health. https://www.salud.pr.gov/CMS/DOWNLOAD/7323

115. Santos-Burgoa, C., A. Goldman, Andrade E., N. Barrett, U. Colon-Ramos, M. Edberg, A. Garcia-Meza, L. Goldman, A. Roess, J. Sandberg, and S. Zeger, 2018: Project Report: Ascertainment of the Estimated Excess Mortality from Hurricane María in Puerto Rico. George Washington University, Milken Institute School of Public Health. https://publichealth.gwu.edu/sites/g/files/zaxdzs4586/files/2023-06/acertainment-of-the-estimated-excess-mortality-from-hurricane-maria-in-puerto-rico.pdf

116. Barbier, E.B., 2016: The protective value of estuarine and coastal ecosystem services in a wealth accounting framework. *Environmental and Resource Economics*, **64** (1), 37–58. https://doi.org/10.1007/s10640-015-9931-z

117. Leemans, R. and R.S. de Groot, 2003: *Ecosystems and Human Well-Being: A Framework for Assessment. Millennium Ecosystem Assessment.* Island Press, Washington, DC. http://pdf.wri.org/ecosystems_human_wellbeing.pdf

118. Barreto-Orta, M., R. Méndez-Tejeda, E. Rodríguez, N. Cabrera, E. Díaz, and K. Pérez, 2019: State of the beaches in Puerto Rico after Hurricane Maria (2017). *Shore & Beach*, **87** (1). https://asbpa.org/publications/shore-and-beach/shore-beach-vol-87-no-1-winter-2019-abstracts/

119. Cox, D., T. Arikawa, A. Barbosa, G. Guannel, D. Inazu, A. Kennedy, Y. Li, N. Mori, K. Perry, D. Prevatt, D. Roueche, T. Shimozono, C. Simpson, E. Shimakawa, T. Shimura, and R. Slocum, 2019: Hurricanes Irma and Maria post-event survey in US Virgin Islands. *Coastal Engineering Journal*, **61** (2), 121–134. https://doi.org/10.1080/21664250.2018.1558920

120. Mendez-Tejeda, R., K.A. Pérez-Valentín, and M. Barreto-Orta, 2020: Impact of extreme weather events on the beaches of Puerto Rico: The case of Ocean Park, San Juan. *American Journal of Marine Science*, **8** (1), 1–5. https://doi.org/10.12691/marine-8-1-1

121. OCM, 2017: Shoreline Mileage of the United States. National Oceanic and Atmospheric Administration, National Ocean Service, Office for Coastal Management. https://coast.noaa.gov/data/docs/states/shorelines.pdf

122. Gochfeld, D.J., J.B. Olson, A. Chaves-Fonnegra, T.B. Smith, R.S. Ennis, and M.E. Brandt, 2020: Impacts of Hurricanes Irma and Maria on coral reef sponge communities in St. Thomas, U.S. Virgin Islands. *Estuaries and Coasts*, **43** (5), 1235–1247. https://doi.org/10.1007/s12237-020-00694-4

123. Toledo-Hernandez, C., C. Ruiz-Diaz, E. Hernandez, and S. Suleimán-Ramos, 2018: Devastation of 15-year old community-based coral farming and reef-restoration sites in Puerto Rico by major Hurricanes Irma and María. *Caribbean Naturalist*, **53**, 1–6. https://www.eaglehill.us/CANAonline/CANA-access-pages/CANA-regular/CANA-053-Toledo-Hernandez.shtml

124. Viehman, T.S., M. Nemeth, S.H. Groves, C.A. Buckel, S. Griffin, D. Field, T.D. Moore, and J. Moore, 2020: Coral Assessment and Restoration in the U.S. Caribbean After 2017 Hurricanes. NOAA Technical Memorandum NOS NCCOS ; 278. National Oceanic and Atmospheric Administration, National Ocean Service and National Marine Fisheries Service. https://doi.org/10.25923/7r0b-wc52

125. Browning, T.N., D.E. Sawyer, G.R. Brooks, R.A. Larson, C.E. Ramos-Scharrón, and M. Canals-Silander, 2019: Widespread deposition in a coastal bay following three major 2017 hurricanes (Irma, Jose, and Maria). *Scientific Reports*, **9** (1), 7101. https://doi.org/10.1038/s41598-019-43062-4

126. Pérez Valentín, J.M. and M.F. Müller, 2020: Impact of Hurricane Maria on beach erosion in Puerto Rico: Remote sensing and causal inference. *Geophysical Research Letters*, **47** (6), e2020GL087306. https://doi.org/10.1029/2020gl087306

127. Bendik, K., A.C. Seymour, and K.S. Doran, 2021: Coastal Cliff Top and Toe Delineation Derived from Lidar for Puerto Rico: 2018. U.S. Geological Survey. https://doi.org/10.5066/f7610xcx

128. Cartier, K.M.S., 2019: Hurricanes hit Puerto Rico's mangroves harder than Florida's. *Eos*, **100**. https://doi.org/10.1029/2019eo137889

129. EPA, 2017: Multi-Model Framework for Quantitative Sectoral Impacts Analysis: A Technical Report for the Fourth National Climate Assessment. EPA 430-R-17-001. U.S. Environmental Protection Agency, Washington, DC. https://www.epa.gov/cira/multi-model-framework-quantitative-sectoral-impacts-analysis

130. Storlazzi, C.D., B.G. Reguero, A.D. Cole, E. Lowe, J.B. Shope, A.E. Gibbs, B.A. Nickel, R.T. McCall, A.R. van Dongeren, and M.W. Beck, 2019: Rigorously Valuing the Role of U.S. Coral Reefs in Coastal Hazard Risk Reduction. USGS Open-File Report 2019–1027. U.S. Geological Survey, Reston, VA, 42 pp. https://doi.org/10.3133/ofr20191027

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

132. Oliver, L.M., W.S. Fisher, L. Fore, A. Smith, and P. Bradley, 2018: Assessing land use, sedimentation, and water quality stressors as predictors of coral reef condition in St. Thomas, U.S. Virgin Islands. *Environmental Monitoring and Assessment*, **190**, 213. https://doi.org/10.1007/s10661-018-6562-1

133. Takesue, R.K., C. Sherman, N.I. Ramirez, A.O. Reyes, O.M. Cheriton, R.V. Ríos, and C.D. Storlazzi, 2021: Land-based sediment sources and transport to southwest Puerto Rico coral reefs after Hurricane Maria, May 2017 to June 2018. *Estuarine, Coastal and Shelf Science*, **259**, 107476. https://doi.org/10.1016/j.ecss.2021.107476

134. Smith, A., S.H. Yee, M. Russell, J. Awkerman, and W.S. Fisher, 2017: Linking ecosystem service supply to stakeholder concerns on both land and sea: An example from Guánica Bay watershed, Puerto Rico. *Ecological Indicators*, **74**, 371–383. https://doi.org/10.1016/j.ecolind.2016.11.036

135. Myers, B., 2019: Drought in the U.S. Caribbean: Impacts on Freshwater Ecosystems. U.S. Department of Agriculture, Caribbean Climate Hub, 2 pp. https://doi.org/10.32747/2019.6886313.ch

136. Gonzalez, G., E. Marín-Spiotta, and M. Matos, 2020: Appendix A: Regional summaries, Caribbean. In: *Forest and Rangeland Soils of the United States Under Changing Conditions*. Pouyat, R.V., D.S. Page-Dumroese, T. Patel-Weynand, and L. Geiser, Eds. Springer Cham, 217–229. https://doi.org/10.1007/978-3-030-45216-2

137. Mau, A.C., S.C. Reed, T.E. Wood, and M.A. Cavaleri, 2018: Temperate and tropical forest canopies are already functioning beyond their thermal thresholds for photosynthesis. *Forests*, **9** (1), 47. https://doi.org/10.3390/f9010047

138. Wood, T.E., M.A. Cavaleri, C.P. Giardina, S. Khan, J. Mohan, A.T. Nottingham, S. Reed, and M. Slot, 2019: Ch. 14. Soil warming effects on tropical forests with highly weathered soils. In: *Ecosystem Consequences of Soil Warming: Microbes, Vegetation, Fauna and Soil Biogeochemistry*. Academic Press, 385–439. https://doi.org/10.1016/b978-0-12-813493-1.00015-6

139. Wood, T.E., M. Detto, and W.L. Silver, 2013: Sensitivity of soil respiration to variability in soil moisture and temperature in a humid tropical forest. *PLoS ONE*, **8** (12), 80965. https://doi.org/10.1371/journal.pone.0080965

140. Zimmerman, J.K., T.E. Wood, G. González, A. Ramirez, W.L. Silver, M. Uriarte, M.R. Willig, R.B. Waide, and A.E. Lugo, 2021: Disturbance and resilience in the Luquillo Experimental Forest. *Biological Conservation*, **253**, 108891. https://doi.org/10.1016/j.biocon.2020.108891

141. Zimmerman, J.K., M.R. Willig, and E.A. Hernández-Delgado, 2020: Resistance, resilience, and vulnerability of social-ecological systems to hurricanes in Puerto Rico. *Ecosphere*, **11** (10), 03159. https://doi.org/10.1002/ecs2.3159

142. Fitzpatrick, S.M. and C.M. Giovas, 2021: Tropical islands of the Anthropocene: Deep histories of anthropogenic terrestrial–marine entanglement in the Pacific and Caribbean. *Proceedings of the National Academy of Sciences of the United States of America*, **118** (40), e2022209118. https://doi.org/10.1073/pnas.2022209118

143. Coleman-Jensen, A., M.P. Rabbitt, C.A. Gregory, and A. Singh, 2016: Household Food Security in the United States in 2015. ERR-215. U.S. Department of Agriculture, Economic Research Service. https://www.ers.usda.gov/publications/pub-details/?pubid=79760

144. Coleman-Jensen, A., M.P. Rabbitt, C.A. Gregory, and A. Singh, 2018: Household Food Security in the United States in 2017. ERR-256. U.S. Department of Agriculture, Economic Research Service. https://www.ers.usda.gov/publications/pub-details/?pubid=90022

145. Santiago-Torres, M., E.M. Román Meléndez, I.R. Rodríguez Ayuso, and Z.L. Ríos Vázquez, 2019: Seguridad Alimentaria en Puerto Rico. Instituto de Estadísticas de Puerto Rico, 51 pp. https://estadisticas.pr/files/Comunicados/Seguridad%20Alimentaria%20en%20Puerto%20Rico%20-%20Final%20%28300519%29.pdf

146. Keith-Jennings, B. and W. Wolkomir, 2020: How Does Household Food Assistance in Puerto Rico Compare to the Rest of the United States? Center on Budget and Policy Priorities, Washington, DC, 16 pp. https://www.cbpp.org/research/food-assistance/how-does-household-food-assistance-in-puerto-rico-compare-to-the-rest-of

147. Diaz, I.I. and C. Hunsberger, 2018: Can agroecological coffee be part of a food sovereignty strategy in Puerto Rico? *Geoforum*, **97**, 84–94. https://doi.org/10.1016/j.geoforum.2018.10.016

148. Gould, W.A., S.J. Fain, I.K. Pares, K. McGinley, A. Perry, and R.F. Steele, 2015: Caribbean Regional Climate Sub Hub Assessment of Climate Change Vulnerability and Adaptation and Mitigation Strategies. U.S. Department of Agriculture, 67 pp. https://www.fs.usda.gov/detail/iitf/research/?cid=fseprd505760

149. Harmsen, E. and R.H. Harmsen, 2019: Agricultural water management and Puerto Rico's food insecurity. Special publication I 2019–2020. *Ethos Gubernamental*. https://issuu.com/eticapr/docs/ethosart_agriculturalwatermanagement_and_pr_foodin

150. Meléndez-Ayala, I. and A. Kennedy, 2021: How the U.S. dictates what Puerto Rico eats. *The New York Times*, October 1, 2021. https://www.nytimes.com/2021/10/01/opinion/puerto-rico-jones-act.html

151. Marrero, A. and J. Mattei, 2022: Reclaiming traditional, plant-based, climate-resilient food systems in small islands. *The Lancet Planetary Health*, **6** (2), e171–e179. https://doi.org/10.1016/s2542-5196(21)00322-3

152. Álvarez-Berríos, N.L., S. Soto-Bayó, E. Holupchinski, S.J. Fain, and W.A. Gould, 2018: Correlating drought conservation practices and drought vulnerability in a tropical agricultural system. *Renewable Agriculture and Food Systems*, **33** (3), 279–291. https://doi.org/10.1017/s174217051800011x

153. Statista, 2022: Puerto Rico: Distribution of Gross Domestic Product (GDP) Across Economic Sectors from 2010 to 2020 [Webpage]. https://www.statista.com/statistics/397789/puerto-rico-gdp-distribution-across-economic-sectors/

154. NASS, 2019: 2017 Census of Agriculture: United States Summary and State Data. AC-17-A-51. U.S. Department of Agriculture, National Agricultural Statistics Service. https://www.nass.usda.gov/publications/agcensus/2017/index.php

155. Ortiz-Colón, G., 2011: Impacto Sobre la Producción Agrícola y Prácticas de Adaptación: La Industria Lechera de Puerto Rico Frente al Cambio Climático. Guía Curricular del Servicio de Extensión Agrícola.

156. Ortiz-Colón, G., S.J. Fain, I.K. Parés, J. Curbelo-Rodríguez, E. Jiménez-Cabán, M. Pagán-Morales, and W.A. Gould, 2018: Assessing climate vulnerabilities and adaptive strategies for resilient beef and dairy operations in the tropics. *Climatic Change*, **146** (1), 47–58. https://doi.org/10.1007/s10584-017-2110-1

157. Iowa State University Food Systems Team, 2020: Virgin Islands Community Food Systems Snapshot. Iowa State University, 35 pp. https://www.extension.iastate.edu/ffed/wp-content/uploads/2020-Final-USVI-Snapshot_red.pdf

158. USVI Division of Economic Research, 2020: USVI's United States and Foreign Imports Annual 2019 Trade Data Report. USVI Office of Management & Budget, Division of Economic Research. https://usviber.org/wp-content/uploads/2022/07/food-imports-report-2019-2.pdf

159. NASS, 2020: Quick Stats. U.S. Department of Agriculture, National Agricultural Statistics Service. https://quickstats.nass.usda.gov/

160. NASS, 2020: 2017 Census of Agriculture—U.S. Virgin Islands Agriculture: Results from the 2018 Census of Agriculture. U.S. Department of Agriculture, National Agricultural Statistics Service. https://www.nass.usda.gov/publications/highlights/2020/census-virginislands.pdf

161. Molina-Rivera, W.L. and M.M. Irizarry-Ortiz, 2021: Estimated Water Withdrawals and Use in Puerto Rico, 2015. USGS Open-File Report 2021-1060. U.S. Geological Survey, 38 pp. https://doi.org/10.3133/ofr20211060

162. Quiñones, F., 2016: Recursos de Agua de Puerto Rico [Webpage]. https://recursosaguapuertorico.com/

163. Ramos-Gines, O., 1994: Effects of Changing Irrigation Practices on the Ground-Water Hydrology of the Santa Isabel-Juana Díaz Area, South Central Puerto Rico. Water-Resources Investigations Report 91-4183. U.S. Geological Survey, Puerto Rico, 22 pp. https://doi.org/10.3133/wri914183

164. Rodríguez, J.M., 2013: Evaluation of Groundwater Quality and Selected Hydrologic Conditions in the South Coast Aquifer, Santa Isabel Area, Puerto Rico, 2008–09. Scientific Investigations Report 2012-5254. U. S. Geological Survey, Reston, VA, 38 pp. https://doi.org/10.3133/sir20125254

165. Torres-Gonzalez, S. and J.M. Rodriguez, 2016: Hydrologic Conditions in the South Coast Aquifer, Puerto Rico, 2010–15. USGS Open-File Report 2015-1215. U.S. Geological Survey, Reston, VA, 32 pp. https://doi.org/10.3133/ofr20151215

166. Eisenhauer, D.E., D.L. Martin, D.M. Heeren, and G.J. Hoffman, 2021: *Irrigation Systems Management*, 1st ed. American Society of Agricultural and Biological Engineers. https://doi.org/10.13031/ism.2021

167. Martinez, O., M. Muth, W.A. Gould, N.L. Álvarez-Berríos, E. Holupchinski, L.A. Rodriguez-Cruz, B. Rippey, and H.J. Jiménez, 2022: Drought Update for Puerto Rico and the U.S. Virgin Islands. National Integrated Drought Information System. https://www.drought.gov/drought-status-updates/drought-update-puerto-rico-and-us-virgin-islands-4-7-22

168. McGinley, K.A., W.A. Gould, N.L. Álvarez-Berríos, E. Holupchinski, and T. Díaz-Camacho, 2022: Ready or not? Hurricane preparedness, response, and recovery of farms, forests, and rural communities in the U.S. Caribbean. *International Journal of Disaster Risk Reduction*, **82** (2), 103346. https://doi.org/10.1016/j.ijdrr.2022.103346

169. Álvarez-Berríos, N.L., S.S. Wiener, K.A. McGinley, A.B. Lindsey, and W.A. Gould, 2021: Hurricane effects, mitigation, and preparedness in the Caribbean: Perspectives on high importance–low prevalence practices from agricultural advisors. *Journal of Emergency Management*, **19** (8), 135–155. https://doi.org/10.5055/jem.0585

170. Marrero, A., A. Lɒpez-Cepero, R. Borges-Méndez, and J. Mattei, 2022: Narrating agricultural resilience after Hurricane María: How smallholder farmers in Puerto Rico leverage self-sufficiency and collaborative agency in a climate-vulnerable food system. *Agriculture and Human Values*, **39** (2), 555–571. https://doi.org/10.1007/s10460-021-10267-1

171. Wiener, S.S., N.L. Álvarez-Berríos, and A.B. Lindsey, 2020: Opportunities and challenges for hurricane resilience on agricultural and forest land in the U.S. Southeast and Caribbean. *Sustainability*, **12** (4), 1364. https://doi.org/10.3390/su12041364

172. Herrera, D. and T. Ault, 2017: Insights from a new high-resolution drought atlas for the Caribbean spanning 1950–2016. *Journal of Climate*, **30** (19), 7801–7825. https://doi.org/10.1175/jcli-d-16-0838.1

173. Wang, R., L. Li, P. Gentine, Y. Zhang, J. Chen, X. Chen, L. Chen, L. Ning, L. Yuan, and G. Lü, 2022: Recent increase in the observation-derived land evapotranspiration due to global warming. *Environmental Research Letters*, **17** (2), 024020. https://doi.org/10.1088/1748-9326/ac4291

174. Mercado-Díaz, J.A., E. Holupchinski, N. Álvarez-Berríos, W.A. Gould, P. Miller, T. Mote, C. Ramseyer, and G. González, 2023: Fostering knowledge-exchange and collaboration among drought-related initiatives in the Caribbean. *Bulletin of the American Meteorological Society*, **104**, E1146–E1153. https://doi.org/10.1175/bams-d-23-0054.1

175. Bucheli, J., T. Dalhaus, and R. Finger, 2022: Temperature effects on crop yields in heat index insurance. *Food Policy*, **107**, 102214. https://doi.org/10.1016/j.foodpol.2021.102214

176. Tubiello, F.N., J.F. Soussana, and S.M. Howden, 2007: Crop and pasture response to climate change. *Proceedings of the National Academy of Sciences of the United States of America*, **104** (50), 19686–19690. https://doi.org/10.1073/pnas.0701728104

177. Wheeler, T.R., P.Q. Craufurd, R.H. Ellis, J.R. Porter, and P.V. Vara Prasad, 2000: Temperature variability and the yield of annual crops. *Agriculture, Ecosystems & Environment*, **82** (1), 159–167. https://doi.org/10.1016/s0167-8809(00)00224-3

178. Hatfield, J.L. and J.H. Prueger, 2015: Temperature extremes: Effect on plant growth and development. *Weather and Climate Extremes*, **10** (Part A), 4–10. https://doi.org/10.1016/j.wace.2015.08.001

179. Gowda, P., J.L. Steiner, C. Olson, M. Boggess, T. Farrigan, and M.A. Grusak, 2018: Ch. 10. Agriculture and rural communities. In: *Impacts, Risks, and Adaptation in the United States: Fourth National Climate Assessment, Volume II*. Reidmiller, D.R., C.W. Avery, D.R. Easterling, K.E. Kunkel, K.L.M. Lewis, T.K. Maycock, and B.C. Stewart, Eds. U.S. Global Change Research Program, Washington, DC, USA, 391–437. https://doi.org/10.7930/nca4.2018.ch10

180. Ziska, L., A. Crimmins, A. Auclair, S. DeGrasse, J.F. Garofalo, A.S. Khan, I. Loladze, A.A. Pérez de León, A. Showler, J. Thurston, and I. Walls, 2016: Ch. 7. Food safety, nutrition, and distribution. In: *The Impacts of Climate Change on Human Health in the United States: A Scientific Assessment*. U.S. Global Change Research Program, Washington, DC, 189–216. https://doi.org/10.7930/j0zp4417

181. El Khayat, M., D.A. Halwani, L. Hneiny, I. Alameddine, M.A. Haidar, and R.R. Habib, 2022: Impacts of climate change and heat stress on farmworkers' health: A scoping review. *Frontiers in Public Health*, **10**, 782811. https://doi.org/10.3389/fpubh.2022.782811

182. Smith, M.R. and S.S. Myers, 2018: Impact of anthropogenic CO_2 emissions on global human nutrition. *Nature Climate Change*, **8** (9), 834–839. https://doi.org/10.1038/s41558-018-0253-3

183. Harmsen, E.W., N.L. Adames, and N.R. Maldonado, 2022: Gridded aquifer recharge estimates for the Puerto Rico south coast aquifer. In: *American Geophysical Union (AGU) 2022 Annual Meeting, Frontiers in Hydrology*. San Juan, PR, 21 June 2022. https://pragwater.com/selected-publications-and-presentations/

184. Irizarry-Ortiz, M. and E.W. Harmsen, 2023: Sensitivity of the Penman–Monteith reference evapotranspiration equation to meteorological variables for Puerto Rico. *Hydrology*, **10** (5), 101. https://doi.org/10.3390/hydrology10050101

185. Moraes, F.D.S., C. Ramseyer, and D. Gamble, 2023: The effects of projected climate change on crop water availability in the U.S. Caribbean. *Journal of Water and Climate Change*, **14** (4), 1176–1191. https://doi.org/10.2166/wcc.2023.398

186. Jhajharia, D., R. Kumar, P.P. Dabral, V.P. Singh, R.R. Choudhary, and Y. Dinpashoh, 2015: Reference evapotranspiration under changing climate over the Thar Desert in India. *Meteorological Applications*, **22** (3), 425–435. https://doi.org/10.1002/met.1471

187. Girija Veni, V., C. Srinivasarao, K. Sammi Reddy, K.L. Sharma, and A. Rai, 2020: Ch. 26. Soil health and climate change. In: *Climate Change and Soil Interactions*. Prasad, M.N.V. and M. Pietrzykowski, Eds. Elsevier, 751–767. https://doi.org/10.1016/b978-0-12-818032-7.00026-6

188. Sharma, K.L., C.S. Rao, D.S. Chandrika, M. Lal, K. Srinivas, K.S. Reddy, and A.K. Indoria, 2016: Effect of 13 years long minimum tillage cum conjunctive nutrient management practices on soil fertility and nitrogen chemical fractions under sorghum (*Sorghum bicolour* (L.) Moench)–mungbean (*Vigna radiata* (L.) Wilczek) system in semi-arid tropical Alfisol (SAT) in southern India. *Communications in Soil Science and Plant Analysis*, **47** (18), 2059–2068. https://doi.org/10.1080/00103624.2016.1225083

189. Zagal, E., C. Muñoz, M. Quiroz, and C. Córdova, 2009: Sensitivity of early indicators for evaluating quality changes in soil organic matter. *Geoderma*, **151** (3), 191–198. https://doi.org/10.1016/j.geoderma.2009.04.004

190. Chessman, D., B.N. Moebius-Clune, B.R. Smith, B. Fisher, 2019: The Basics of Addressing Resource Concerns with Conservation Practices within Integrated Management Systems on Cropland. Soil Health Technical Note No. 450-04. U.S. Department of Agriculture, Natural Resources Conservation Service. https://directives.sc.egov.usda.gov/opennonwebcontent.aspx?content=44293.wba

191. Porch, T.G., J.S. Beaver, and M.A. Brick, 2013: Registration of tepary germplasm with multiple-stress tolerance, TARS-Tep 22 and TARS-Tep 32. *Journal of Plant Registrations*, **7** (3), 358–364. https://doi.org/10.3198/jpr2012.10.0047crg

192. Cabrera, I., E.W. Harmsen, and A. Vélez, 2019: The effect of shade houses on the insect pests and yield of three important plant crops in Puerto Rico: Pepper, *Capsicum annuum* (Solanaceae), watermelon, *Citrullus lanatus* (Cucurbitaceae), and cabbage, *Brassica oleracea* (Brassicaceae). *Life: The Excitement of Biology*, **7** (1), 5–21. https://doi.org/10.9784/leb7(1)cabrera.01

193. Mathanker, S., 2021: A precision agriculture technology course for regions with lower technology adoption levels. *Applied Engineering in Agriculture*, **37** (5), 871–877. https://doi.org/10.13031/aea.14669

194. Harmsen, E.W., 2012: A simple web-based method for scheduling irrigation in Puerto Rico. *The Journal of Agriculture of the University of Puerto Rico*, **96** (3-4), 235–243. https://revistas.upr.edu/index.php/jaupr/article/view/3171/2692

195. Harmsen, E.W., 2018: Ch. 1. Simple spreadsheet method for scheduling irrigation. In: *Technological Interventions in Management of Irrigated Agriculture*. Apple Academic Press, 15. https://doi.org/10.1201/9781315204307-1

196. Mecikalski, J.R. and E.W. Harmsen, 2019: The use of visible Geostationary Operational Meteorological Satellite imagery in mapping the water balance over Puerto Rico for water resource management. In: *Satellite Information Classification and Interpretation*. Rustamov, R.B., Ed. IntechOpen. https://doi.org/10.5772/intechopen.82460

197. Mejia Manrique, S.A., E.W. Harmsen, R.M. Khanbilvardi, and J.E. González, 2021: Flood impacts on critical infrastructure in a coastal floodplain in western Puerto Rico during Hurricane María. *Hydrology*, **8** (3), 104. https://doi.org/10.3390/hydrology8030104

198. Lim, Y.-K., S.D. Schubert, R. Kovach, A.M. Molod, and S. Pawson, 2018: The roles of climate change and climate variability in the 2017 Atlantic hurricane season. *Scientific Reports*, **8** (1), 16172. https://doi.org/10.1038/s41598-018-34343-5

199. Culbertson, S., B. Nunez-Neto, J.D. Acosta, C.R. Cook, A. Lauland, K.J. Leuschner, S. Nataraj, B.L. Preston, S.A. Resetar, A.C. Resnick, P.S. Roberts, and H.J. Shatz, 2020: Recovery in the U.S. Virgin Islands: Progress, Challenges, and Options for the Future. RR-A282-1. Homeland Security Operational Analysis Center, RAND Corporation, Santa Monica, CA, 384 pp. https://doi.org/10.7249/rra282-1

200. USVI Task Force Advisory Committee, 2018: USVI Hurricane Recovery and Resilience Task Force. Government of the U.S. Virgin Islands, St. Thomas, USVI. https://cfvi.net/wp-content/uploads/2019/05/USVI_HurricaneRecoveryTaskforceReport_DIGITAL.pdf

201. Alderson, D.L., 2019: Ch. 5. Overcoming barriers to greater scientific understanding of critical infrastructure resilience. In: *Handbook on Resilience of Socio-Technical Systems*. Matthias Ruth and S. Goessling-Reisemann, Eds. Edward Elgar Publishing, 66–88. https://doi.org/10.4337/9781786439376.00010

202. Helmrich, A., S. Markolf, R. Li, T. Carvalhaes, Y. Kim, E. Bondank, M. Natarajan, N. Ahmad, and M. Chester, 2021: Centralization and decentralization for resilient infrastructure and complexity. *Environmental Research: Infrastructure and Sustainability*, **1** (2), 021001. https://doi.org/10.1088/2634-4505/ac0a4f

203. O'Neill-Carrillo, E. and M.A. Rivera-Quinones, 2018: Energy policies in Puerto Rico and their impact on the likelihood of a resilient and sustainable electric power infrastructure. *CENTRO: Journal of the Center for Puerto Rican Studies*, **30** (3), 147–171. https://go.gale.com/ps/i.do?id=GALE%7CA581024268&sid=googleScholar&v=2.1&it=r&linkaccess=abs&issn=15386279&p=AONE&sw=w

204. Puerto Rico Climate Change Council, 2013: Puerto Rico State of the Climate 2010–2013: Assessing Puerto Rico's Social-Ecological Vulnerabilities in a Changing Climate. Puerto Rico Coastal Zone Management Program, Department of Natural and Environmental Resources, NOAA Office of Ocean and Coastal Resource Management, San Juan, PR. http://www.adaptationclearinghouse.org/resources/puerto-rico-state-of-the-climate-2010-2013-assessing-puerto-rico-eys-social-ecological-vulnerabilities-in-a-changing-climate.html

205. Seager, T.P., S.S. Clark, D.A. Eisenberg, J.E. Thomas, M.M. Hinrichs, R. Kofron, C.N. Jensen, L.R. McBurnett, M. Snell, and D.L. Alderson, 2017: Ch. 3. Redesigning resilient infrastructure research. In: *Resilience and Risk*. Linkov, I. and J.M. Palma-Oliveira, Eds. Springer, Dordrecht, Netherlands, 81–119. https://doi.org/10.1007/978-94-024-1123-2_3

206. Kossin, J.P., 2018: A global slowdown of tropical-cyclone translation speed. *Nature*, **558** (7708), 104–107. https://doi.org/10.1038/s41586-018-0158-3

207. Sadler, J.M., J.L. Goodall, M. Behl, B.D. Bowes, and M.M. Morsy, 2020: Exploring real-time control of stormwater systems for mitigating flood risk due to sea level rise. *Journal of Hydrology*, **583**, 124571. https://doi.org/10.1016/j.jhydrol.2020.124571

208. Shen, Y., M.M. Morsy, C. Huxley, N. Tahvildari, and J.L. Goodall, 2019: Flood risk assessment and increased resilience for coastal urban watersheds under the combined impact of storm tide and heavy rainfall. *Journal of Hydrology*, **579**, 124159. https://doi.org/10.1016/j.jhydrol.2019.124159

209. Vosper, E.L., D.M. Mitchell, and K. Emanuel, 2020: Extreme hurricane rainfall affecting the Caribbean mitigated by the Paris Agreement goals. *Environmental Research Letters*, **15**, 104053. https://doi.org/10.1088/1748-9326/ab9794

210. Guannel, G., N. Beck, J. Dwyer, J. Buchanan, G. Bove, and T. Hamlin, 2022: U.S. Virgin Island Coastal Vulnerability Index. University of the Virgin Islands, Caribbean Green Technology Center, St. Thomas, USVI, 50 pp. https://dpnr.vi.gov/wp-content/uploads/2023/05/Coastal-Vulnerability-Index-for-the-USVI.pdf

211. Campbell, J.D., M.A. Taylor, A. Bezanilla-Morlot, T.S. Stephenson, A. Centella-Artola, L.A. Clarke, and K.A. Stephenson, 2021: Generating projections for the Caribbean at 1.5, 2.0 and 2.5 °C from a high-resolution ensemble. *Atmosphere*, **12** (3), 328. https://doi.org/10.3390/atmos12030328

212. FEMA, 2021: *Effects of Saltwater Intrusion in Puerto Rico [Video]*. U.S. Department of Homeland Security, Federal Emergency Management Agency. https://groundwateru.org/effects-of-saltwater-intrusion-in-puerto-rico/

213. USGS, 2016: Puerto Rico and the U.S. Virgin Islands regional summary. In: *Ground Water Atlas of the United States*. U.S. Geological Survey. https://pubs.usgs.gov/ha/ha730/ch_n/N-PR_VItext1.html

214. EPA, 2019: TRI Explorer: 2019 TRI Factsheet: City—Guayama, PR. U.S. Environmental Protection Agency. https://enviro.epa.gov/triexplorer/tri_factsheet.factsheet?pzip=&pstate=PR&pcity=GUAYAMA&pcounty=&pyear=%202019&pParent=TRI&pDataSet=TRIQ1

215. DRNA, 2019: Programas y Proyectos—Zona Costanera. Departamento de Recursos Naturales y Ambientales, San Juan, PR. https://www.drna.pr.gov/cat/programas-y-proyectos/zona-costanera/

216. PRDOH, 2023: CDBG-MIT Action Plan Amendment 2 (Substantial). Puerto Rico Department of Housing. https://cdbg-dr.pr.gov/en/download/cdbg-mit-action-plan-amendment-2-substantial/

217. Burillo, D., M. Chester, and B. Ruddell, 2017: Power system planning and operation across multiple coincident non-stationary temperature futures. In: *International Conference on Sustainable Infrastructure*. American Society of Civil Engineers, 293–302. https://doi.org/10.1061/9780784481196.026

218. Hughes, J., K. Cowper-Heays, E. Olesson, R. Bell, and A. Stroombergen, 2021: Impacts and implications of climate change on wastewater systems: A New Zealand perspective. *Climate Risk Management*, **31**, 100262. https://doi.org/10.1016/j.crm.2020.100262

219. Brinton, A., D.C. Diehl, T.G. Townsend, K. Deliz Quiñones, and M.M. Lichtenstein, 2022: Trees, trash, and hurricanes: The case study of Puerto Rico and vegetative disaster debris management after Hurricanes Irma and Maria. *International Journal of Disaster Risk Reduction*, **82**, 103298. https://doi.org/10.1016/j.ijdrr.2022.103298

220. Brown, C., M. Milke, and E. Seville, 2011: Disaster waste management: A review article. *Waste Management*, **31** (6), 1085–1098. https://doi.org/10.1016/j.wasman.2011.01.027

221. Romanello, M., A. McGushin, C. Di Napoli, P. Drummond, N. Hughes, L. Jamart, H. Kennard, P. Lampard, B. Solano Rodriguez, N. Arnell, S. Ayeb-Karlsson, K. Belesova, W. Cai, D. Campbell-Lendrum, S. Capstick, J. Chambers, L. Chu, L. Ciampi, C. Dalin, N. Dasandi, S. Dasgupta, M. Davies, P. Dominguez-Salas, R. Dubrow, K.L. Ebi, M. Eckelman, P. Ekins, L.E. Escobar, L. Georgeson, D. Grace, H. Graham, S.H. Gunther, S. Hartinger, K. He, C. Heaviside, J. Hess, S.-C. Hsu, S. Jankin, M.P. Jimenez, I. Kelman, G. Kiesewetter, P.L. Kinney, T. Kjellstrom, D. Kniveton, J.K.W. Lee, B. Lemke, Y. Liu, Z. Liu, M. Lott, R. Lowe, J. Martinez-Urtaza, M. Maslin, L. McAllister, C. McMichael, Z. Mi, J. Milner, K. Minor, N. Mohajeri, M. Moradi-Lakeh, K. Morrissey, S. Munzert, K.A. Murray, T. Neville, M. Nilsson, N. Obradovich, M.O. Sewe, T. Oreszczyn, M. Otto, F. Owfi, O. Pearman, D. Pencheon, M. Rabbaniha, E. Robinson, J. Rocklöv, R.N. Salas, J.C. Semenza, J. Sherman, L. Shi, M. Springmann, M. Tabatabaei, J. Taylor, J. Trinanes, J. Shumake-Guillemot, B. Vu, F. Wagner, P. Wilkinson, M. Winning, M. Yglesias, S. Zhang, P. Gong, H. Montgomery, A. Costello, and I. Hamilton, 2021: The 2021 report of the Lancet Countdown on health and climate change: Code red for a healthy future. *The Lancet*, **398** (10311), 1619–1662. https://doi.org/10.1016/s0140-6736(21)01787-6

222. Ferrario, F., M.W. Beck, C.D. Storlazzi, F. Micheli, C.C. Shepard, and L. Airoldi, 2014: The effectiveness of coral reefs for coastal hazard risk reduction and adaptation. *Nature Communications*, **5** (1), 3794. https://doi.org/10.1038/ncomms4794

223. Lewsey, C., G. Cid, and E. Kruse, 2004: Assessing climate change impacts on coastal infrastructure in the Eastern Caribbean. *Marine Policy*, **28** (5), 393–409. https://doi.org/10.1016/j.marpol.2003.10.016

224. Narayan, S., M.W. Beck, B.G. Reguero, I.J. Losada, B. van Wesenbeeck, N. Pontee, J.N. Sanchirico, J.C. Ingram, G.-M. Lange, and K.A. Burks-Copes, 2016: The effectiveness, costs and coastal protection benefits of natural and nature-based defences. *PLoS ONE*, **11** (5), e0154735. https://doi.org/10.1371/journal.pone.0154735

225. Tomiczek, T., A. Wargula, N.R. Hurst, D.B. Bryant, and L.A. Provost, 2021: Engineering with Nature: The Role of Mangroves in Coastal Protection. ERDC/TN EWN-21-1. U.S. Army Corps of Engineers, Engineer Research and Development Center, 19 pp. https://doi.org/10.21079/11681/42420

226. Djakouré, S., M. Araujo, A. Hounsou-Gbo, C. Noriega, and B. Bourlès, 2017: On the potential causes of the recent Pelagic Sargassum blooms events in the tropical North Atlantic Ocean. *Biogeosciences Discussions*, 1–20. https://doi.org/10.5194/bg-2017-346

227. *Oversight Hearing on the Puerto Rico Electric Power Authority (Prepa) Postimplementation of the Luma Transmission and Distribution Contract, U.S. House of Representatives, Committee on Natural Resources*, 2021: United States Congress, One Hundred Seventeenth, First Session. https://www.congress.gov/event/117th-congress/house-event/114107

228. UNEP-CEP, 2021: Sargassum white paper–turning the crisis into an opportunity. In: *Ninth Meeting of the Scientific and Technical Advisory Committee (STAC) to the Protocol Concerning Specially Protected Areas and Wildlife (SPAW) in the Wider Caribbean Region*. Kingston, Jamaica. United Nations Environment Programme-Caribbean Environment Programme. https://www.unep.org/cep/resources/publication/sargassum-white-paper-turning-crisis-opportunity

229. USVI Office of the Governor, 2022: Executive Order No. 525-2022: Order and Proclamation by the Governor of the United States Virgin Islands Declaring State of Emergency in the United States Virgin Islands Due to Unprecedented Influx of Sargassum Seaweed Affecting the Territory Water Supply. U.S. Virgin Islands, Office of the Governor, Charlotte Amalie, VI. https://www.vi.gov/wp-content/uploads/2022/07/exo-523-2022-state-of-emergency-sargassum-2022-07.22.pdf

230. Fischbach, J.R., L. Warren May, K. Whipkey, S.R. Shelton, C.A. Vaughan, D. Tierney, K.J. Leuschner, L.S. Meredith, and H.J. Peterson, 2020: *After Hurricane Maria: Predisaster Conditions, Hurricane Damage, and Recovery Needs in Puerto Rico*. RAND Corporation, Santa Monica, CA. https://doi.org/10.7249/rr2595

231. Joseph, S.R., C. Voyles, K.D. Williams, E. Smith, and M. Chilton, 2020: Colonial neglect and the right to health in Puerto Rico after Hurricane Maria. *American Journal of Public Health*, **110** (10), 1512–1518. https://doi.org/10.2105/ajph.2020.305814

232. Park, J., T.P. Seager, P.S.C. Rao, M. Convertino, and I. Linkov, 2013: Integrating risk and resilience approaches to catastrophe management in engineering systems. *Risk Analysis*, **33** (3), 356–367. https://doi.org/10.1111/j.1539-6924.2012.01885.x

233. Woods, D.D., 2015: Four concepts for resilience and the implications for the future of resilience engineering. *Reliability Engineering & System Safety*, **141**, 5–9. https://doi.org/10.1016/j.ress.2015.03.018

234. Blondeau, J., M. Brandt, C. Donovan, M. Eakin, K. Edwards, K. Edwards, P. Edwards, I. Enochs, M. Feeley, C. Fleming, N. Formel, E. Geiger, M. Gorstein, J. Grove, S. Groves, L. Henderson, M. Hibbert, N. Holloway, M. Johnson, T. Kelley, H. Kelsey, J. Koss, D. Manzello, N. Miller, C. Pott, T. Smith, E. Towle, and S. Viehman, 2020: Coral Reef Condition: A Status Report for the U.S. Virgin Islands. National Oceanic Atmospheric Administration, Coral Reef Conservation Program. https://doi.org/10.25923/53gr-cn06

235. Roth, K., 2019: U.S. Climate Resilience Toolkit: Aquifer Storage and Recovery: A Strategy for Long-Term Water Security in Puerto Rico. U.S. Global Change Research Program. https://toolkit.climate.gov/case-studies/aquifer-storage-and-recovery-strategy-long-term-water-security-puerto-rico

236. Soanes, L.M., S. Pike, S. Armstrong, K. Creque, R. Norris-Gumbs, S. Zaluski, and K. Medcalf, 2021: Reducing the vulnerability of coastal communities in the Caribbean through sustainable mangrove management. *Ocean & Coastal Management*, **210**, 105702. https://doi.org/10.1016/j.ocecoaman.2021.105702

237. Akpinar Ferrand, E. and F. Cecunjanin, 2014: Potential of rainwater harvesting in a thirsty world: A survey of ancient and traditional rainwater harvesting applications. *Geography Compass*, **8** (6), 395–413. https://doi.org/10.1111/gec3.12135

238. Silva, A., M. Rosano, L. Stocker, and L. Gorissen, 2017: From waste to sustainable materials management: Three case studies of the transition journey. *Waste Management*, **61**, 547–557. https://doi.org/10.1016/j.wasman.2016.11.038

239. NASA, 2022: Responding to Climate Change. National Aeronautics and Space Administration, Jet Propulsion Laboratory, California Institute of Technology. https://climate.nasa.gov/solutions/adaptation-mitigation/

240. Pauliuk, S., N. Heeren, P. Berrill, T. Fishman, A. Nistad, Q. Tu, P. Wolfram, and E.G. Hertwich, 2021: Global scenarios of resource and emission savings from material efficiency in residential buildings and cars. *Nature Communications*, **12** (1), 5097. https://doi.org/10.1038/s41467-021-25300-4

241. Rothausen, S.G.S.A. and D. Conway, 2011: Greenhouse-gas emissions from energy use in the water sector. *Nature Climate Change*, **1** (4), 210–219. https://doi.org/10.1038/nclimate1147

242. Surana, K. and S.M. Jordaan, 2019: The climate mitigation opportunity behind global power transmission and distribution. *Nature Climate Change*, **9** (9), 660–665. https://doi.org/10.1038/s41558-019-0544-3

243. EPA, 2021: Power Plants and Neighboring Communities. U.S. Environmental Protection Agency. https://www.epa.gov/airmarkets/power-plants-and-neighboring-communities

244. Darghouth, N.R., E. O'Shaughnessy, S. Forrester, and G. Barbose, 2022: Characterizing local rooftop solar adoption inequity in the US. *Environmental Research Letters*, **17** (3), 034028. https://doi.org/10.1088/1748-9326/ac4fdc

245. Goldstein, B., T.G. Reames, and J.P. Newell, 2022: Racial inequity in household energy efficiency and carbon emissions in the United States: An emissions paradox. *Energy Research & Social Science*, **84**, 102365. https://doi.org/10.1016/j.erss.2021.102365

246. Adeh, E.H., S.P. Good, M. Calaf, and C.W. Higgins, 2019: Solar PV power potential is greatest over croplands. *Scientific Reports*, **9** (1), 11442. https://doi.org/10.1038/s41598-019-47803-3

247. Beller, W.S., P.G. D'Ayala, and P. Hein, 1990: Sustainable development and environmental management of small islands. In: *Man and the Biosphere Series*. UNESCO, 419. https://portals.iucn.org/library/taxonomy/term/36861

248. Robinson, S.-A., 2020: Climate change adaptation in SIDS: A systematic review of the literature pre and post the IPCC Fifth Assessment Report. *WIREs Climate Change*, **11** (4), e653. https://doi.org/10.1002/wcc.653

249. Jacobs, K.R., S.J. Fain, S. Henry, W. Archibald, and W.A. Gould, 2016: Synthesis of Climate Change Related Knowledge and Information in the United States Virgin Islands: An Institutional Analysis. Report for the U.S. Department of Interior, Office of Insular Affairs. U.S. Department of Agriculture, Caribbean Climate Hub, U.S. Forest Service, International Institute of Tropical Forestry, 177 pp. https://www.fs.usda.gov/detail/iitf/research/?cid=fseprd707155

250. Keenan, J.M. and M.E. Hauer, 2020: Resilience for whom? Demographic change and the redevelopment of the built environment in Puerto Rico. *Environmental Research Letters*, **15** (7), 074028. https://doi.org/10.1088/1748-9326/ab92c2

251. OCM, 2018: Final Evaluation Findings: U.S. Virgin Islands Coastal Management Program. National Oceanic and Atmospheric Administration, National Ocean Service, Office for Coastal Management. https://coast.noaa.gov/data/czm/media/usvi-cmp.pdf

252. Alderson, D.L., B.B. Bunn, D.A. Eisenberg, A.R. Howard, D.A. Nussbaum, and J. Templeton II, 2018: Interdependent Infrastructure Resilience in the U.S. Virgin Islands: Preliminary Assessment. NPS-OR-18-005. Naval Postgraduate School, Monterey, CA, 128 pp. https://faculty.nps.edu/dlalders/usvi/nps-or-18-005.pdf

253. Nunez-Neto, B., A. Lauland, J. Aguirre, G. Castro, I.A. Gutierrez, M. Lara, E. Rosas, and B.A. Weidmer, 2020: Municipalities on the Front Lines of Puerto Rico's Recovery: Assessing Damage, Needs, and Opportunities for Recovery After Hurricane Maria. RR-2604-DHS. RAND Corporation, Santa Monica, CA, 216 pp. https://doi.org/10.7249/rr2604

254. Santiago, L., M. Barreto, A. Montañez-Acuña, T. Flecha, N. Cabrera, V. Bonano, L.B. Marrero, and E. Díaz, 2021: A coastal vulnerability framework to guide natural infrastructure funds allocation in compressed time. *Environmental Management*, **67** (1), 67–80. https://doi.org/10.1007/s00267-020-01397-z

255. Puerto Rico Climate Change Mitigation, Adaptation, and Resilience Act. No. 33-2019, Government of Puerto Rico, May 22, 2019. https://bvirtualogp.pr.gov/ogp/Bvirtual/leyesreferencia/PDF/2-ingles/0033-2019.pdf

256. USVI Office of the Governor, 2015: Executive Order No. 474-2015: Preparing the Virgin Islands of the United States for Adapting to the Impacts of Climate Change. U.S. Virgin Islands, Office of the Governor, Charlotte Amalie, VI. https://www.fdpi.org/wp-content/uploads/2016/01/USVI-Climate-Change-Executive-Order_474-2015.pdf

257. Engelman, A., M.T. Guzzardo, M. Antolin Muñiz, L. Arenas, and A. Gomez, 2022: Assessing the emergency response role of community-based organizations (CBOs) serving people with disabilities and older adults in Puerto Rico post-Hurricane María and during the COVID-19 pandemic. *International Journal of Environmental Research and Public Health*, **19** (4), 2156. https://doi.org/10.3390/ijerph19042156

258. Filantropía Puerto Rico, 2022: Estudio Sobre el Impacto Económico y Social de las Organizaciones sin Fines de Lucro en Puerto Rico, 2022. Filantropía Puerto Rico, Inc. https://filantropiapr.org/estudio-sobre-el-impacto-economico-y-social-de-las-organizaciones-sin-fines-de-lucro-en-puerto-rico-2022/

259. Rivas, M., 2018: La respuesta al desastre y las organizaciones sin fines de lucro en Puerto Rico. *Revista De Administración Pública*, **49**, 39–65. https://revistas.upr.edu/index.php/ap/article/view/13778

260. Roque, A.D., D. Pijawka, and A. Wutich, 2020: The role of social capital in resiliency: Disaster recovery in Puerto Rico. *Risk, Hazards & Crisis in Public Policy*, **11** (2), 204–235. https://doi.org/10.1002/rhc3.12187

261. McKayle, C., G. Guannel, M. Taylor, and T. Stephenson, 2019: Climate Change Adaptation Planning Assessment and Implementation: Final Vulnerability and Risk Assessment Report. University of the Virgin Islands and University of the West Indies, Mona. https://www.doi.gov/sites/doi.gov/files/1.-usvi-climate-vulnerability-and-risk-assessment-report-final.pdf

262. Towe, V.L., E.L.P. Sayers, E.W. Chan, A.Y. Kim, A. Tom, W.Y. Chan, J.P. Marquis, M.W. Robbins, L. Saum-Manning, M.M. Weden, and L.A. Payne, 2020: Community Planning and Capacity Building in Puerto Rico After Hurricane Maria: Predisaster Conditions, Hurricane Damage, and Courses of Action. RAND Corporation, Homeland Security Operational Analysis Center. https://doi.org/10.7249/rr2598

263. Rudge, K., 2021: Changing climate, changing discourse: Analyzing reporting of climate change and economic development in the U.S. Virgin Islands. *Climate Risk Management*, **33**, 100350. https://doi.org/10.1016/j.crm.2021.100350

264. Díaz-García, R., M. Feliciano, A. Cases, and K. Ruiz-Serrano, 2021: Adulto Mayor 2019. División de Prevención y Control de Enfermedades Crónicas, Secretaría de Promoción para la Salud del Departamento de Salud de Puerto Rico. https://www.salud.pr.gov/CMS/DOWNLOAD/5543

265. Instituto del Desarrollo de la Juventud, 2021: Perfil de Niños, Niñas y Jóvenes Viviendo en Pobreza en Puerto Rico: 2021. Instituto del Desarrollo de la Juventud. https://assets.website-files.com/60f311e9e2e57d2e3028bb6f/615fab750b18ba319f0e9ed3_perfiledejovenesviviendoenpobreza.pdf

266. Lafarga Previdi, I. and C.M. Vélez Vega, 2020: Health Disparities Research Framework adaptation to reflect Puerto Rico's socio-cultural context. *International Journal of Environmental Research and Public Health*, **17** (22), 8544. https://doi.org/10.3390/ijerph17228544

267. Farber, D.A., 2018: Response and Recovery After Maria: Lessons for Disaster Law and Policy. UC Berkeley Public Law Research Paper. University of California, Berkeley. https://doi.org/10.2139/ssrn.3174466

268. Ma, C., A.C. Baker, and T.E. Smith, 2021: How income inequality influenced personal decisions on disaster preparedness: A multilevel analysis of homeowners insurance among Hurricane Maria victims in Puerto Rico. *International Journal of Disaster Risk Reduction*, **53**, 101953. https://doi.org/10.1016/j.ijdrr.2020.101953

269. Eckstein, D., V. Künzel, and L. Schäfer, 2021: *Who suffers Most from Extreme Weather Events? Weather-Related Loss Events in 2019 and 2000 to 2019. Global Climate Risk Index 2021.* Germanwatch, Berlin, Germany. https://www.germanwatch.org/en/19777

270. Migration Data Portal, 2021: Migration Data in the Caribbean. Global Migration Data Portal. https://www.migrationdataportal.org/regional-data-overview/migration-data-caribbean

271. Piguet, E., 2022: Linking climate change, environmental degradation, and migration: An update after 10 years. *WIREs Climate Change*, **13** (1), 746. https://doi.org/10.1002/wcc.746

272. Arrieta, A., S. Chen, J. Sarmiento, and R. Olson, 2021: Real-Time Migration Tracking to Puerto Rico after Natural Hazard Events. Natural Hazards Center Public Health Report Series, 4. University of Colorado Boulder, Natural Hazards Center, Boulder, CO. https://hazards.colorado.edu/public-health-disaster-research/real-time-migration-tracking-to-puerto-rico-after-natural-hazard-events

273. Chandrasekhar, D., I. García, and S. Khajehei, 2022: Recovery capacity of small nonprofits in post-2017 hurricane Puerto Rico. *Journal of the American Planning Association*, **88** (2), 206–219. https://doi.org/10.1080/01944363.2021.1938637

274. Rosas, E., P.S. Roberts, A. Lauland, I.A. Gutierrez, and B. Nuñez-Neto, 2021: Assessing the impact of municipal government capacity on recovery from Hurricane Maria in Puerto Rico. *International Journal of Disaster Risk Reduction*, **61**, 102340. https://doi.org/10.1016/j.ijdrr.2021.102340

275. CRS, 2021: FEMA Pre-Disaster Mitigation: The Building Resilient Infrastructure and Communities (BRIC) Program. CRS Report IN11515. Congressional Research Service. https://crsreports.congress.gov/product/pdf/in/in11515

276. GAO, 2019: Emergency Management: FEMA Has Made Progress, but Challenges and Future Risks Highlight Imperative for Further Improvements. GAO-19-617T. U.S. Government Accountability Office. https://www.gao.gov/products/gao-19-617t

277. GAO, 2022: Update on FEMA's Disaster Recovery Efforts in Puerto Rico and the U.S. Virgin Islands. GAO-22-106211. U.S. Government Accountability Office. https://www.gao.gov/assets/gao-22-106211.pdf

278. Global Infrastructure Hub, 2022: A G20 Initiative: Lastest from the GI Hub. Global Infrastructure Hub. https://www.gihub.org/

279. Governors' Institute on Community Design, 2017: Final Report: Sea Level Rise and the Impact on Economic Activity in Coastal Communities—A Workshop for the U.S. Virgin Islands. Governors' Institute on Community Design, 34 pp. https://www.fdpi.org/wp-content/uploads/2022/07/Report-of-Workshop-on-the-Impact-of-Sea-Level-Rise-on-the-U.S.-Virgin-Islands_GICD-2017.pdf

280. Kuhl, L., 2021: Policy making under scarcity: Reflections for designing socially just climate adaptation policy. *One Earth*, **4** (2), 202–212. https://doi.org/10.1016/j.oneear.2021.01.008

281. Pitter, J., 2021: Equitable Infrastructure: A Resource Framing Infrastructure Types Using an Equitable Placemaking Lens. Community Foundations of Canada, 24 pp. https://torontolip.com/resources/resource/equitable-infrastructure-a-resource-framing-infrastructure-types-using-an-equitable-placemaking-lens/

282. Office of the High Commissioner for Human Rights, 2022: Annual Report of the United Nations High Commissioner for Human Rights on the Situation of Human Rights in Nicaragua. United Nations. https://www.ohchr.org/en/statements/2022/03/annual-report-united-nations-high-commissioner-human-rights-situation-human

283. Multihazard Mitigation Council, 2017: Natural Hazard Mitigation Saves 2017 Interim Report: An Independent Study–Summary of Findings. Principal Investigator Porter, K.; co-Principal Investigators Scawthorn, C.; Dash, N.; Santos, J.; P. Schneider, Director, MMC. National Institute of Building Sciences, Washington, DC. https://www.fema.gov/sites/default/files/2020-07/fema_ms2_interim_report_2017.pdf

284. UNDRR, 2016: UNISDR Annual Report 2015. United Nations Office for Disaster Risk Reduction, Geneva, Switzerland, 75 pp. https://www.undrr.org/publication/unisdr-annual-report-2015

285. VIHFA, 2021: United States Virgin Islands CDBG-Mitigation Action Plan. Virgin Islands Housing Finance Authority. https://cdbgdr.vihfa.gov/wp-content/uploads/2023/08/USVI-HUD-Approved-Mitgation-Action-Plan-7142021-compressed.pdf

286. Kompaniyets, L., A.B. Goodman, B. Belay, D.S. Freedman, M.S. Sucosky, S.J. Lange, A.V. Gundlapalli, T.K. Boehmer, and H.M. Blanck, 2021: Body mass index and risk for COVID-19–related hospitalization, intensive care unit admission, invasive mechanical ventilation, and death—United States, March–December 2020. *Morbidity and Mortality Weekly Report*, **70**, 355–361. https://doi.org/10.15585/mmwr.mm7010e4

287. Maldonado, J., I.F.C. Wang, F. Eningowuk, L. Iaukea, A. Lascurain, H. Lazrus, C.A. Naquin, J.R. Naquin, K.M. Nogueras-Vidal, K. Peterson, I. Rivera-Collazo, M.K. Souza, M. Stege, and B. Thomas, 2021: Addressing the challenges of climate-driven community-led resettlement and site expansion: Knowledge sharing, storytelling, healing, and collaborative coalition building. *Journal of Environmental Studies and Sciences*, **11** (3), 294–304. https://doi.org/10.1007/s13412-021-00695-0

288. Seara, T., R. Pollnac, and K. Jakubowski, 2020: Impacts of natural disasters on subjective vulnerability to climate change: A study of Puerto Rican fishers' perceptions after Hurricanes Irma & Maria. *Coastal Management*, **48** (5), 418–435. https://doi.org/10.1080/08920753.2020.1795969

289. Dawson, T., 2013: Erosion and coastal archaeology: Evaluating the threat and prioritising action. In: *Ancient Maritime Communities and the Relationship between People and Environment along the European Atlantic Coasts*. Daire, M.-Y., C. Dupont, A. Baudry, C. Billard, J.-M. Large, L. Lespez, E. Normand, and C. Scarre, Eds. Archeopress, Oxford, UK, 77–83. http://hdl.handle.net/10023/4183

290. Finneran, N.P., 2017: The materiality of human–water interaction in the Caribbean: An archaeological perspective. *WIREs Water*, **4** (5), e1235. https://doi.org/10.1002/wat2.1235

291. Kohler, T.A. and M. Rockman, 2020: The IPCC: A primer for archaeologists. *American Antiquity*, **85** (4), 627–651. https://doi.org/10.1017/aaq.2020.68

292. Perdikaris, S., R. Boger, E. Gonzalez, E. Ibrahimpašić, and J.D. Adams, 2021: Disrupted identities and forced nomads: A post-disaster legacy of neocolonialism in the island of Barbuda, Lesser Antilles. *Island Studies Journal*, **16** (1), 115–134. https://doi.org/10.24043/isj.130

293. Rockman, M. and C. Hritz, 2020: Expanding use of archaeology in climate change response by changing its social environment. *Proceedings of the National Academy of Sciences of the United States of America*, **117** (15), 8295–8302. https://doi.org/10.1073/pnas.1914213117

294. NCHS, 2019: Potentially Excess Deaths. Centers for Disease Control and Prevention, National Center for Health Statistics, accessed April 3, 2023. https://www.cdc.gov/nchs/nvss/potentially_excess_deaths.htm

295. d'Alpoim Guedes, J., S. Gonzalez, and I. Rivera-Collazo, 2021: Resistance and care in the time of COVID-19: Archaeology in 2020. *American Anthropologist*, **123** (4), 898–915. https://doi.org/10.1111/aman.13669

296. Isabel Rivera-Collazo (Author), March 2021: Oral communications with multiple elders of Puerto Rican towns, Jayuya, Utuado, and Lajas.

297. Veenema, T.G., Z. Rush, K. Depriest, and L. Mccauley, 2019: Climate change-related hurricane impact on Puerto Rico and the US Virgin Islands, environment risk reduction, and the social determinants of health. *Nursing Economics*, **37** (1), 13–22. https://tools.niehs.nih.gov/cchhl/index.cfm/detail/18106

298. Main, J., M.K. Dillard, E.D. Kuligowski, B. Davis, J.D. Dukes, K.W. Harrison, J. Helgeson, K.J. Johnson, M.L. Levitan, J. Mitrani-Reiser, S.J. Weaver, D. Yeo, L.D. Bermúdez, J. Cline, and T. Kirsch, 2021: Learning from Hurricane Maria's Impacts on Puerto Rico: A Progress Report. NIST Special Publication 1262. National Institute of Standards and Technology. https://doi.org/10.6028/nist.sp.1262

299. Pasch, R.J., A.B. Penny, and R. Berg, 2023: Tropical Cyclone Report: Hurricane Maria. National Oceanic and Atmospheric Administration, National Weather Service, National Hurricane Center, 48 pp. https://issuu.com/coleccionpuertorriquena/docs/al152017_maria

300. DRNA, 2016: Informe Sobre la Sequía de 2014–2016 en Puerto Rico. Departamento De Recursos Naturales Y Ambientales, División Monitoreo del Plan de Aguas, San Juan, PR. https://www.drna.pr.gov/wp-content/uploads/2017/01/Informe-Sequia-2014-2016.compressed.pdf

301. NIDIS, 2023: Drought Status Update Repository. National Integrated Drought Information System and National Oceanic and Atmospheric Administration. https://www.drought.gov/drought-status-updates

302. Rodriguez-Cruz, L.A. 2022: Adaptive Capacity and [un]Natural Disasters: Puerto Rican Farmers' Adaption and Food Security Outcomes After Hurricane Maria. Doctor of Philosophy in Food Systems, University of Vermont. https://scholarworks.uvm.edu/graddis/1509

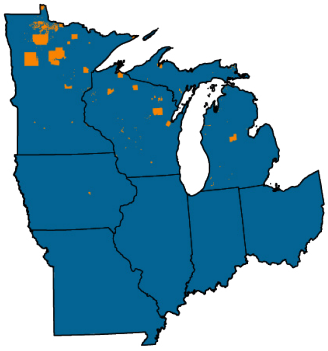
303. Environmental Defense Fund, 2021: Climate Change-Resilient Fisheries in the Caribbean–Focus on Cuba, the Dominican Republic and Puerto Rico: Summary. Environmental Defense Fund. https://www.edf.org/sites/default/files/2022-06/Caribbean%20Climate%20Resilient%20Fisheries%20Seminar%20Report_ENGLISH.pdf

304. Global Programme on Risk Assessment and Management for Adaptation to Climate Change, 2021: Climate Change and Small-Scale Fisheries: A Climate Risk Management Perspective for the Caribbean. Deutsche Gesellschaft für Internationale Zusammenarbeit, Bonn, Germany, 9 pp. https://www.adaptationcommunity.net/publications/climate-change-and-small-scale-fisheries-a-climate-risk-management-perspective-for-the-caribbean/

305. Yandle, T., J. Sweeney Tookes, and C.A. Grace-McCaskey, 2020: US Virgin Islands fishing community resilience: Informing a research agenda. *Coastal Management*, **48** (5), 481–504. https://doi.org/10.1080/08920753.2020.1796191

Fifth National Climate Assessment: Chapter 24

Midwest



Chapter 24. Midwest

Authors and Contributors

Federal Coordinating Lead Author

John M. Baker, USDA Agricultural Research Service

Chapter Lead Author

Aaron B. Wilson, The Ohio State University, Byrd Polar and Climate Research Center

Chapter Authors

Elizabeth A. Ainsworth, USDA Agricultural Research Service
Jeffrey Andresen, Michigan State University
Jay A. Austin, University of Minnesota Duluth
Jeffrey S. Dukes, Carnegie Institution for Science
Elizabeth Gibbons, Farallon Strategies LLC
Brendalynn O. Hoppe, University of Minnesota Climate Adaptation Partnership
Olivia E. LeDee, US Geological Survey
James Noel, NOAA National Weather Service, Ohio River Forecast Center
Heidi A. Roop, University of Minnesota Climate Adaptation Partnership
Sara A. Smith, Oneida Nation and College of Menominee Nation
Dennis P. Todey, USDA Agricultural Research Service, National Laboratory for Agriculture and the Environment
Ray Wolf, NOAA National Weather Service (retired)
Jeffrey D. Wood, University of Missouri, School of Natural Resources

Technical Contributors

Sean Burkholder, University of Pennsylvania
Sean Cavanaugh, MITRE Corporation
Trent W. Ford, University of Illinois, Prairie Research Institute
Jennifer Richkus, MITRE Corporation

Review Editor

Thomas W. Bonnot, US Fish and Wildlife Service

Cover Art

Nikki Way

Recommended Citation

Wilson, A.B., J.M. Baker, E.A. Ainsworth, J. Andresen, J.A. Austin, J.S. Dukes, E. Gibbons, B.O. Hoppe, O.E. LeDee, J. Noel, H.A. Roop, S.A. Smith, D.P. Todey, R. Wolf, and J.D. Wood, 2023: Ch. 24. Midwest. In: *Fifth National Climate Assessment*. Crimmins, A.R., C.W. Avery, D.R. Easterling, K.E. Kunkel, B.C. Stewart, and T.K. Maycock, Eds. U.S. Global Change Research Program, Washington, DC, USA. https://doi.org/10.7930/NCA5.2023.CH24

Table of Contents

Introduction 5

Key Message 24.1
Climate-Smart Practices May Offset Complex Climate Interactions in Agriculture 6

Risk 6
Impacts 6
Climate-Smart Agriculture 10

Key Message 24.2
Adaptation May Ease Disruptions to Ecosystems and Their Services 12

Risk 12
Impacts 12
Nature-Based Solutions for Adaptation and Mitigation 15

Key Message 24.3
Climate Adaptation and Mitigation Strategies Improve Individual and Community Health 17

Risk 17
Impacts 17
Climate Resilience for Healthier Outcomes 20
Box 24.1. Midwest Educational Resources 20

Key Message 24.4
Green Infrastructure and Investment Solutions Can Address Costly Climate Change Impacts 21

Risk 21
Impacts 21
Innovative Finance and Investments 25

Key Message 24.5
Managing Extremes Is Necessary to Minimize Impacts on Water Quality and Quantity 26

Risk 26
Impacts 26
Managing Hydrologic Complexity and Extremes 32

Traceable Accounts 33
Process Description 33
Key Message 24.1 33
Key Message 24.2 35
Key Message 24.3 36
Key Message 24.4 38
Key Message 24.5 39

References 41

Introduction

The Midwest is diverse in landscapes, people, and culture. The region covers more than 328 million acres, with approximately 284 million acres covered by croplands and forests or designated as public land. It sustains vital ecosystems and wildlife and provides refuge and recreation for its residents, including 35 Federally Recognized Tribes and numerous other state-recognized and non-recognized Tribes. More than 40,000 natural lakes and thousands more human-made reservoirs and ponds dot the landscape. The Midwest borders four of the five Great Lakes; together, the five Great Lakes contain approximately 21% of the world's surface freshwater supply, and about 10% of the US population lives within the Great Lakes basin. There are more than 500,000 miles of rivers and streams flowing through the region, including the Mississippi, Missouri, and Ohio Rivers—critical lifelines enabling the exchange of goods and services throughout the country. The Midwest is linked by more than 2 million miles of roads, 160,000 bridges, 34,000 rail miles, and 3,000 airports. It has 41 cities with at least 100,000 residents, including 5 of the 30 most populated cities in the United States. All of the Midwest states except Illinois have lower urban populations than the national average, and 74.3% of the Midwest population lives in urban areas.[1]

The climate of the Midwest has warmed since the first half of the 20th century, and annual precipitation has increased (Figure 2.4). Sub-annual changes, such as the recent lack of warming during summer and rapid oscillations between extreme wet and dry periods (Figure 24.1), increase the complexity and uncertainty of future impacts. Nonetheless, these changes have impacted agriculture (KM 24.1), natural resources (KM 24.2), health and well-being (KM 24.3), the built environment and transportation (KM 24.4), and water quality and quantity (KM 24.5) in societally important and interconnected ways. Increasing temperatures and oscillations between extreme droughts and floods threaten field crops, specialty crops, and animal production across the Midwest,[2,3] which have direct and inequitable impacts on global food supply and security (KM 11.2). These rapid oscillations in hydrology will continue to transform aquatic and terrestrial ecosystems, many of which strongly influence individual and community health and the built environment. These observed and projected changes greatly limit access to natural areas, including those intimately tied to winter ice.[4] Not only does climate change threaten recreation and the economy of this region, but it also disrupts important identity connections between Indigenous Peoples and their ancestral lands (KM 16.1).[5] Individual and community health is at risk, with cascading impacts on social and cultural connections that highlight inequitable health disparities tied to race, ethnicity, age, and income (KMs 14.1, 15.2). Aging infrastructure creates uncertainty in the ability to meet current and future energy needs and withstand increasing volumes of water. Although rural landscapes dominate the Midwest, urban centers concentrate climate risks and socioeconomic inequities (KM 12.2). NOAA's Billion-Dollar Weather and Climate Disasters report (Figure 2.6) does not fully account for the burden felt by low-income populations of urban centers due to chronic, smaller-scale flooding events. Finally, projected increases in temperature and precipitation variability threaten the ability to maintain water quality and manage the Mississippi, Missouri, and Ohio Rivers in ways that maintain the flow of goods and services throughout the region and the country. The Great Lakes indicators, from fish consumption to invasive species, show diverse conditions. Many of the complex interactions between climate changes, the lakes, and their surrounding land and populations raise uncertainty in long-term projections of lake levels and trends in environmental and ecosystem metrics (Table 24.1),[6] and this uncertainty has important implications for international collaboration and adaptive management in the Great Lakes (Box 4.3).

Despite these many risks to the economy and identity of the Midwest, people are responding in ways that offer hope for the future. Researchers are identifying climate-smart agriculture practices that could help boost profitability and improve economic and environmental sustainability (Figure 24.4). There is growing recognition that undeveloped natural lands provide economic and social benefits by contributing to climate mitigation and adaptation (providing nature-based solutions through effective resource management)

and that collaboration with Tribes on land issues improves climate outcomes for all residents. Within communities, people are engaging with one another to identify solutions to address structural, institutional, and systemic factors that contribute to inequities and climate injustice. Researchers and practitioners are collaborating to build transportation and energy networks that are resilient to climate change while also maintaining social cohesion in the process. For example, experimental port management in the Great Lakes is assuming the role of ecological restoration, which also improves the social health of the region (Figure 24.9). Communities like Milwaukee have developed public–private partnerships and increased green stormwater infrastructure. Finally, federal partners are working with state and local agencies to build tools and approaches to address climate-related challenges such as drought and harmful algal blooms.

Key Message 24.1

Climate-Smart Practices May Offset Complex Climate Interactions in Agriculture

Crop production is projected to change in complex ways (*likely*, *medium confidence*) due to increasing extreme precipitation events and transitions between wet and dry conditions (*likely*, *medium confidence*), as well as intensification of crop water loss (*likely*, *low confidence*). Changes in precipitation extremes, timing of snowmelt, and early-spring rainfall are expected to pose greater challenges for crop and animal agriculture, including increased pest and disease transmission, muddier pastures, and further degradation of water quality (*likely*, *high confidence*). Climate-smart agriculture and other adaptation techniques provide a potential path toward environmental and economic sustainability (*medium confidence*).

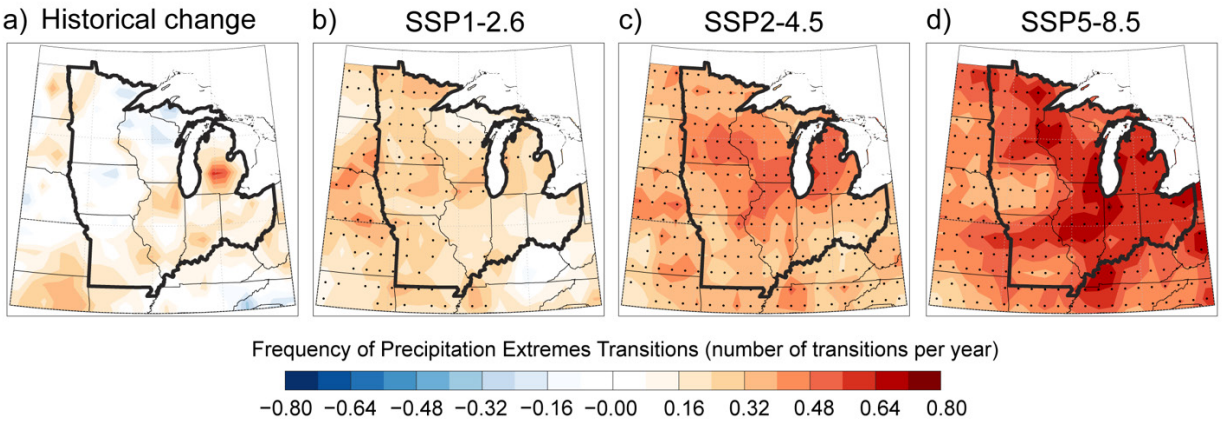
Risk

The Midwest is among the most intensive agricultural regions globally, producing more than 30% and 32% of the world's corn and soybeans, respectively; numerous specialty crops; and livestock in concentrated animal operations.[7,8] Climate change is already affecting Midwest agriculture, and projected climate changes increase these risks.

Impacts

Annual precipitation increased by 5%–15% across much of the Midwest during 1992–2021 (compared to the 1901–1960 average), with some areas experiencing reduced precipitation during summer (Figure 2.4).[9,10,11,12] These trends, particularly across the north-central region of the US, have been partly attributable to human influence.[13,14] Projections (under low [RCP2.6] to very high [RCP8.5] scenarios) suggest precipitation increases across the Midwest ranging from 8% to 20% by midcentury relative to the previous five decades, with individual model uncertainty regarding the degree, direction (wetter or drier), and regional spatial characteristics (KM 3.3).[10,12,15,16,17] Rapid transitions between precipitation extremes are expected to increase across all of the Midwest by late century (2071–2100) compared to historical conditions (Figure 24.1).[17,18] Amplified precipitation variability and more frequent wet–dry transitions increase the risks of transient drought and harm to crops, requiring changes in management systems to maintain food security.[19,20,21]

Change in Frequency of Transitions Between 1-Month Precipitation Extremes



The frequency of wet–dry and dry-wet transitions across the Midwest is projected to increase by late century (2071–2100).

Figure 24.1. Transitions between wet and dry periods are expected to become more frequent across the Midwest. Observed changes in transition frequency (from wet to dry or dry to wet) are based on the Standardized Precipitation Index (SPI), represented by the difference between the periods 1951–1980 and 1981–2010 (historical change, panel **a**). SPI is a common statistical index that quantifies the relative intensity of drought or wetness, and monthly SPI values are utilized to show transitions over short periods. Projected changes in transition frequency under low (SSP1-2.6; **b**), intermediate (SSP2-4.5; **c**), and very high (SSP5-8.5; **d**) scenarios are represented by the difference between the periods 2071–2100 and 1981–2010. The black boundary outlines the Midwest region. Black dots indicate grid cells where the model-projected transition frequency is significantly different from the historical climatology. Adapted from Chen and Ford 2023[18] [CC BY 4.0].

Although average corn and soybean yields increased in recent decades in the Midwest,[22] both excessive moisture (flooding) and extreme droughts significantly decreased corn yields in some locations and years by up to 37%.[2,23] Excessive spring moisture has delayed corn planting by up to a month,[24] while episodic droughts have reduced yields[2] despite increasing annual rainfall.[25]

Future projections suggest further changes in seasonality and increases in variability. Earlier snowmelt is expected to increase daily maximum spring streamflow.[26] Intermediate (RCP4.5) to very high (RCP8.5) scenarios show both an increase in the frequency of wet springs and decreasing summer precipitation and drier soils.[15,27,28] More intense precipitation during the early spring, when soils are largely uncovered and wetter, increases soil erosion[3] and leaching of nitrogen fertilizer.[10] Additionally, water quality concerns (KM 24.5) are compounded due to more frequent spring manure storage overflow and increased pressure on farmers to spread manure early.

Temperature increases directly affect crop development and physiology[29,30,31] and lead to increases in evapotranspiration and stress during dry conditions.[32] While daily minimum temperatures have increased, daytime maximum (summer) temperatures have cooled in some areas of the Midwest (1991–2021 compared to 1901–1960; see Figure 2.4). This is an important trend for the Midwest and differs from that of other regions (Figure 3.11). Often referred to as the "warming hole,"[33] this trend may be partly explained by the expansion of croplands and increased transpiration over parts of the Midwest and Northern Great Plains (KM 25.2).[34,35,36,37,38] Increased transpiration may have also induced observed summer rainfall increases over parts of the region.[34] These changes may have contributed to improved corn yields.[39,40,41] Projections across a range of scenarios (low [SSP1-2.6] to very high [SSP5-8.5]), however, show that rising temperatures will reduce corn and soybean productivity while maintaining wheat production by the end of the century.[31,42,43] Higher temperatures also increase atmospheric vapor pressure deficit (VPD), enhancing crop water loss. Without expansion of irrigation, projected increases in VPD are expected to limit corn yields.[44,45]

Irrigation in the Midwest affects climate as well. Across the Wisconsin Central Sands region, for instance, irrigated agriculture, compared to rainfed agriculture, has contributed to decreased maximum temperatures, increased minimum temperatures, increased VPD, and decreased evaporative demand.[46] This land-use change/microclimate complexity introduces uncertainty regarding future projections of temperatures and moisture across the Midwest (KM 6.2).

Animal production in the Midwest is also vulnerable to climate change. Increases in winter and spring precipitation and temperature are expected to result in muddier paddocks and pastures, which can decrease fetal growth during late gestation.[47,48,49] Perennial forage crops are under a greater risk of winter injury with climate change because of a greater frequency of above-freezing temperatures during winter.[23] However, there are potential gains in forage productivity with a warmer and wetter climate, longer growing seasons, and higher carbon dioxide concentrations, although with potential declines in quality.[50] Other important livestock impacts include feed shortages, loss of shade structures, nutritional restrictions, disease transmission, and biosecurity concerns (e.g., feral hogs and waterfowl may contaminate existing stocks as they seek higher ground).[51] Increasing temperatures and higher dewpoints place demands on livestock management and housing needs to limit productivity losses or mortality. Heat stress limits livestock production[51,52] and dairy quality.[53] Under intermediate (RCP4.5) and very high (RCP8.5) scenarios, more intense heat abatements (e.g., fans, misting, sprinklers, ventilation) could be necessary to sustain recent production increases,[54] and environmental impacts on dairy production will increase by 2050.[55]

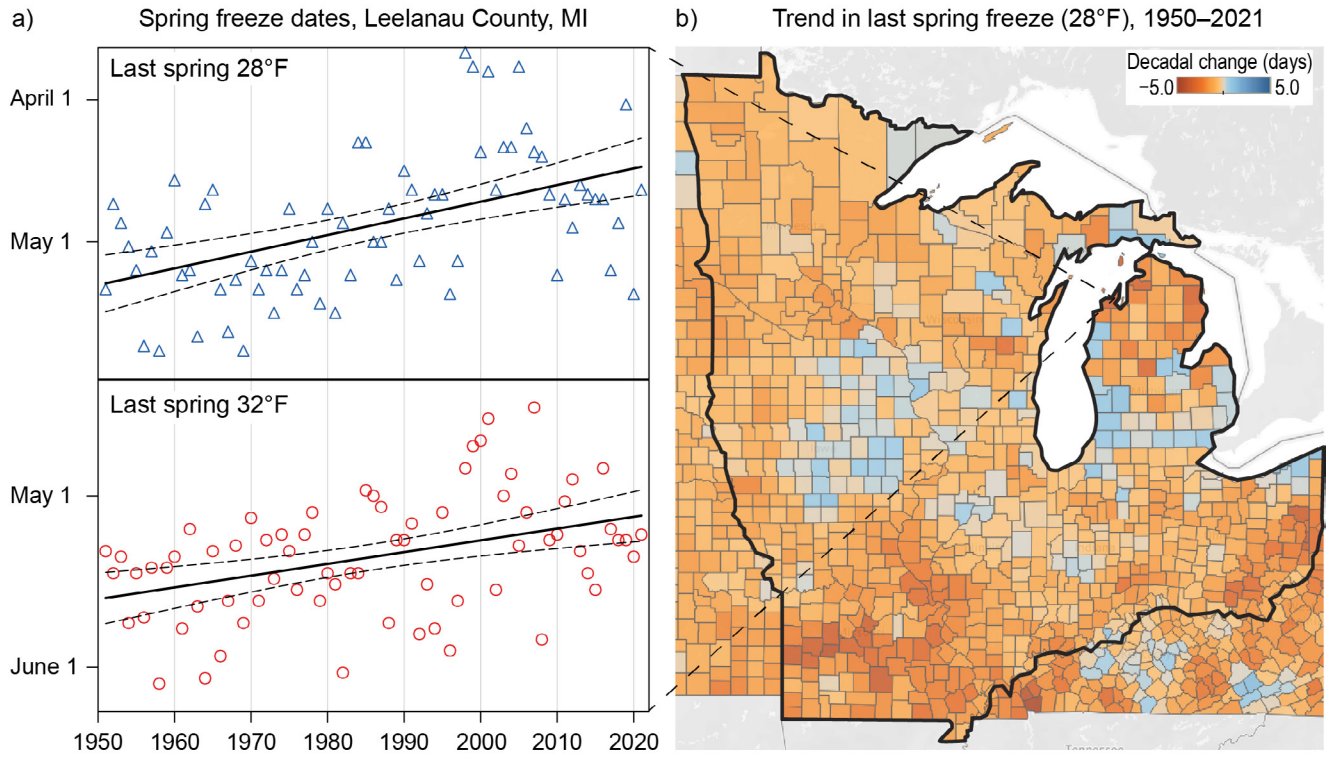
Specialty crops, such as tree fruit and vegetables (e.g., pumpkin and berries), represent a $7.1 billion industry (in 2022 dollars) and have higher potential market values and production-related risks than commodity crops due to their dependence on flavor and appearance.[56,57] Cold injury and damaging frosts during the spring are concerns for both perennial and annual crops (Figure 24.2), and excessive moisture has been associated with significant crop losses for growers throughout the year.[58] Early-season flowering followed by spring freezes (Figure 24.3) has resulted in premature phenological development of tree fruit crops, erratic flowering, and increased risk of freezing injury in April and May.[23,58] Current understanding of future impacts on specialty and horticultural crops across projected climate changes is limited. As temperatures increase, shifts in the timing and growing zones of crops have caused observed pollinator population declines that have translated directly into decreased crop production.[59,60,61] Projected temperature increases suggest continued challenges related to crop growing zones and timing.[62]

Freeze-Damaged Apple Blossoms

Early warmth and flowering followed by freezing temperatures in the spring poses risks to perennial and annual crops.

Figure 24.2. Apple blossoms are damaged by a freeze event on May 9, 2020, in Berrien County, Michigan. Photo credit: ©Dr. Mike Reinke, Michigan State University.

Trends in Last Freeze Dates for Spring



Last spring freezes are occurring earlier over most of the Midwest region.

Figure 24.3. (**a**) Trends (solid black lines) show that the last date in spring when minimum temperatures fall to either 28°F or 32°F in Leelanau County, Michigan, are occurring earlier in the year. For example, the last 28°F temperature commonly occurred after May 1 during the 1950s–1970s, with earlier dates noted since the 1980s. Note the large variability in dates. The statistical significance of the trends (dashed black lines; based on a 95% confidence interval) shows the range of values of the trend line based on the observed dates. In all cases, these confirm there is a trend toward earlier last freeze dates. Panel (**b**) shows change in the number of days per decade of the last spring freeze (28°F) over the period 1950–2021. The black boundary outlines the Midwest region. Orange shading indicates trends toward earlier last spring freeze dates, blue shading indicates trends towards later last spring freeze dates, and gray shading indicates no trend. Adapted with permission from the Midwestern Regional Climate Center's Freeze Date Tool (https://mrcc.purdue.edu/freeze/freezedatetool). Map base layer on right is ©Mapbox ©OpenStreetMap.

Evidence suggests that pest distributions have shifted northward since the early 20th century, and projections indicate that increasing temperatures will allow pests (e.g., brown marmorated stink bug, corn earworm, Japanese beetle, Mexican bean beetle, and potato leafhopper) to continue expanding northward across the Midwest.[63,64,65,66,67,68] Warming winters lead to insect population expansion throughout the Great Lakes (e.g., Kiefer et al. 2021[69]), while hotter, drier conditions exacerbate yield loss from weed competition.[70] Higher dew points (humidity) increase disease risk for numerous crops, including soybean and apples.[21,71,72]

Most Midwestern row crops are insured, providing growers with some economic security against weather- and climate-related risks.[73] However, US crop insurance losses continue to rise, with an estimated $31.9 billion (in 2022 dollars) attributed to climate change over the last three decades.[74] Drought payments represent the largest percentage of indemnities, although wetness losses are increasing.[75] Evidence suggests an overall decline in drought across the region since 1895;[76] however, an increased occurrence of flash drought (rapid depletion of soil moisture), along with soil degradation[77] and more productive crops,[8] has resulted in moisture stress to crops and native vegetation.[78,79] Damages from droughts and other climate-related financial losses have implications on farmers' mental health as well (KM 24.3).

Climate-Smart Agriculture

According to the United Nations Food and Agriculture Organization, "climate-smart agriculture defines an agriculture that sustainably increases productivity [and] resilience (adaptation), reduces/removes GHGs (mitigation), and enhances the achievement of national food security and development goals."[80] Climate-smart strategies include, but are not limited to, the use of cover crops, reduced- or no-tillage operations, improved nutrient and manure management, wetland and grassland management, agroforestry, bioenergy crops, on-site carbon sequestration, and agrivoltaics (the integration of agricultural production activities and solar energy generation; Figure 24.4). However, there are uncertainties about the climate benefits and detriments of these techniques, particularly in field settings.[81] Cover crops can improve soil health, reduce erosion, and increase soil organic carbon. Five percent of agricultural fields in the Midwest were cover-cropped in 2017, up from 2.6% in 2012.[82] A reduction in yields for cash crops may deter further adoption of cover crops, and recent analyses suggest that non-legume cover crop adoption reduced maize yields by 3.9% to 5.5% in the Midwest.[82,83] Billions of dollars of investment to encourage producers to test various climate-smart practices have come from federal programs and legislation. Precision agriculture, which maximizes the efficiency of input application (e.g., fertilizers, herbicides) allows for homogeneously managed zones within the same field.[84,85] Such approaches have the potential to increase production efficiency; increase resilience to climate-related risks, particularly the loss of nitrogen fertilizer;[86,87] and yield co-benefits for Midwestern ecosystems (KM 24.2). Corn remains the major bioenergy crop in the US, providing ethanol as a biofuel.[88] Whether corn ethanol is a climate-smart practice is heavily debated.[88] Second-generation biofuels from cellulosic biomass feedstocks, including dedicated energy crops (grown specifically for energy and not food production); agricultural crop residues (materials left on land after crop harvest); and wood residues have greater potential to reduce greenhouse gas emissions, with limited adverse impacts on food crop prices and indirect land-use changes compared to corn ethanol.[89,90,91] Additional techniques concerning animal agriculture and greenhouse gas emissions are explored in KM 11.1.

Environmental Impacts from Conventional Versus Climate-Smart Practices

Climate-smart agricultural strategies may have adaptation and mitigation advantages that balance agricultural needs and environmental impacts.

Figure 24.4. The figure shows examples of conventional and climate-smart production methods: (**clockwise from top center**) wheat field in Brownsburg, Indiana; spring corn under fair skies in southwest Ohio with infield soil sampling probe; outlet from water control structure to agricultural drainage ditch; inter-seeded annual ryegrass, clovers, and radishes growing in young corn in Carroll County, Iowa; macrotopograhic feature (ridge and swale) on a wetland restoration easement in Starke County, Indiana; planting green: no-till drilling soybeans into standing cereal rye in Washington County, Iowa; Forage Systems Research Center in Missouri works to improve the quality of forage grass, promotes management-intensive grazing, rotational grazing, cattle management, and the economics of beef and forage; an example of agrivoltaics—combining solar energy production on agricultural production lands; farmer tilling fields: traditional practice to break up soil in preparation for planting; farmer harvesting soybean with combine. The center diagrams compare the agricultural needs (blue ovals and text) with environmental impacts (green ovals and text) for both conventional and climate-smart agriculture. As shown, there is an imbalance between the agricultural needs and environmental impacts of conventional agriculture (represented by the blue and green ovals); whereas climate-smart agriculture may provide more balance between the two. Adapted with permission from Foley et al. 2011.[92] Photo credits: (top left; left, second from top) United Soybean Board [CC BY 2.0]; (top center) Carly Whitmore, NRCS; (top right) ©Elizabeth Hawkins; (right, second and third from top; bottom left) NRCS/SWCS photo by Lynn Betts [CC BY 2.0]; (bottom right) Carly Whitmore, NRCS; (bottom center) Kyle Spradley [CC BY 2.0]; (left, third from top) ©Tony Mancuso.

Key Message 24.2

Adaptation May Ease Disruptions to Ecosystems and Their Services

Ecosystems are already being affected by changes in extreme weather and other climate-related changes, with negative impacts on a wide range of species (*likely*, *high confidence*). Increasing incidence of flooding and drought is expected to further alter aquatic ecosystems (*likely*, *medium confidence*), while terrestrial ecosystems are being reshaped by rising temperatures and decreasing snow and ice cover (*very likely*, *high confidence*). Loss of ecosystem services is undermining human well-being, causing the loss of economic, cultural, and health benefits (*medium confidence*). In response, communities are adapting their cultural practices and the ways they manage the landscape, preserving and protecting ecosystems and the services they provide (*low confidence*).

Risk

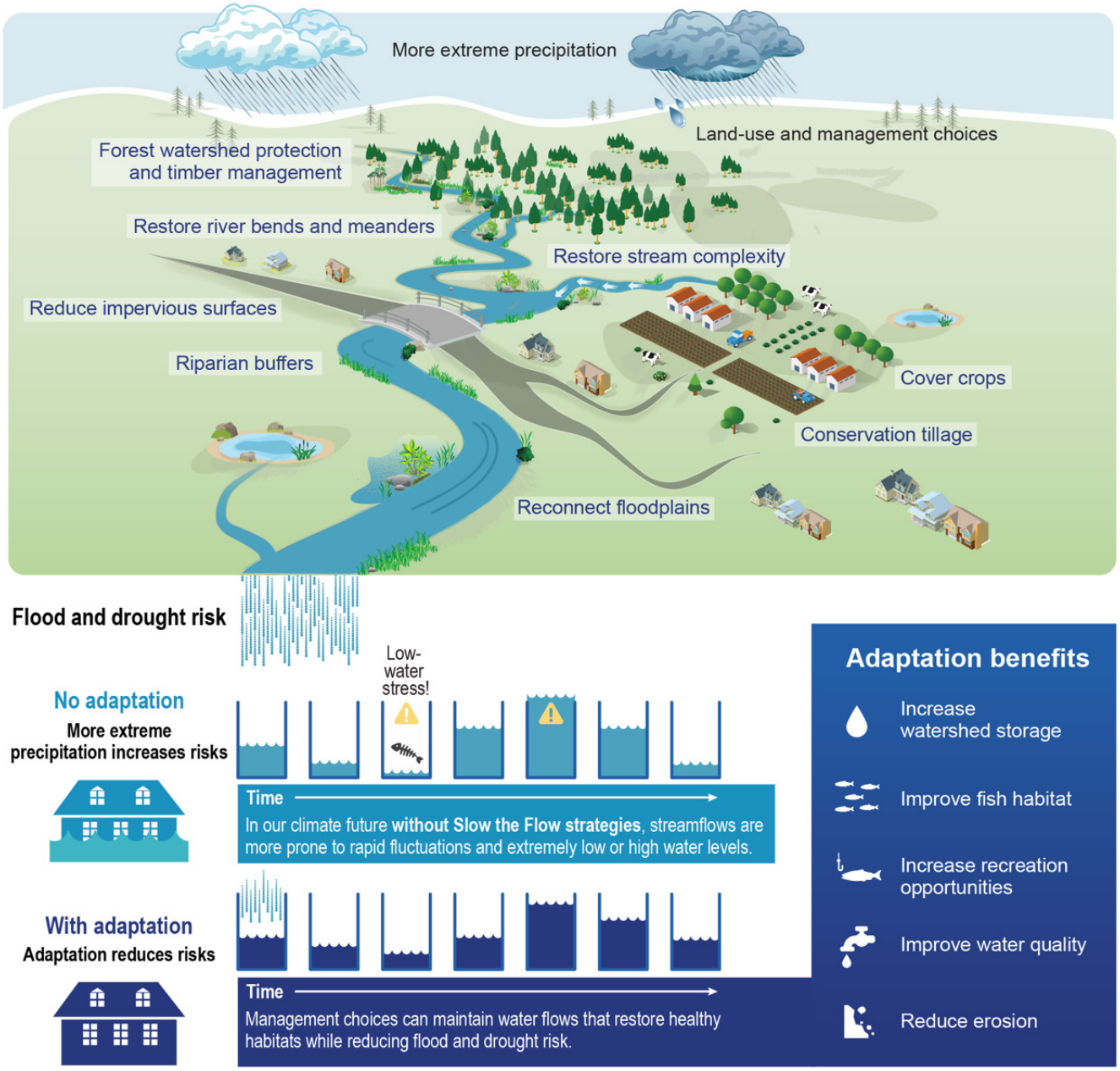
The Midwest is home to many communities and cultures that appreciate and rely on fish, wildlife, waters, and lands. Indigenous communities throughout the Midwest recognize natural resources as persons and extended family (a kin-centric viewpoint) and at times may use terminology such as relatives or beings to refer to them.[93] These relatives support intergenerational continuity, heritage, and spiritual practice. Fishing, hunting, and wildlife viewing are common recreational activities and contribute billions of dollars to the regional economy.[94] Exposure to natural environments enhances human well-being and health,[95] while limited access to natural resources contributes to health inequality.[96]

Impacts

Midwestern aquatic ecosystems are being harmed by rising temperatures and increased precipitation.[97] Climate change intersects with invasive species, land-use change, and human consumption to affect nutrient pollution, water quality, and water levels.[98,99,100,101] For example, invasive species and habitat degradation are negatively affecting walleye growth, survival, and abundance.[98,102,103,104] Mass fish die-offs due to extreme summer heat are projected to double by midcentury (under a very high scenario [RCP8.5]) in northern temperate lakes.[105] Indeed, the Fond du Lac Band of Lake Superior Chippewa has documented an increase in lethal stream temperatures and a decline in brook trout harvest.[5]

Extreme precipitation events degrade riparian ecosystems, erode river and stream banks, disperse contaminants, disrupt plant and animal cycles, and spread invasive species; however, there may be benefits to flooding, including increases in connectivity for aquatic organisms, habitat complexity, and size of the floodplain.[106] Reduced snowmelt is projected to shift spring peak flow earlier in the year.[107,108] Rapid transitions in hydrology (Figure 24.5) and increasing temperatures are projected to cause widespread changes in stream conditions, shifting habitats for invertebrates and fishes.[109] While broad declines in brook and brown trout populations are projected, streams with enhanced groundwater sources have demonstrated resilience to warming and the ability to maintain a viable fishery.[110] Climate-driven changes in heavy rainfall are magnified by land use, with pronounced negative effects in urban[111] and agricultural watersheds.[26]

Extreme Precipitation Impacts



Extreme precipitation events have adverse impacts on aquatic and terrestrial ecosystems, human health, infrastructure, and economies. Conservation and management strategies can help moderate these impacts.

Figure 24.5. Extreme precipitation events can degrade aquatic ecosystems, threaten human health and safety, damage infrastructure and communities, and yield billions of dollars in economic damage. The conservation and management of natural lands can reduce these negative effects—reducing erosion and flood risk, improving water quality, increasing carbon sequestration, and reducing the economic cost of flooding. This conceptual drawing, showing a Midwestern landscape with an extreme storm on the horizon and water flowing into streams and rivers, illustrates how land management choices affect downstream flooding, infrastructure, and ecosystem services. Landscape features and land management practices that slow the flow of water across the surface can improve habitat and water quality, reduce flood and drought risks, and have a variety of other benefits. Adapted with permission from Palmer et al. 2020.[112]

As in the Northern Great Plains (KM 25.4), agricultural expansion threatens Midwestern grasslands[113] via habitat loss and land fragmentation, which exacerbates the vulnerability of grassland wildlife.[114,115] In Indiana, high temperatures and drought contributed to the local extirpation of the endangered Karner blue butterfly,[116] and portions of the Midwest may become inhospitable for the monarch butterfly due to climate change.[117] While the composition of grassland communities is changing in response to climate change, land use, and management,[118] the adoption of mowing and prescribed burning may offset global and regional drivers to retain biodiversity in these threatened ecosystems.[119,120]

Increasing temperatures are projected to increase wildfire risks to Midwestern forests.[121,122,123] Flash droughts, characterized by sudden onset and rapid intensification,[124,125] have increased in frequency since 1980—although it is unclear whether current frequencies reflect a departure from the past (i.e., before the instrumental record began[126]). Flash droughts not only impact crops (KM 24.1) but also induce significant water stress in thin-soiled forests, inciting pathogen infection that increases tree mortality.[127] Additionally, climate change combined with river management for navigation strains the health of floodplain forests that are important hotspots of ecological activity.[128,129]

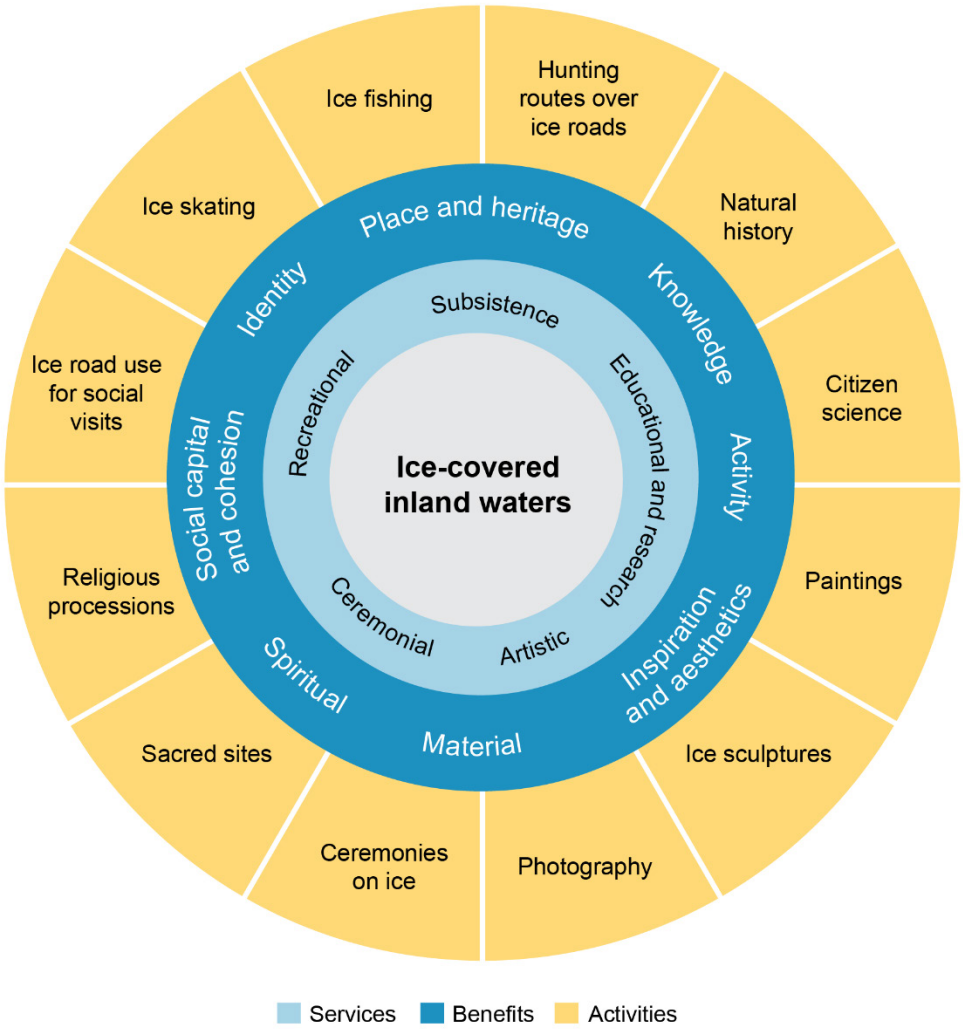
The threat of invasive species is amplified by climate change.[130,131] However, invasive species can be perceived in different ways: many Indigenous communities have holistic views of invasives, or non-local beings, who encompass both positive and negative attributes. For example, dandelions and common plantain are used medicinally in Anishinaabe communities. Understanding the gifts and teachings that beings have can change our interactions and resource management.[93,132]

Warming has shortened the length of persistent cold conditions and decreased snow cover in the Upper Midwest.[133,134] Snow supports the survival of boreal wildlife, providing insulation from cold conditions.[135] Some types of wildlife, such as moose, are threatened by warming winter conditions;[133] declining moose populations have been recorded in the 1854 Ceded Territory over the last three decades.[136,137] This loss, in turn, has cascading impacts on cultural practices, human well-being, subsistence harvesting, and tourism.[133,138,139]

Climate change accelerates the loss of beings, access, and connection to the land for Indigenous Peoples (Ch. 16).[133,140,141,142,143] Wild rice is one of the most vulnerable culturally significant species to Midwest Tribes,[5,144] and harvest rates have decreased due to warming and altered hydrology,[136,145] potentially leading to a loss of cultural identity.[5,146] Sugar maple is also culturally and economically important to Indigenous communities.[133,145,147] Warming winters have altered the timing and length of maple sugaring.[136,145] Seasonal changes and shifting habitats can impact Traditional Knowledge, language, physical health, and mental well-being by altering the timing of cultural ceremonies, availability of beings needed for the ceremonies, and potential loss of culturally significant relatives (KMs 8.2, 16.1).[145,148]

Nature-based recreation is transitioning, affecting opportunity, economy, and safety (KM 8.3). For example, climate change limits the availability of fish such as walleye and trout, sometimes leading to reduced catch limits[104] and food insecurity.[149] Ice cover, an important feature of northern lake systems, is declining in response to rising winter air temperatures,[150] with the most abrupt changes beginning in the 1990s.[4] Loss of ice cover is projected to continue through the end of the century, with greater losses under high scenarios,[150] threatening some cultural activities and services (Figure 24.6).[151] Winter drownings have also increased along with temperatures, which have decreased ice cover.[152]

Ecological Services of Ice-Covered Inland Waters



Rising winter temperatures are decreasing inland lake ice cover and the associated ecosystem services, benefits, and activities it provides.

Figure 24.6. Ice-covered inland waters provide humans with important cultural ecosystem services (light blue ring), benefits (dark blue ring), and activities (yellow ring) that are central to people's well-being, culture, and identity across the Midwest. Adapted from Knoll et al. 2019[151] [CC BY 4.0].

Nature-Based Solutions for Adaptation and Mitigation

Land managers are actively managing Midwestern forests to adapt to climate change[153] by reducing stressors, restoring native species diversity, increasing structural diversity (e.g., variation in age structure), and shifting forest composition to species better adapted to future climate conditions.[153,154] Additional studies can inform the introduction of species adapted to future climate to achieve desired forest management outcomes.[155]

Fish managers have ways to reduce the effects of increased water temperatures, novel invasive species, and other climate-driven changes.[97] They have combined socioeconomic and ecological data to prioritize lakes and identify suitable management techniques.[156] Current management interventions include acquisitions and easements, reducing runoff, protecting in-lake habitats, managing invasive species, changing harvest regulations, and adjusting stocking priorities.[156] Improvements in lake modeling and forecasting of harmful

algal blooms, as well as better information about invasive species and resilient fisheries, have the potential to improve adaptation efforts.[157]

Climate adaptation and mitigation can be achieved in part through nature-based solutions, including the protection and management of natural lands. These approaches have the additional advantage of providing social, ecosystem, and economic benefits.[158,159] Since 1980, the Midwest has incurred $49–$109 billion (CPI-adjusted to 2022 dollars) in economic damages due to flooding,[160] with losses projected to increase with further climate change.[161] Natural floodplains can reduce flood damages and yield benefit-to-cost ratios of up to 5 to 1.[162] Moreover, a targeted 10% increase of wetland area within the Mississippi River basin could decrease nitrogen loading to the Gulf of Mexico by more than 40%.[163] Additionally, climate-smart strategies on agricultural lands (Figure 24.4)[164] can yield co-benefits for Midwestern ecosystems.

There is also growing enthusiasm for natural climate solutions, which are specifically designed to increase carbon storage or decrease greenhouse gas emissions through conservation, restoration, and improved land management.[165,166,167,168] Some Midwestern forests are already being managed to bolster carbon storage,[169] and there is much room for expansion of these practices in the region (KMs 7.2, 8.3). Ongoing changes in the climate and atmosphere are expected to accelerate growth of the region's grasslands, which, depending on how they are managed, could increase their carbon storage.[170] Extensive peatlands in the region historically sequestered carbon, but much of this carbon has already been released by draining wetland areas.[171,172]

The long-term mitigation potential of Midwestern ecosystems has large sources of uncertainty related to climate-driven risk factors such as fire, drought, and pests;[165] offsets from increased soil microbial respiration;[173] and warming-induced losses of carbon stored in peatlands.[174]

Tribal Nations have made considerable progress in adaptation, including collaboration on guidance, vulnerability assessments, and implementation (KM 21.4; Ch. 16).[132,144,175] Adaptation strategies vary among Tribal Nations and their values. For example, one being might be a suitable substitute for another, such as birch trees instead of sugar maples for syrup tapping; however, beings that are tied tightly to a Tribal Nation's cultural identity (e.g., wild rice) cannot be substituted.[145] Therefore, adaptation strategies for those beings could mean collaborating and building relationships with Tribes and agencies outside of traditional harvesting lands and jurisdictional boundaries.[132,145] Inclusion of cultural knowledge and language can strengthen adaptation planning and implementation.[132,141,143,144] Guidance for incorporating this information and Tribal input by non-Tribal entities can inform respectful and reciprocal collaboration.[132,176,177]

Key Message 24.3

Climate Adaptation and Mitigation Strategies Improve Individual and Community Health

Climate change has wide-ranging effects on lives and livelihoods (*very likely*, *very high confidence*), healthcare systems (*high confidence*), and community cohesion (*high confidence*). These diverse impacts will require integrated, innovative response from collaborations between public health and other sectors, such as emergency management, agriculture, and urban planning. Because of historical and systemic biases, communities of color are especially vulnerable to these negative impacts (*very likely*, *very high confidence*). Mitigation and adaptation strategies, such as expanded use of green infrastructure, heat-health early warning systems, and improved stormwater management systems, when developed in collaboration with affected communities, have the potential to improve individual and community health (*high confidence*).

Risk

The health of Midwestern populations is at risk from increased extreme heat, precipitation, drought, and flooding, along with reductions in air quality and increased incidence of vector- and waterborne illnesses (Ch. 15). Physical injury and illness resulting from climate-related hazards may also influence mental health and can reduce quality of life and community function as traditional forms of connection and culture are lost or diminished.[178,179]

An individual's exposure and sensitivity to climate change are influenced by preexisting health conditions, age and gender, race and ethnicity, access to resources, and the level of local adaptive capacity.[179,180,181,182] Therefore, climate change impacts on health are not distributed equally across populations. Historical policies and systemic racism have created conditions that leave lower-income individuals and people of color more vulnerable to climate-related hazards (KMs 15.2, 16.1).[179,182,183,184] Environmental and social conditions such as old or deteriorating housing stock, inadequate tree cover, poor or degraded stormwater infrastructure, increased exposure to air pollution, limited transportation access, and lack of preventive healthcare services amplify climate-related hazards in the Midwest.[181,183,185]

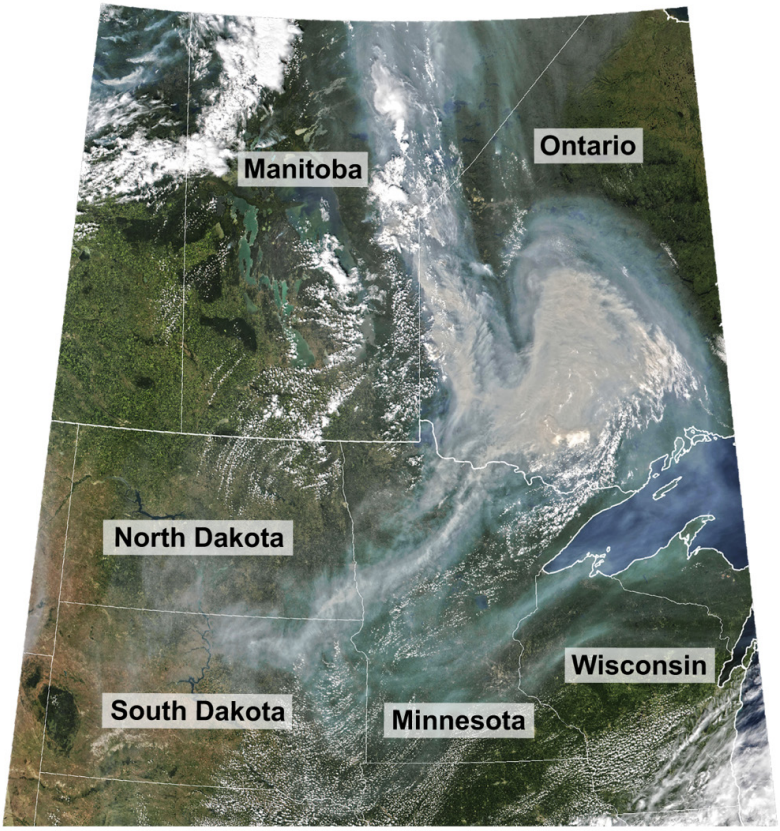
Impacts

Rising temperatures can increase the production of ground-level ozone and particulate matter (KM 14.1). Exposure to these air pollutants can cause or worsen cardiovascular and respiratory illnesses and lead to premature death.[186,187] Future warming under a very high scenario (RCP8.5) is projected to increase exposure to ground-level ozone by midcentury, with higher ozone-attributable death rates in counties in the Midwest and Great Plains than in the rest of the United States.[188] This association may be impacted by population factors, such as density and baseline death rates.[188] Mitigation efforts that reduce ozone can yield large reductions in associated healthcare costs.[189]

Projected increases in extreme heat events across the Midwest amplify the risk of heat-related and respiratory illnesses. A July 2012 extreme heat event in Wisconsin was associated with approximately $290.3 million (in 2022 dollars) in damages due to loss of life, hospitalizations, lost wages, and other health-related costs.[190] By the end of the century, approximately 1,200 deaths related to extreme heat would be avoided under an intermediate scenario (RCP4.5) compared to a very high scenario (RCP8.5).[191]

While many of the worst wildfires occur in the western US, there are scattered areas of high wildfire risk throughout the Upper Midwest (Focus on Western Wildfires).[192] Wildfire smoke from both local and distant sources (Figure 24.7) poses a threat to human health by aggravating cardiovascular and respiratory conditions such as heart arrhythmias and asthma.[89,193] A study of hospital admissions across the US between 2006 and 2015 found that an increase of 10 micrograms per cubic meter in wildfire-related particulate matter in a hospital's zip code was associated with a nearly 3% increase in probability of an intensive-care-unit admission.[194] Compared to other US census areas, this association was most consistent across Midwestern zip codes. This may be due to the larger population in this region compared to other study regions or the lack of personal protective behaviors.[194] Based on very high (RCP8.5) and intermediate (RCP4.5) future climate projections, many Midwest counties will experience increased exposure to wildfire smoke.[195]

Impacts from Wildfire Smoke in the Midwest



Wildfire smoke from both local and distant sources threatens human health.

Figure 24.7. This satellite image shows wildfire smoke from Canada moving down over the northern Midwest on July 11, 2021. Satellite image credit: Joshua Stevens, NASA Earth Observatory, using VIIRS data from NASA EOSDIS LANCE, GIBS/Worldview, and the Joint Polar Satellite System (JPSS).

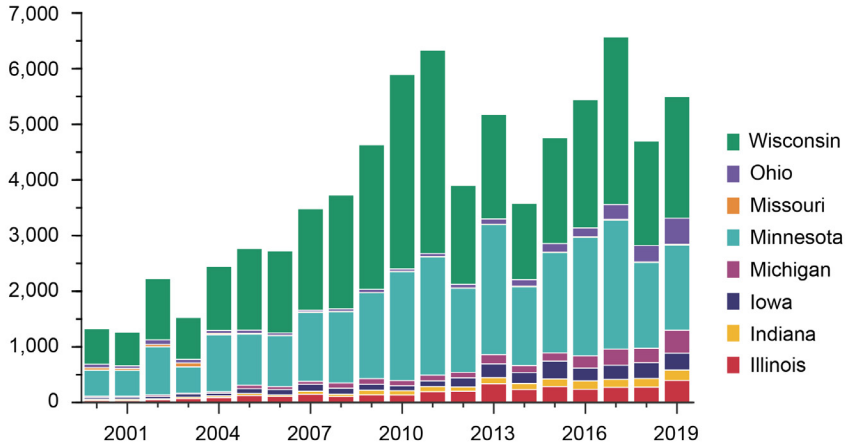
Increasing spring and fall temperatures are leading to rising pollen counts, which can worsen allergies, asthma, and other respiratory conditions (KM 14.4).[196,197] By 2050, increased oak pollen is projected to lead to a 7% annual increase in asthma-related emergency room visits for the Midwest under a very high scenario (RCP8.5) compared to 2% under an intermediate scenario (RCP4.5).[198] Notably, when sensitive individuals are simultaneously exposed to allergens and air pollutants, respiratory reactions can become more severe.[199] Black, Hispanic, and Indigenous populations tend to be disproportionately exposed to air pollution[181] and have the highest rates of asthma and asthma-related deaths and hospitalizations in the United States.[200]

The amount of precipitation falling in the most intense 1% of events increased significantly (45%) in the Midwest between 1958 and 2021 (Figure 2.8a). Under a global warming level of 3.6°F (2°C), extreme precipitation intensity is projected to increase 10%–15%, and perhaps more than 20% in some areas (Figure 2.12). Public health concerns related to flooding in the Midwest include drowning and injury, exposure to mold or waterborne pathogens, economic losses and fiscal strain, employment loss, mental stress, disruption of essential health services, and displacement from the community.[179,184,201,202]

Increases in extreme rainfall are stressing stormwater systems across urban and rural landscapes in the Midwest (KM 24.5).[164,201] Resulting sewage overflow threatens surface water and water distribution networks and increases exposure to waterborne pathogens.[201] By midcentury, precipitation changes are projected to increase the rate of gastrointestinal illness among children due to contaminated drinking water.[203] Under a very high scenario (RCP8.5), some Midwest households that rely on private wells for drinking water, most of which are outside of urban areas, are projected to be at higher risk for nitrate contamination from heavy rainfall and flooding.[204]

Rising temperatures, particularly in winter, and increasing precipitation contribute to the geographic spread of disease-carrying vectors (e.g., ticks and mosquitoes) into and across the Midwest.[205,206] Lyme disease, caused by the bacterium *Borrelia burgdorferi*, is the most prevalent vector-borne disease in the United States and is now endemic to the Midwest (Figure 24.8).[207] Health costs related to Lyme disease are substantial. One study estimated that in 2012, the health-related costs of treating Lyme disease in Michigan, which at the time was not a high-incidence state, was approximately $9 million (in 2022 dollars).[190] The tick species *Amblyomma americanum*, linked to ehrlichiosis and other serious diseases, has already been reported in the Upper Midwest, and projections indicate considerable potential expansion throughout this century.[208]

Midwest Region Lyme Disease Case Counts by State (2000–2019)



Lyme disease incidence has increased across the Midwest.

Figure 24.8. The graph shows annual reports of Lyme disease incidence across the Midwest between 2000 and 2019. Factors such as rising temperatures, increased precipitation, warmer winters and land-use change have contributed to an increase in the incidence of Lyme disease across the region. Figure credit: University of Minnesota Climate Adaptation Partnership, NOAA NCEI, and CISESS NC.

Milder winter temperatures and changes in precipitation patterns are also increasing the risk of mosquito-borne arboviruses such as dengue, chikungunya, Zika, yellow fever, and West Nile virus.[209] By 2050, areas like the Ohio Valley are projected to have approximately 99–201 annual cases of West Nile virus under an intermediate scenario (RCP4.5) or 112–231 annual cases under a very high scenario (RCP8.5).[210]

Stress associated with experiencing climate-related disasters is impacting the mental health of people living in the Midwest[179,211] and is expected to increase as the frequency of extreme events rises. The trauma caused by a disaster, such as losing one's home, job, or livelihood or being displaced from one's community, can contribute to chronic depression, anxiety, and post-traumatic stress disorder.[212,213] In addition, people can suffer a loss of social connections, bear witness to people being harmed and landscapes destroyed, and confront an uncertain future, any of which can trigger or intensify adverse mental health conditions.[178,214] Farmers and others dependent on agriculture for their livelihood are particularly at risk.[212,215,216] Many rural Midwesterners already experience obstacles to utilizing healthcare services,[217] including mental health services.[218,219]

Climate Resilience for Healthier Outcomes

Without efforts to reduce emissions and promote climate resilience, the Midwest will experience an increase in climate-related deaths, injury, and disease and a decrease in mental wellness.[220,221] Furthermore, because these health outcomes are linked to key social and environmental determinants of health, they are expected to disrupt community well-being, with costs and consequences for livelihood, social and cultural connections, education, transportation, and access to essential services.[178,182,221,222] Health disparities tied to race, ethnicity, age, and income are linked to an inequitable distribution of these climate-related health outcomes at individual and population levels.[179,184]

Actions and investments to reduce climate-related health and community impacts such as increased tree cover, weatherization programs, improved stormwater management, heat-health early warning systems, and culturally relevant climate education and climate services (Box 24.1) can yield multiple benefits for individual and community health while helping to advance more equitable climate adaptation.[182,223,224,225,226,227] Sufficient data, technical services, and tools on climate-related health risks, racial and socioeconomic disparities, and socioenvironmental determinants of health would help increase the effective management of emerging and anticipated climate and health-related risks.[182,204,227] For example, the CDC has advanced a framework for cross-sector collaboration that identifies a broad range of resources to reduce climate-related health risks.

Leadership efforts by the emergency management sector in the Midwest to address climate threats to individual and community health highlight the important role for this sector in adaptation planning.[220,228,229] The increased frequency of extreme events is expanding the need for more resources to support disaster preparedness and response, especially for vulnerable communities.[182,228,230]

Box 24.1. Midwest Educational Resources

The Midwest has a rich and expanding body of formal and informal climate education and services available to educators and resource managers of all ages and backgrounds. These efforts help build a climate-informed and responsive society and connect to impacts as well as adaptation and mitigation activities discussed throughout this chapter. Built on the National Research Council (NRC) Framework for K–12 Science Education,[231] educators from across the country created the Next Generation of Science Standards (NGSS), which includes contemporary climate science.[232] Incorporation of these standards varies across the Midwest. Illinois, Iowa, and Michigan have adopted the NGSS, while others have developed their own standards based on the NRC framework.[233] In response, educators have created new climate curriculums and activities for students across K–12 (e.g., Muhich and Rood 2022[234]). Recent federal investments, such as one establishing the Midwest Climate Adaptation Science Center,[235] augment climate research and outreach across the region, connecting with more communities and developing a stronger climate adaptation and community of practice. Since the publication of the Fourth National Climate Assessment in 2018, coordinated efforts have increased among extension professionals, who help translate climate research into practice to help rural and urban communities prepare for and respond to climate change. These and many other university, Tribal, and private entities are collaborating to expand the breadth and reach of climate education and services across the Midwest.

Key Message 24.4

Green Infrastructure and Investment Solutions Can Address Costly Climate Change Impacts

Increases in temperatures and extreme precipitation events are already challenging aging infrastructure and are expected to impair surface transportation, water navigation, and the electrical grid (*likely*, *medium confidence*). Shifts in the timing and intensity of rainfall are expected to disrupt transportation along major rivers and increase chronic flooding (*likely*, *high confidence*). Green infrastructure and public and private investments may mitigate losses, provide relief from heat, and offer other ways to adapt the built environment to a changing climate (*medium confidence*).

Risk

Midwest infrastructure, including dams, bridges, roads, wastewater facilities, and energy generation and distribution systems, need repair,[236] with estimated costs for upgrading these systems totaling $7,547 (in 2022 dollars) on average per capita across the Midwest. Projected changes in precipitation and temperatures increase the risk of failure and cost. Although the Midwest has had numerous state-level and federally declared flood disasters, the risk of loss due to recurrent, underreported inland and urban flooding events increases as the frequency of intense precipitation events rises. Fluctuating water levels make efficient navigation of goods and services through the region's rivers and the Great Lakes more challenging.

Impacts

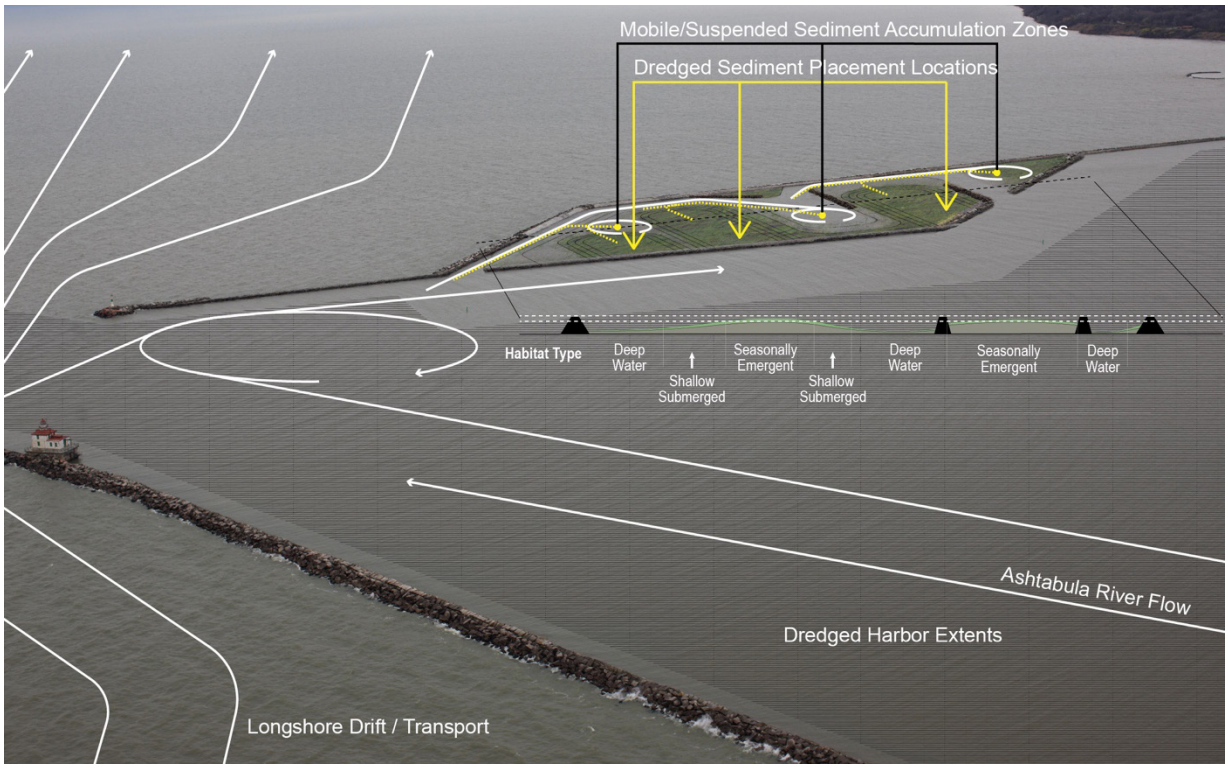
Interest in the impacts of climate change on infrastructure has grown significantly over the last decade.[237] Although improvements have been made, recent grades based on capacity, condition, funding, future need, operations and maintenance, public safety, resilience, and innovation across Midwestern states vary from a C to a D+.[236] Significant repairs are needed in surface transportation, wastewater and stormwater, dams, ports, and the energy grid. Projected increases in temperature and more intense precipitation under a very high scenario (RCP8.5) are expected to increase costs associated with rail and roads (amounting to hundreds of billions of dollars annually by 2090), with significant reductions to these estimates under an intermediate scenario (RCP4.5).[238] For instance, projected rises in temperature are expected to increase the width of cracks caused by deicing salts in reinforced-concrete bridges.[239]

The commercial transport of goods and services along the major rivers (Mississippi, Missouri, and Ohio Rivers; KM 24.5), largely controlled by a system of locks and dams, is at risk from increased precipitation extremes. High-flow events reduce traffic on the river systems, which may be limited to daytime operation only or cease altogether. During low-flow events, channels are reduced and potentially need dredging. These hydrologic extremes increase costs and lead to delays in the delivery of commodities like food and fertilizer. Along the main stem of the Ohio River, increases in the spring (March) maximum and decreases in the fall (October) minimum flow discharge are projected for 2070–2099 under high (SRES [Special Report on Emissions Scenarios] A1B) and very high (SRES A2) scenarios, with up to a 35% change expected relative to 1952–2011.[240] Without coordinated adjustments to monitoring, water releases, and communications along the river, significant disruptions to traffic flow and volume of goods transported are expected.

Water transport is the most carbon- and fuel-efficient means of transport, especially compared to rail and truck.[241] Fluctuating Great Lakes water levels, coupled with diverse ecological and geophysical conditions, create unique coastal environments that necessitate funding and construction strategies that are closely

tied to local ecological, economic, and social conditions. The period 1998–2013 saw some of the lowest water levels on the Great Lakes in recorded history, whereas the 2020s have seen some of the highest on record.[242] Great Lakes ports (Figure 24.9) are located at the vital intersections of ecological, cultural, and infrastructural systems, and port operations attempt to serve these overlapping, and at times conflicting, value systems.[243,244,245] In some cases, ports are taking on the work of ecological restoration as well as protection, property management, and urban industrial remediation—the types of efforts that can promote industrial opportunities, urban well-being, and ecological health. A good example of this is Toledo's More Than a Port initiative.[246] Another example is the multiyear Healthy Port Futures initiative, supported by the Great Lakes Protection Fund. This project reimagines how ports can function to enhance the ecological and social health of the surrounding community and ecosystem through sediment management, as well as through the ways it informs the design and restoration of public landscapes in critical nearshore habitats across the region.

Beneficial Use Wetland Creation for Healthy Ports



Innovative design of coastal infrastructure, such as the Ashtabula Port, allows the built environment to deliver social and environmental services.

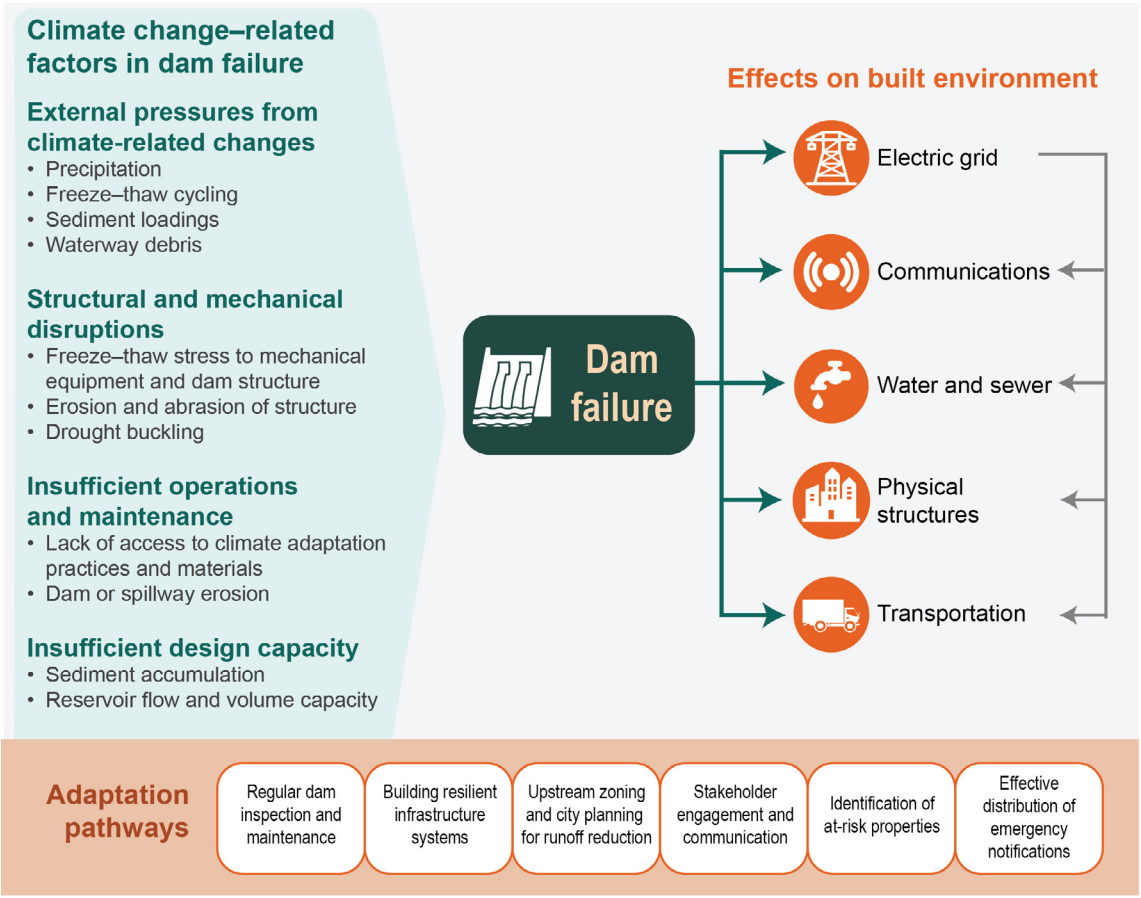
Figure 24.9. The image shows an overview of the harbor in Ashtabula, Ohio, the site of a wetland creation project by the US Army Corps of Engineers with support from Healthy Port Futures. This project, which works with the flow on the Ashtabula River into Lake Erie, was one of the first attempts in the Great Lakes to establish a partially open wetland system with reused dredge material. This design permits an occasional, ecologically necessary disturbance that will promote wetland complexity while also allowing for an important hydrological connection to the nearshore. The figure highlights areas of material placement (solid yellow lines) and sediment movement and accumulation (solid white lines, including sediment transported naturally along the shore). Sediment that accumulates in the wetland channels is placed in the dredged sediment placement locations (dashed yellow lines) every two to three years. This way, the project can employ an adaptive management approach and respond to successes and challenges that may arise. The project will create diverse habitat types including deep water, shallow submerged areas, seasonally emergent areas, and the adjacent open water areas (habits indicated by the light beige and green shading). The built project differs slightly from what is shown here. Adapted from Burkholder et al. 2022.[247]

An aging energy grid, combined with the extent and timing of a transition to different sources of energy generation, creates uncertainty about the impact of climate change on the grid itself. Increases in air temperature, rainfall, and the intensity and frequency of wildfires and storms are expected to disrupt grid efficiency and function, including maximum capacities and outage rates of transmission lines, transformers, and substations.[248] Climate change will reduce US transmission capacity by roughly 2%–8% during peak demand periods by 2100 across a range of scenarios (low [RCP2.6] to very high [RCP8.5]). Average summertime transmission line capacity reductions could range from 2%–6% under the same scenarios by the midcentury, with the Midwest seeing the largest reductions.[249] Transmission infrastructure failures, including those caused by mechanical failures and unplanned surges in electrical current, are projected to occur more frequently.[248] Given the strong push toward renewable energy and electrification of all systems, including transportation, it is uncertain whether the current grid will be able to handle the ongoing and anticipated changes in energy generation and distribution.

Renewable energy production in the Midwest has grown by more than 275% over the last decade,[250] reducing carbon emissions from the energy sector, although less so than in other regions. The growth of investment in renewable energy is contributing to the Midwest's economy. In Iowa, public interest coupled with public and private investment has advanced the state to the second-highest wind energy–producing state in the country and leading the Nation in megawatt capacity per capita. In Adair County, Iowa, investments by MidAmerican Energy Company have led to the installation of two large wind farms that are cumulatively expected to produce 550 megawatts of capacity to the grid and provide well-paying jobs.[251] However, the extent of growth in solar and wind power across the Midwest is constricted by a patchwork of state and local land-use laws and ordinances banning or regulating the siting of solar and wind power generation projects.[252]

Illinois, Iowa, Missouri, Wisconsin, and Minnesota are at high risk for increased riverine flood damage.[253] Of nearly 92,000 dams inventoried by the US Army Corps of Engineers, the average dam age is 61 years, an age when many dams require expensive repairs, and 75% are classified as high hazard potential. Climate-forced external pressures interact in complex ways, leading to effects on the built environment (Figure 24.10). Increased occurrence of extreme precipitation events stresses aging infrastructure and exacerbates the risk dams pose;[254] since 2018, 30 dam failures or near failures have occurred across the Midwest.

Climate Change–Related Factors in Dam Failure



Climate change–related factors contribute to dam failure, with cascading impacts on the built environment.

Figure 24.10. The graphic shows contributing causes for dam failure related to climate change, first-order effects of dam failure on the built environment, and adaptation pathways. Dam systems may experience climate change–related impacts independently or in parallel, and these impacts can have cascading effects. Damage to transportation, power, water, and communication infrastructure can limit a community's ability to access health services. Damage to infrastructure, land, and the built environment can negatively impact local businesses and the economy. Adaptation pathways provide a basis for communities to address dam risk from a variety of system viewpoints. Figure credit: MITRE, University of Pennsylvania, American Society of Adaptation Professionals, and The Ohio State University.

Increases in extreme rainfall events (Figure 2.8) negatively impact property, public health and safety, and transportation systems. Urban and rural communities are at risk from projected increases in frequency and intensity of extreme rainfall events. Even when events are not categorized as state or federal disasters, communities and households experience property damage from basement flooding, health impacts from sewer overflows, and traffic disruptions from storm damage.[179,255] Increases in state and federally declared disasters are expected to become more frequent. NOAA's Billion-Dollar Weather and Climate Disasters tracking data now offer a detailed analysis of disasters reaching this cost impact, but smaller events are difficult to assess.[160]

Moving away from disaster-struck areas is more difficult for people with low income than it is for wealthier populations.[256,257,258] Billion-dollar disasters and smaller-scale disasters alike have led to individual property damage and, in some cases, complete loss. A history of repairing buildings after repeated disasters has led to cases where structures have been rebuilt more than 30 times at a cost of nearly 100 times the value of the property.[259] Between January 1989 and August 2019, more than 18,000 structures experienced chronic

losses in Ohio, Iowa, Illinois, and Missouri.[260] Repetitive losses are trending upward due to increases in extreme storms and flooding across the region. Some Midwest communities are facing relocation due to projected increases in heavy precipitation and increased flood risk. Managed retreat, or community relocation—moving an entire community out of harm's way—is often discussed as a coastal adaptation measure, but it has applied to the Midwest for decades. Examples, including the town of Valmeyer, Illinois, and the relocation of the Bad River Band of Lake Superior Chippewa in Odanah, Wisconsin, offer lessons on the benefits and drawbacks of flood-induced relocation. Equitable and effective relocation benefits from the coordination of dozens of jurisdictions and substantial funding and often takes years to achieve.[259] These relocation efforts can disrupt social relationships and institutions.[261] As described in Box 20.1, successful and equitable relocation programs require strong community engagement and an open recognition of the multiple drivers of migration, including environmental, economic, and governance conditions.

Innovative Finance and Investments

Recent federal funding from the Infrastructure Investment and Jobs Act is pushing funding to state and local governments to support long-delayed infrastructure upgrades and repairs. As of March 2023, more than $36 billion (in 2022 dollars) in project funding has been invested or announced for infrastructure projects in the Midwest, with an average 15.5% of funding directed toward climate, energy, and environment projects.[262] Along with this infusion of public dollars, the infrastructure investment landscape is changing, with private investment, environmental impact bonds (EIBs), and other financing tools being used in the region. An EIB is a financing tool that allows private investors to provide up-front capital for a pilot project or to scale up an existing project, with the goal of achieving a set of environmental outcomes. Some localities have combined innovative infrastructure approaches, including green infrastructure, with new funding models like EIBs or public–private partnerships. An innovative finance and construction approach being used by the Milwaukee Metropolitan Sewer District (MMSD) is an example of proactive climate adaptation. The MMSD reduced the annual number of combined sewer overflow events from 50–60 in the early 1990s to 2.3 in 2019. Using a community-based public–private partnership, the MMSD is now looking to add an additional 20 million gallons of green stormwater infrastructure (GSI) capture capacity beyond the current capacity of 40 million gallons. The project will allow for public and private investment to support local business and achieve massive green infrastructure benefits by 2026.[263] Other municipalities are implementing GSI, and it is estimated that private investments across Ohio, Wisconsin, Minnesota, Illinois, and Indiana can support more than a billion dollars of GSI.[264] Aside from leveraging private investment, some municipalities are combining funding from multiple public sources, including from different agencies and at different scales of government (federal and state) to fully fund projects. In the case of the Bee Branch Watershed Flood Mitigation Project in Dubuque, Iowa, eight federal and three state funding sources have been applied to the $250 million (dollar year not reported) project.[265]

Careful placement and design of green infrastructure provides benefits beyond flood reduction, such as reducing the urban heat island effect and providing relief to city residents during heatwaves. Green infrastructure such as increased vegetation, stormwater capture systems such as bioswales (vegetative areas that concentrate and move stormwater while filtering for debris and pollution) and detention ponds, and open green spaces can significantly lower temperatures and channel natural airflow, which enhances the cooling effect from the green infrastructure.[266]

Key Message 24.5

Managing Extremes Is Necessary to Minimize Impacts on Water Quality and Quantity

Climate-related changes to water quantity and quality are increasing the risks to ecosystem health, adequate food production, surface water and groundwater uses, and recreation (*high confidence*). Projected increases in droughts, floods, and runoff events across the Mississippi River basin and the Great Lakes will adversely impact ecosystems through increased erosion, harmful algal blooms, and expansion of invasive species (*likely*, *high confidence*). Federal and state agencies and nongovernmental organizations are cooperating on adaptation efforts related to streamflow, water quality, and other water issues (*high confidence*).

Risk

Climate change is affecting the quality and quantity of water in the Midwest, as well as management practices related to the health of human and natural systems.[267] Across both the Mississippi River and Great Lakes basins, climate change has impacted streams, rivers, and lakes—all vital to urban, rural, and Tribal communities. Drinking water sources, private wells, and agricultural irrigation sources are at risk. Observed changes in hydrology include increases in the variability of lake levels, evaporation, and water temperatures, along with more intense precipitation,[268] including lake-effect snow, and shorter duration of snow and ice cover. These changes impact food production, businesses, industries, tourism, and recreation. Ecologically sensitive aquatic systems in the Great Lakes are at risk due to changes in lake temperatures and invasive species (KM 24.2).[269]

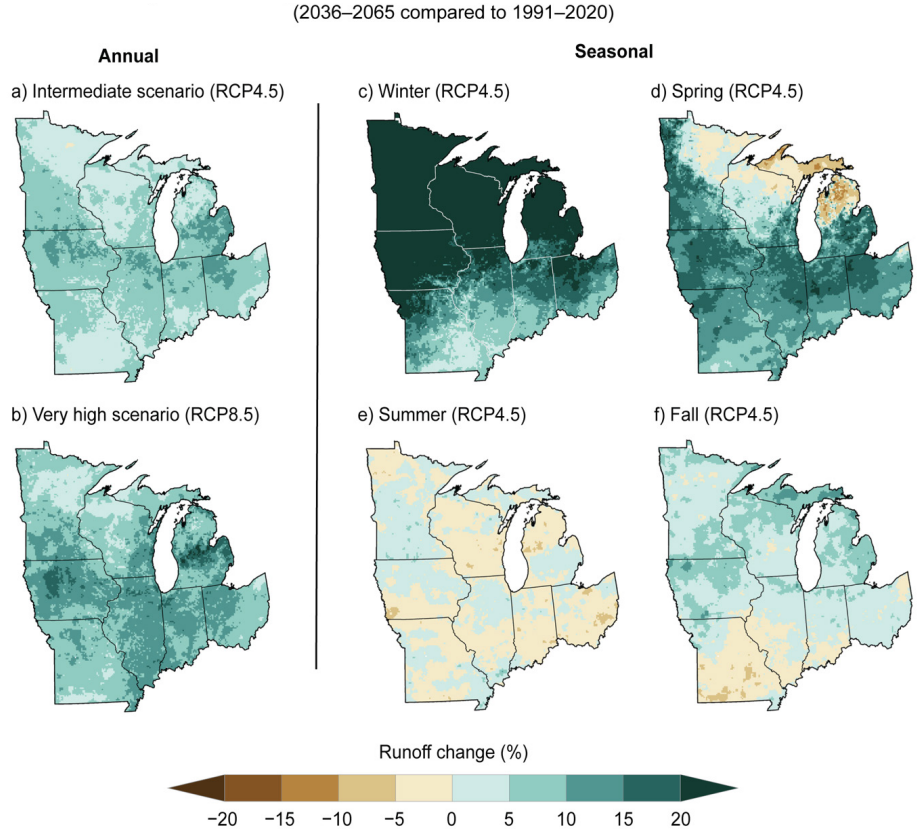
Impacts

Mississippi River System

The Ohio River, upper Mississippi River, and lower Missouri River are susceptible to floods and droughts based on projected changes in precipitation, evapotranspiration, and soil moisture (Ch. 4). Precipitation has increased in recent decades (Ch. 2) with more extreme variability and rapid shifts between wet and dry periods (Figure 24.1). Projections across a range of scenarios (low [SSP1-2.6], intermediate [SSP2-4.5], and very high [SSP5-8.5]) indicate future increases in annual precipitation of 0.3% to 1.5% per decade in the eastern Midwest and 0.2% to 0.5% in the western Midwest.[15] Winter and spring precipitation is expected to increase, while summer and autumn precipitation is projected to be more variable.[15]

Cumulative runoff has increased in recent decades[240] and is projected to continue increasing through midcentury (Figure 24.11), leading to increased riverine flooding in the Ohio, upper Mississippi, and parts of the Missouri River basins. Prolonged periods of increased cumulative runoff have adversely impacted ecosystems and commerce and are projected to continue to do so.[240] Observed decreases in the length of winter have reduced snowfall across the Midwest,[270] with negative impacts for snow-dependent winter tourism for the Midwest and Great Lakes (KM 24.2).[178] By the end of the century, projections indicate reductions in snowstorm frequency and size and snow-water equivalent totals;[271] shorter snow seasons; and fewer intense snowfall events.[272]

Projected Changes in Cumulative Seasonal and Annual Runoff



Projected changes in cumulative local runoff will lead to increased flooding susceptibility in winter and spring, with increased flash drought potential in summer.

Figure 24.11. The maps show projected changes in the annual approximate cumulative gridded local runoff generation (referred to as cumulative runoff) for intermediate (RCP4.5) and very high (RCP8.5) scenarios (**a**, **b**) and seasonal approximate cumulative runoff for an intermediate (RCP4.5) scenario (**c**–**f**). The cumulative runoff is defined as the gridded cell-by-cell ability of the landscape to generate excess water for potential downstream river runoff using the Variable Infiltration Capacity (VIC) land-surface model. The cumulative runoff was developed using Coupled Model Intercomparison Project Phase 5–modeled scenarios and the VIC hydrology model. Cumulative runoff is projected to increase annually across the Midwest between 2036 and 2065 compared to 1991–2020 (shown in percent changes). Cumulative runoff increases are expected throughout the region in winter and across all but the northern Great Lakes in spring and southern Midwest in fall. Summer cumulative runoff is projected to be more variable. The result of the projected increases (and in summer, both increases and decreases) in cumulative runoff will be increased stresses to ecosystems, the built environment, natural and water resources, and agriculture. Figure credit: NOAA NWS, NOAA NCEI, and CISESS NC.

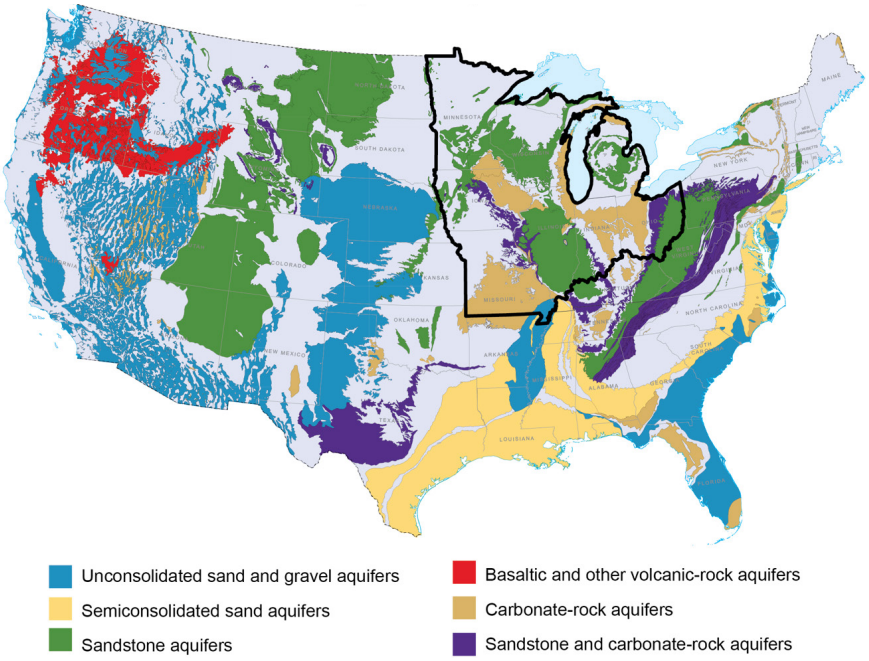
Midwest droughts develop in response to precipitation deficits or extremely high temperatures and evapotranspiration (KM 4.1). In recent decades, evapotranspiration has become, and is expected to continue to be, the dominant driver of drought,[273,274] especially across the eastern Midwest.[275] Precipitation deficiencies remain the primary driver of increased drought in the southwestern Midwest.[276]

Groundwater storage is important for water resource management, including wastewater permitting, water supply, and fisheries. Groundwater recharge is projected to be variable in the Midwest,[277] with water imbalances[28] resulting from precipitation and evapotranspiration changes. Failure of private wells is expected to increase during droughts as water tables drop with increased irrigation and water usage.

Vulnerability to water shortages and water quality depend, in part, on the primary source for water use and drinking water for any given location (aquifers/deep groundwater versus surface/shallow groundwater;

Figure 24.12). Thus, drought occurrences will have different impacts based on the source. For surface water, decreases in summer runoff (Figure 24.11) can reduce water quality and streamflows.[278] Aquifers, on the other hand, are more resilient to rapid hydrological transitions but are still impacted by longer-term drought conditions.[278] Precipitation is projected to increase in all seasons, while runoff is projected to increase in the cool season but become more variable in the warm season (Figure 24.11). The combination of warming temperatures and more variable summer runoff suggests an increased risk of drought for people, crops, livestock, and ecosystems across the region.[240] At the same time, increased precipitation and runoff events (Figure 24.11; KM 4.1) are expected to increase nuisance flooding (KM. 24.4) and sewage spills and resulting odor releases, as well as deteriorate water quality due to increased uncontrolled discharges. Stormwater runoff increases are expected to harm aging infrastructure and lead to higher costs for new systems (KM 24.4). Thus, urban and rural managers are implementing best practices for water quality across diverse landscapes, from agriculture (Figure 24.4) to forests (Figure 24.5) and the built environment (KM 24.4).[164]

Map of US Aquifers



Vulnerability to disruptions in water quality and quantity varies by location, depending on the primary source of water for drinking and other uses.

Figure 24.12. The USGS Ground Water Atlas of the United States provides a complete summary of the Nation's groundwater resources and includes the location, geography, geology, and hydrologic characteristics of the major US aquifers. Surface water and groundwater (aquifers) are the primary sources of water in the Midwest and Great Lakes. The areas highlighted in color represent groundwater aquifers, while areas in gray represent surface water as the main source. The black boundary outlines the Midwest region. Changes in rainfall and runoff patterns impact water availability and water tables differently across the Midwest, depending on whether the main source of water is surface- or aquifer-based. For more information on aquifers outside the contiguous US, visit the USGS Ground Water Atlas of the United States and Principal Aquifers of the United States. Adapted from USGS 2021.[279]

Harmful algal blooms (HABs) and their impacts to water quality, food production, recreation, tourism, and ecosystems continue to be a major concern across parts of the Midwest. Observed increases in precipitation[15,268] are resulting in, and are projected to continue to result in, increases of sediment and nutrient loads in the Mississippi River system. However, research has been inconsistent about whether HAB severity and magnitude in the Midwest have been increasing, remaining constant, or decreasing.[280,281]

Great Lakes

The Great Lakes are the largest freshwater ecosystem on Earth[282] and are among the fastest-warming lakes in the world.[283] The Great Lakes Water Quality Agreement between the United States and Canada established a suite of nine indicators to assess the ecosystem health of the Great Lakes (Table 24.1). While efforts to restore and protect the Great Lakes are ongoing, this ecosystem is at risk from shifts in seasonality (changes in the timing of the formation and destruction of temperature stratification) and from changes in ice cover, maximum summer temperatures, and oxygen levels, which have significant impacts on fisheries and habitats in the lakes.[282] Invasive species and threats to biodiversity are the greatest concerns of the Great Lakes.[282] Aquatic invasive species (KM 24.2) can degrade water quality by decreasing water clarity, concentrating toxins, and altering nutrient flows within the food web. Great Lakes water quality across a wide range of metrics currently ranges from fair to good.[282]

Table 24.1. State of the Great Lakes 2022 Assessment

CAPTION: The EPA and Environment and Climate Change Canada work jointly to meet the mission of the Great Lakes Water Quality Agreement. As part of this effort, the State of the Great Lakes Report is released every three years. The following table details the state of the Great Lakes using 10 Indicators. The assessments are basin-wide and typically vary between lakes. The metrics listed are synthesized to determine the status and trends of each indicator. The definitions for "poor," "fair," and "good" are quantitative, vary between indicators, and are documented in the report (ECCC and EPA, 2022).[282] Status assessments are not provided for the climate trends indicators. Adapted from ECCC and EPA 2022.[282]

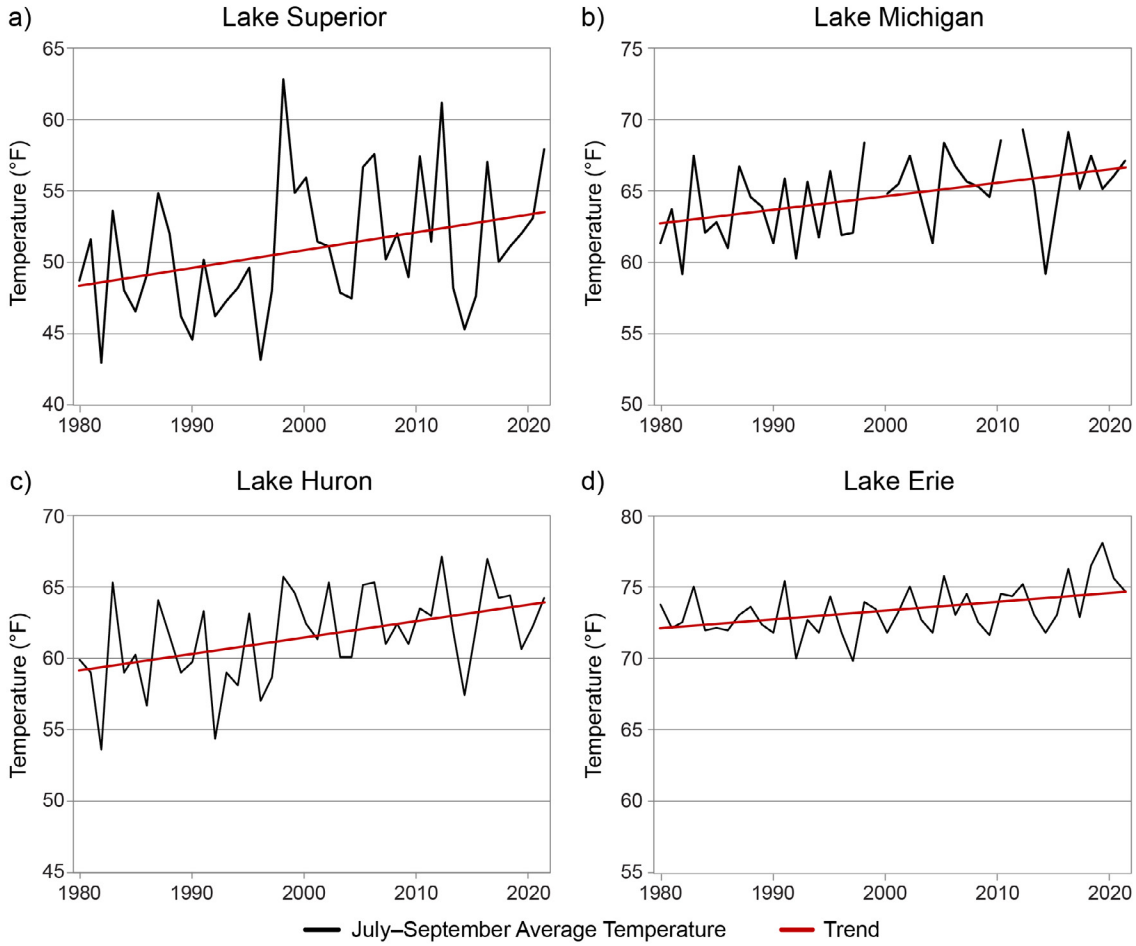
Great Lakes Indicator	Metric	Status	Trend
Drinking Water	US/Canadian drinking water standards (microbial, radiological, chemical)	Good	Unchanging
Beaches	*E. coli* assays	Good	Unchanging–improving
Fish Consumption	Polychlorinated biphenyls [PCBs] and mercury in fish flesh	Fair	Improving
Toxic Chemicals	Concentrations of compounds (PCBs, mercury, polybrominated diphenyl ethers, and others) in sediment, water, whole fish, and herring gull eggs	Fair	Unchanging–improving
Habitat and Species	Overall health and habitat conditions and availability of invertebrates, fish, amphibians, birds, plants, connectivity	Fair	Unchanging
Nutrients and Algae	Nutrient concentration, harmful algal blooms, *Cladophora*	Fair	Unchanging
Invasive Species	Rate of introduction	Good	Unchanging
Invasive Species	Aquatic invasive species impacts	Poor	Deteriorating–unchanging
Groundwater	Chloride/nitrate concentrations	Good	Undetermined
Watershed Impacts	Forest and land cover, hardened shorelines, tributary water quality, human population	Fair	Unchanging
Climate Trends	Lake levels	N/A	Unchanging–increasing
Climate Trends	Surface water temperature	N/A	Increasing
Climate Trends	Ice cover	N/A	Decreasing

The Great Lakes have witnessed significant water-level variability over the last several decades, with low water levels from 1998 to 2013 and high-water levels since 2015. This variability is due in part to changes in the seasonality and intensity of precipitation (including lake-effect snow), warmer lake temperatures, lake evaporation, and loss of ice cover.[284] The twin stressors of increases in precipitation and air temperature result in increased interannual variability in lake levels.[285] However, the complex interactions between lakes, land, and atmosphere make the system difficult to model, so that long-term projections of net basin supply and lake levels have high uncertainty.[6] These climate changes impede current water management practices for the Great Lakes, which are similar to those elsewhere in the Midwest, with the added challenge of transboundary water agreements with Canada (Ch. 4). For example, low water levels limit power production from hydropower facilities and pose risks to shipping[286] and ports (KM 24.4), while high water levels lead to shoreline erosion, loss of coastal habitat[287] and flooded communities. Shorelines are also at risk from high-wind events during high-water-level episodes.[288]

Great Lakes water and air temperatures have been rising since 1980[282] (Figure 24.13). Summer surface water temperatures recorded by offshore buoys have shown nearly uniform increases across the upper Great Lakes (Superior, Michigan, and Huron). Lake Erie shows slower warming rates, while there are not enough data from Ontario to make a determination. Increases in lake surface temperatures are expected on all five lakes.[289] Although uncertainty remains on the seasonal and spatial variability, increased temperatures are expected to result in loss of suitable fish habitat.[290] How the surface warming will affect the rest of the water column and the overall impact on the ecosystem is not as well characterized. Coupled with increasing water temperatures is a decrease in winter ice cover,[291] which is observed on all five lakes and has cascading impacts on ecosystems and culture (KM 24.2; Figure 24.6).

Great Lakes Summer Surface Water Temperature Trends

(1980–2021)



Summer surface water temperatures have been increasing for Lakes Superior, Michigan, Huron, and Erie since the late 1970s.

Figure 24.13. The graphs show summer (July–September) surface water temperatures for the period 1980–2021 observed from buoys in the offshore waters of Lakes Superior, Michigan, Huron, and Erie. The upper lakes (Superior, Michigan, and Huron; **a**–**c**) show similar trends toward warmer temperatures against a background of strong interannual variability, while Lake Erie (**d**) shows a weaker but still positive trend. To facilitate comparison of trends, a temperature range of 25°F is used for the vertical axis on all four charts, with actual temperatures varying across the different lakes. Figure credit: University of Minnesota Duluth, NOAA NCEI, and CISESS NC

HABs occurring in portions of all five of the Great Lakes, including western Lake Erie and parts of Lake Superior, are affecting people through poor water quality and advisories against swimming and beachgoing. HABs also negatively impact habitats and fisheries. Projected increases in cumulative annual runoff (Figure 24.11), which elevate the risk of nonpoint-source pollution (natural and human-made pollutants that are carried from many sources by precipitation and runoff) and warming trends across the Great Lakes (Figure 24.13), are expected to promote the growth of HABs through midcentury. Although the direction of change of HABs across the Midwest is inconsistent,[280,281] recent trends in western Lake Erie show a significant increase in the extent and severity of HAB events over the last 20 years.[282]

Managing Hydrologic Complexity and Extremes

Federal, state, and local governments and institutions are working with communities on initiatives to adapt to and/or lessen the impacts of climate change. For example, the US Army Corps of Engineers has partnered with federal agencies, nongovernmental organizations, and institutions on the Ohio River Basin Climate Change project.[240] The goal was to create a comprehensive plan to address changing streamflows and identify adaptations needed to deal with water quantity, quality, and management challenges related to regulations, recreation, navigation, and aquatic habitats (e.g., fisheries). A similar study with NOAA and the University of Minnesota for the upper Mississippi River basin kicked off in 2022. Additionally, a number of climate resilience partnerships throughout the Midwest and Great Lakes have been completed.[292]

As part of the National Integrated Drought Information System, the Midwest Drought Early Warning System was established in 2016 to advance drought monitoring, forecasting, and preparedness in the region and to improve regional capacity to respond to drought.[293,294]

To adapt to extreme runoff, strong private and public partnerships can help formulate best management practices for reducing nutrient and sediment loads into streams and rivers. NOAA is accomplishing this through the Runoff Risk Decision Support project.[295] NOAA is working with state departments of agriculture in parts of the Midwest and Great Lakes, including Minnesota, Wisconsin, Michigan, and Ohio, as well as New York. The NOAA Runoff Risk Decision Support tool provides the agriculture community with timely forecast information on when to apply fertilizers. Most fertilizer applications are executed in the Midwest and Great Lakes during the winter into spring just before planting season, which is also peak runoff season. A significant percentage of total nutrient and sediment losses typically occur from a small number of runoff events each year.[296,297] The information provided by this tool allows farmers to make better-informed decisions on when to apply manure and fertilizer. The correct application of manure and fertilizer will reduce the risk of chemicals entering into river systems. The reduction of excess chemicals, including nitrogen and phosphorus, entering into waterways is important, since high nutrient and sediment loads contribute to impactful environmental HAB and hypoxia (low oxygen level) events.[297] The Mississippi River/Gulf of Mexico Hypoxia Task Force and the US/Canada Great Lakes Water Quality Agreement highlight the need for nutrient load reductions in the Mississippi and Great Lakes watershed systems, due to increasing impacts on both the public health system and ecosystems.[298]

Traceable Accounts

Process Description

The Midwest chapter authors were identified and recruited in August and September of 2021. The goal was to construct the team with at least one author from each of the Midwest states, with attention to geography, interconnected systems, level of expertise, gender, and diversity. The selection of authors was based on Federal Registry Notice comments, USGCRP (US Global Change Research Program) Research Gaps Summary for the Midwest, and author nominations, as well as discussions and nominations by the chapter lead, coordinating lead author, agency chapter lead, and National Coordination Office point of contact. Authors were added iteratively, with those who accepted early providing additional suggestions for subsequent nominations. All but two of the invited authors agreed to participate.

Regular virtual meetings were held during the fall of 2021, with the Zero Order Draft finalized in December 2021. The Midwest chapter hosted a virtual public engagement workshop on January 24, 2022. The key topics selected were well received, with ample discussion and feedback. Authors considered the comments along with inputs provided in the public call for technical material and incorporated the available recent scientific literature in developing the Key Messages for the First Order Draft. Author consensus was built through routine meetings and based on feedback from the NOAA Technical Support Unit (TSU); federal agencies; the National Academies of Sciences, Engineering, and Medicine; and public comment review periods. This iterative process occurred between the Second and Fourth Order Drafts, from the winter of 2022 to the spring of 2023.

Key Message 24.1

Climate-Smart Practices May Offset Complex Climate Interactions in Agriculture

Description of Evidence Base

There is strong evidence that increasing extreme precipitation events, changing seasonality, and rapid transitions between hydrologic conditions are negatively impacting soil conditions and challenging traditional row crop agricultural production in the Midwest, with uncertainty remaining due to local climate influences and limitations with downscaled climate data.[12,18] Studies link the loss of soil and applied nutrients to increasing rainfall, with cascading impacts including financial loss and increased water quality issues. Numerous studies point to future decreases in corn production, in combination with episodic drought, and increases in the production of some crops like wheat due to cooler-season changes including warmer springs and greater rainfall (e.g., Li et al. 2019[2]). Impacts on animal agriculture in the region remain an understudied topic, although some studies have shown impacts are already occurring (e.g., Crist et al. 2020[51]). Many of these projected impact studies rely heavily on a very high scenario (e.g., RCP8.5), which limits the assessment of the full range of uncertainty.

Reports and studies strongly demonstrate the economic importance of specialty crops to the Midwest and their vulnerability to climate change.[56] Most studies to date focus on the impact of spring-freeze injury, although a limited number of studies address other impacts such as excessive moisture, disease, and pest pressure. Evidence suggests a wide range of future outcomes to specialty crops based on species and location of cropping systems within the Midwest. Studies on the direct impacts of rising temperature and altered precipitation patterns on specialty crops across the Midwest remain limited. The evidence base for the impacts of climate change on important pollinators and insect species distributions is growing.

An increasing number of studies address agriculture's impact on climate, particularly the intensification of cropping systems and potential impacts from increased irrigation.[46] Impacts on atmospheric moisture and feedback loops within the system are ongoing.

Studies have linked, at least in part, climate change to crop insurance losses across the US and the Midwest.[75] These losses are related to drought and excess moisture. Building resilience to these hazards is part of a climate-smart approach. Studies to evaluate specific benefits and other impacts from varying climate-smart techniques are evolving.

Major Uncertainties and Research Gaps

Current climate trends are, in some ways, counter to projected climate conditions and differ from other regions of the country. For example, summer daytime warming trends (daily maxima) and drought are not occurring as projected by previous model simulations. Historical changes have been much more seasonally dependent, with the largest increases in temperature occurring during the cooler seasons rather than the summer. A high degree of uncertainty also exists in individual model-projected changes in the intensity and seasonality of future precipitation, as well as the attribution of these complexities to anthropogenic sources. While model consensus strongly points to overall increases in annual temperature, additional investigations on the interactions between agriculture and its impact on climate in the region would help resolve seasonal discrepancies. Reductions in model and scenario uncertainty would improve local impact assessments and decision-making.

More detailed information about projected changes in other climate parameters (e.g., vapor pressure deficit, soil moisture, extremes, and severe events) and impacts on specific crops would be needed for a broader understanding of the potential impacts on agricultural production and increased confidence in the findings. This includes studies beyond corn, soybean, and wheat, including other cash and specialty crops (e.g., apples, pumpkins, cucumbers). Detailed information on secondary climate change impacts (i.e., increased insect, disease, and weed pressure on production) is less well understood as well. Analyses of historical changes in the distributions of agricultural pests are limited, as are model projections of their future distributions.

With respect to social equity and justice concerns for agriculture in the Midwest, identifying and increasing engagement with BIPOC (Black, Indigenous, and People of Color) communities and low-resourced communities across the Midwest could increase the sharing of information and bring resources to these communities to enhance their climate adaptation and mitigation activities already underway. This would lead to a more informed and full assessment of the impacts, adaptation, and mitigation agricultural activities already taking place within these communities. There have been recent federal investments, for example, that have infused support into National Institute of Food and Agriculture programs that bring social and physical scientists together to help fill in this knowledge gap. Work from these new projects could be sought for future National Climate Assessment reports.

Research activities on the ability for climate-smart practices to help agriculture adapt to changing climate conditions and lessen future issues are increasing. However, further investigation of the potential trade-offs between strategies and a diverse set of outcomes based on crop, cover, soil type, and local changes in climate would be needed to increase confidence in their use and whether they reach desired outcomes. Research does support some climate-smart practices, but widespread implementation and interaction of various practices is poorly understood.

Description of Confidence and Likelihood

Based on numerous studies and converging evidence, there is *high confidence* and it is *likely* that climate change is negatively impacting agriculture in various ways. Examinations of historical extreme precipitation events and rapid transitions between hydrological states through novel analysis techniques show that these phenomena are *likely* increasing in number, and projections show that they are *likely* to continue throughout the 21st century. The team focused on the challenges, including poor field conditions and potential crop losses, that are *likely* to accompany these changes in the hydrological conditions. Although crop impacts are *likely* based on similar results across scales and methods, uncertainty in specific impacts by species (crop, insect, etc.) leads to *medium confidence* in future outcomes of row and, especially, specialty crops. Other *likely* changes, including snowmelt timing and extreme precipitation events in spring, will lead to additional impacts on animal agriculture in the region, and attention was given to dairy production as a major component of animal agriculture in the Midwest (*high confidence*). Climate-smart adaptation techniques provide a potential path toward environmental and economic sustainability, but the limited converging evidence and adoption to date lead to overall *medium confidence* in their ability to mitigate future agricultural challenges.

Key Message 24.2

Adaptation May Ease Disruptions to Ecosystems and Their Services

Description of Evidence Base

Strong convergent evidence from many sources in the published and gray literature shows that climate change is impacting natural resources in the Midwest and that these impacts will further intensify with advancing climatic change. However, the amount of evidence varies by ecosystem, the particular type of environmental change, and geographic location within the Midwest.

Strong convergent evidence from published studies shows that Midwestern aquatic ecosystems are responding to increasing temperatures and to changes in extreme weather.[97,99] There is a moderate amount of evidence demonstrating that these systems are responding to increasing precipitation. Several studies show that flooding and drought pose increasing risk to aquatic ecosystems, specifically by altering structure and community dynamics.

The evidence from published studies demonstrating that terrestrial ecosystems are being altered by climate change is strong overall (e.g., Contosta et al. 2019[133]), although the amount of evidence for any given ecosystem type being affected by any given environmental change is variable. Evidence supports the finding that impacts have been more pronounced in more northerly parts of the Midwest. Overall, there is unequivocal evidence that Midwestern ecosystems have been and will continue to be affected by landscape change, and many studies link changes in the functioning of these systems to rising temperatures and reduced snow and ice cover.[133,151] There is strong evidence that these climatic factors have been changing in the Midwest.

Major Uncertainties and Research Gaps

Much of the uncertainty concerning Midwestern natural resource responses to climate change is linked to the varying responses across species, ecosystems, and geographic location. Many species and some ecosystems are subjects of few or no direct studies; some variables have been studied in only one location within the Midwest; and species interact in complex ways that could potentially lessen or reverse direct effects of climate change in some cases—all of which increase the uncertainties of projected climate change responses.

Assessing projected responses to climate change can be challenging because of scale mismatches with climate model output. For example, streams are much smaller than climate model grids and as such require offline downscaling. Although this has been done, it has not covered the breadth of Shared Socioeconomic Pathway (SSP) scenarios.

There is significant uncertainty concerning how widely human communities are adapting their cultural practices to climate change and whether adaptation strategies have documented benefits. Case studies are available,[145] but more information is needed across the full spectrum of Midwestern communities.

Description of Confidence and Likelihood

Broad evidence from published studies indicates it is *likely* that climate change is impacting natural resources in the Midwest (*high confidence*). Published studies show that flooding and drought *likely* pose increasing risk to aquatic ecosystems by altering structure and community dynamics, although agreement on the precise magnitudes of effects is less clear (*medium confidence*). Numerous studies show that rising temperatures, altered winter conditions, and landscape changes are *very likely* altering terrestrial ecosystems and limiting their adaptive capacity (*high confidence*). This is particularly pronounced in northern ecosystems. Emerging evidence shows that losses of ecosystem services are undermining human well-being, causing the loss of economic, cultural, and health benefits (*medium confidence*). Owing to the site- and ecosystem-specific nature of the evidence, it is difficult to make broad generalizations across the Midwest. People are adapting management and cultural practices in response to climate change, particularly for inland lakes and forest systems; many of these practices have co-benefits for ecosystem services, including mitigation of climatic changes (*low confidence*). The authors assess with *low confidence* because of noted knowledge gaps across the Midwest concerning both community actions and documented responses.

Key Message 24.3

Climate Adaptation and Mitigation Strategies Improve Individual and Community Health

Description of Evidence Base

There is strong evidence that increasing temperatures and changes in historical precipitation patterns are occurring across the Midwest and will *likely* continue through the end of the century. The level of air contaminants, such as particulate matter, ozone, and pollen, are positively associated with rising temperatures, and there are numerous studies describing the link between exposure to these contaminants and increased morbidity and mortality.[186,187]

Exposure to climate-related events, such as extreme heat and flooding, has been shown to impact the health and well-being of Midwest communities, as well as degrade social and environmental determinants of health.[178,179] The occurrence of extreme heat and precipitation events is projected to rise across the Midwest. However, there are few in-depth qualitative assessments that capture and report person- or community-specific information from those impacted, particularly the short- and long-term effects of experiencing a climate-related hazard. Increases in intense rainfall have been linked to increased exposure to waterborne contaminants in both public and private drinking water systems in the Midwest.[201,204] Studies using climate projection data have shown that climate-related seasonal precipitation changes will increase the rates of gastrointestinal illness in children.[203]

There is strong evidence that rising temperatures are contributing to the expansion of disease-carrying vectors like ticks and mosquitoes into and across the Midwest.[207] Modeling using climate projections

predicts that the range of many established and newly invasive species will increase throughout the century, increasing the risk of various zoonotic diseases like Lyme disease and West Nile virus.[208]

Climate change is associated with negative impacts on mental health.[211] However, there are few studies, particularly based on Midwest populations, that link robust measures of climate change or climate-related events with clinically validated psychiatric diagnoses.

There is a substantial increase in the number of climate assessments conducted for Midwest states and cities that emphasize the need to address systemic injustice and historical racism and prioritize equity in climate resilience decision-making.[32,299,300] Many of these reports also acknowledge the need to involve disproportionately impacted communities in the design and implementation of resilience strategies. These assessments are not part of the peer-reviewed literature and thus were not considered as part of the evidence base for this section. However, it is notable that many Midwest climate assessments have not only included but also prioritized these issues as part of their climate resilience planning.

Major Uncertainties and Research Gaps

While there are many studies linking climate change to impacts on health and community well-being, only a small number of these studies have been conducted directly or solely on Midwest populations. Furthermore, to capture the breadth of potential impacts, these studies could consider a range of scenarios, not just the highest or worst-case scenarios.

There is a gap in research characterizing how climate-related health impacts differ based on local population-specific characteristics and shared realities, particularly across the urban–rural gradient and multiple Tribal Nations and as a result of increasing immigration. This is particularly true for specific health outcomes (e.g., mental health) and health determinants (e.g., livelihood). Such information would be useful for developing targeted, effective intervention strategies that address existing inequities and historical racism.

The literature currently lacks studies specific to the Midwest that attempt to quantify the cost burden associated with climate impacts on health and key health determinants like livelihood or housing security. Thus, there is uncertainty about how much climate change impacts are costing Midwest communities in terms of injury, disease, job loss, property damage, healthcare utilization, and more.

Certain emerging topics for climate and health in the Midwest, including climate-driven migration and concerns for people with disabilities, were not covered due to a lack of literature specific to the Midwest region. Thus, it is uncertain what the attending health impacts may be related to these topics and how they may be distributed throughout a community.

Description of Confidence and Likelihood

There is *high confidence* and it is *very likely* that climate change will impact the health and well-being of individuals and communities in the Midwest across a wide range of exposure pathways. Literature shows that these pathways include extreme events, such as flooding, drought, heatwaves, and wildfires, that all pose an increasing risk to physical and mental health by direct exposure. Studies show that indirect exposure through degrading air and drinking water quality threatens livelihoods and strains essential health and emergency-related services. An individual's exposure and sensitivity to climate change is *very likely* influenced by preexisting health conditions, income, race and ethnicity, age, and access to resources (*high confidence*). Evidence illustrates that health disparities tied to racism and income inequality are *likely* linked to an inequitable distribution of climate-related health outcomes. Actions and investments to reduce climate-related health and community impacts can yield multiple health benefits while helping to advance more equitable climate adaptation (*high confidence*).

Key Message 24.4

Green Infrastructure and Investment Solutions Can Address Costly Climate Change Impacts

Description of Evidence Base

Based on numerous independent analyses, much of the infrastructure of the Midwest is aging, and repairing this infrastructure will come at a significant cost (e.g., American Society of Civil Engineers Report Card for America's Infrastructure).[248] These costs require new forms of financing, data, and expertise, much of which is just emerging. The infrastructure deficit in the Midwest is articulated through academic literature and practitioner resources and research,[236,248] all demonstrating that the infrastructure of the Midwest is aging and that repairing it will come at a significant cost. These costs require new forms of financing, data, and expertise, much of which are just emerging.[236] There is strong evidence showing that increasing storm damages to infrastructure across the Midwest disproportionately impact people with low income and BIPOC populations.[258] Numerous studies of social vulnerability and adaptive capacity demonstrate that individuals with lower vulnerability and higher adaptive capacity are better able to prepare for and recover from disaster.

Major Uncertainties and Research Gaps

Storm damages not captured through disaster declarations are difficult to identify, and midsize disasters are difficult to quantify. One method for quantifying these midsize disasters could be to report on the total times states in the Midwest declare a state of emergency in response to a weather- or climate-related event. There is a gap in aggregated and standardized reporting of state-declared disaster events and related losses. Another approach could be to calculate insurance losses as reported by private insurance companies with holdings in the region. State-level data and private insurance datasets are accessible but require analysis and synthesis to be usable by decision-makers. The US Billion-Dollar Weather and Climate Disasters report, developed by NOAA's National Centers for Environmental Information, has become a common way to understand the increasing cost incurred by climate change and related extreme events. However, many smaller-scale yet damaging storm events occur annually and lead to damage or destroyed infrastructure, loss of life, and harm to the health and well-being of people in the Midwest. One measure of these events is through the National Flood Insurance Program database. Tracking these events and the related economic impact could enable more effective and equitable distribution of resources before and following extreme storms.

Climate migration is an area of uncertainty, yet information is highly sought within academic and public spheres. Literature and resources on community relocation within the region exist, but literature and evidence on climate-induced migration of people moving into the region is not currently available.

Description of Confidence and Likelihood

There is strong evidence that climate change *likely* threatens built infrastructure, especially if a heavy dependence on conventional road transportation continues. Uncertainty about the modes of transportation that will exist in the future and uncertain trends toward electrification result in an assignment of *medium confidence*. More certain are the impacts from increased precipitation extremes and transitions between wet and dry conditions on riverine and Great Lakes environments (*likely*, *high confidence*). The emergence of new investments offers alternative methods toward development, but volatility in the economy leaves some uncertainty whether more communities and local businesses will embrace these tools (*medium confidence*).

Key Message 24.5

Managing Extremes Is Necessary to Minimize Impacts on Water Quality and Quantity

Description of Evidence Base

There is strong evidence that the Midwest and Great Lakes water is and will continue to be impacted by climate change, with associated adverse effects for both human society and ecosystems.[267] The evidence for change is supported by the trends in temperature, precipitation, runoff, and evapotranspiration.[268] Further, reasonably good climate-based scenario model performance in the past provides confidence in those predictions going forward.

The evidence and research were more consistent for water quantity and water management than for water quality.[280,281] This is due, in part, to the more complex nature of water quality. The biggest areas for lack of agreement were in harmful algal blooms (HABs) and how global climate scenario-based models deal with the regional representation of the Great Lakes.

Major Uncertainties and Research Gaps

The lack of robust model simulations of how the Great Lakes physically operate is a major gap and uncertainty. Climate processes in the Great Lakes region are difficult to simulate due to the complexity of lake–land–atmosphere interactions.[6] Even the most sophisticated climate models for the Great Lakes region have deficient physical representations of the key hydrological components that make up a lake's net basin supply (i.e., precipitation, evaporation, and runoff).[6] Therefore, high levels of uncertainty are associated with future lake-level projections that are based on simulated changes to these hydrological components. However, higher variability in future water levels is anticipated, which will impact the entire ecosystem (KM 24.2), ports (KM 24.4), and coastlines.[284,301] Better physical representation of the Great Lakes would enhance confidence in how increases in the water temperatures of the lakes (both surface and deep lake) could impact the ecosystem.

HAB research across the Midwest and Great Lakes is conflicting and limited.[280,281] While research has been more conclusive in the Great Lakes with increasing HAB severity, research has been inconclusive in the Midwest as to whether HAB severity has been increasing, remaining constant, or decreasing. Connections to agricultural tiling and septic systems and their impacts on water bodies are additional knowledge and data gaps.

Temperature, precipitation, and runoff research is much more comprehensive in the Midwest than streamflow research.[268] There is limited available work on large basin–scale streamflow to assess climate impacts. The Ohio River Basin Climate Change project, by the US Army Corps of Engineers and NOAA,[240] is one of the US's largest and most comprehensive climate change–related projects on water quantity, quality, and management for streamflows on medium- to larger-scale systems. A similar Midwest project by NOAA's North Central River Forecast Center and the University of Minnesota is underway for the upper Mississippi River basin. More large-scale hydrologic projects, including in the Missouri River basin and Great Lakes, would aid in understanding large-scale streamflow changes and projected impacts. The absence of more such projects limits the ability to have higher confidence in some areas of water quantity, quality, and management. Combining Coupled Model Intercomparison Project Phase 5 with the Variable Infiltration Capacity hydrology modeling is a step in the right direction.

Description of Confidence and Likelihood

Confidence and likelihood were assigned based on the consistency of the information in trends and research combined with strengths and weaknesses in the climate scenario models. For the Midwest and Great Lakes, there is consistent information to support *high confidence* for air temperatures, precipitation, and runoff trends and projections and the impacts to water quantity, water quality, water management practices, ecosystem health, food production, and recreation.[15] Based on literature and projections, it is *likely* and there is *high confidence* that increases in runoff (in all seasons but summer, where some decreases are projected), drought, and flooding will adversely affect ecosystems through increased erosion and the expansion of invasive species. This applies to enhanced erosion and expansion of invasive species. For harmful algal blooms (HABs), the literature and projections support *high confidence* for continued HABs in the Great Lakes. For the Midwest, confidence is lower that increased temperatures and precipitation and runoff will continue to lead to variable changes in HAB events (increasing, decreasing, or remaining unchanged). This will *likely* result in continued adverse impacts to water quality and ecosystems. There are numerous examples where federal and state agencies along with nongovernmental organizations are collaborating on adaptation efforts related to water in the Midwest (*high confidence*).

References

1. U.S. Census Bureau, 2020: Explore Census Data. U.S. Department of Commerce, U.S. Census Bureau, accessed May 5, 2023. https://data.census.gov/

2. Li, Y., K. Guan, G.D. Schnitkey, E. DeLucia, and B. Peng, 2019: Excessive rainfall leads to maize yield loss of a comparable magnitude to extreme drought in the United States. *Global Change Biology*, **25** (7), 2325–2337. https://doi.org/10.1111/gcb.14628

3. Srivastava, A., O. Yetemen, N. Kumari, and P.M. Saco, 2019: Aspect-controlled spatial and temporal soil moisture patterns across three different latitudes. In: *Proceedings of the 23rd International Congress on Modelling and Simulation*. Canberra, ACT, Australia, 1–6 December 2019, 979–985. https://doi.org/10.36334/modsim.2019.k6.srivastava

4. Sharma, S., D.C. Richardson, R.I. Woolway, M.A. Imrit, D. Bouffard, K. Blagrave, J. Daly, A. Filazzola, N. Granin, J. Korhonen, J. Magnuson, W. Marszelewski, S.-I.S. Matsuzaki, W. Perry, D.M. Robertson, L.G. Rudstam, G.A. Weyhenmeyer, and H. Yao, 2021: Loss of ice cover, shifting phenology, and more extreme events in Northern Hemisphere lakes. *Journal of Geophysical Research: Biogeosciences*, **126** (10), e2021JG006348. https://doi.org/10.1029/2021jg006348

5. Schlinger, C., O. Conroy-Ben, C. Cooley, N. Cooley, M. Cruz, D. Dotson, J. Doyle, M.J. Eggers, P. Hardison, M. Hatch, C. Hogue, K. Jacobson Hedin, C. Jones, K. Lanphier, D. Marks-Marino, D. Mosley, F. Olsen Jr., and M. Peacock, 2021: Ch. 4.2. Water. In: *Status of Tribes and Climate Change Report*. Marks-Marino, D., Ed. Institute for Tribal Environmental Professionals, Flagstaff, AZ, 98–141. http://nau.edu/stacc2021

6. Briley, L.J., R.B. Rood, and M. Notaro, 2021: Large lakes in climate models: A Great Lakes case study on the usability of CMIP5. *Journal of Great Lakes Research*, **47** (2), 405–418. https://doi.org/10.1016/j.jglr.2021.01.010

7. FAO, 2022: FAOSTAT. Food and Agriculture Organization of the United Nations. https://www.fao.org/faostat/en/#home

8. NASS, 2022: Quarterly Hogs and Pigs Inventory–United States. U.S. Department of Agriculture, National Agricultural Statistics Service. https://usda.library.cornell.edu/concern/publications/rj430453j?locale=en

9. Angel, J.R., M. Markus, K.A. Wang, B.M. Kerschner, and S. Singh, 2020: Precipitation frequency study for Illinois. *Illinois State Water Survey Bulletin*, **75**, 130. https://hdl.handle.net/2142/106653

10. Baule, W.J., J.A. Andresen, and J.A. Winkler, 2022: Trends in quality controlled precipitation indicators in the United States Midwest and Great Lakes region. *Frontiers in Water*, **4**, 817342. https://doi.org/10.3389/frwa.2022.817342

11. Hayhoe, K., D.J. Wuebbles, D.R. Easterling, D.W. Fahey, S. Doherty, J. Kossin, W. Sweet, R. Vose, and M. Wehner, 2018: Ch. 2. Our changing climate. In: *Impacts, Risks, and Adaptation in the United States: Fourth National Climate Assessment, Volume II*. Reidmiller, D.R., C.W. Avery, D.R. Easterling, K.E. Kunkel, K.L.M. Lewis, T.K. Maycock, and B.C. Stewart, Eds. U.S. Global Change Research Program, Washington, DC, USA, 72–144. https://doi.org/10.7930/nca4.2018.ch2

12. Wilson, A.B., A. Avila-Diaz, L.F. Oliveira, C.F. Zuluaga, and B. Mark, 2022: Climate extremes and their impacts on agriculture across the eastern Corn Belt region of the U.S. *Weather and Climate Extremes*, **37**, 100467. https://doi.org/10.1016/j.wace.2022.100467

13. Guo, R., C. Deser, L. Terray, and F. Lehner, 2019: Human influence on winter precipitation trends (1921–2015) over North America and Eurasia revealed by dynamical adjustment. *Geophysical Research Letters*, **46** (6), 3426–3434. https://doi.org/10.1029/2018gl081316

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

15. Almazroui, M., M.N. Islam, F. Saeed, S. Saeed, M. Ismail, M.A. Ehsan, I. Diallo, E. O'Brien, M. Ashfaq, D. Martínez-Castro, T. Cavazos, R. Cerezo-Mota, M.K. Tippett, W.J. Gutowski, E.J. Alfaro, H.G. Hidalgo, A. Vichot-Llano, J.D. Campbell, S. Kamil, I.U. Rashid, M.B. Sylla, T. Stephenson, M. Taylor, and M. Barlow, 2021: Projected changes in temperature and precipitation over the United States, Central America, and the Caribbean in CMIP6 GCMs. *Earth Systems and Environment*, **5** (1), 1–24. https://doi.org/10.1007/s41748-021-00199-5

16. Dahal, V., S. Gautam, and R. Bhattarai, 2018: Analysis of long-term temperature trend in Illinois and its implication on the cropping system. *Environmental Processes*, **5** (3), 451–464. https://doi.org/10.1007/s40710-018-0306-7

17. Ford, T.W., L. Chen, and J.T. Schoof, 2021: Variability and transitions in precipitation extremes in the Midwest United States. *Journal of Hydrometeorology*, **22** (3), 533–545. https://doi.org/10.1175/jhm-d-20-0216.1

18. Chen, L. and T.W. Ford, 2023: Future changes in the transitions of monthly-to-seasonal precipitation extremes over the Midwest in Coupled Model Intercomparison Project Phase 6 models. *International Journal of Climatology*, **43** (1), 255–274. https://doi.org/10.1002/joc.7756

19. Anderson, R., P.E. Bayer, and D. Edwards, 2020: Climate change and the need for agricultural adaptation. *Current Opinion in Plant Biology*, **56**, 197–202. https://doi.org/10.1016/j.pbi.2019.12.006

20. Baldwin-Kordick, R., M. De, M.D. Lopez, M. Liebman, N. Lauter, J. Marino, and M.D. McDaniel, 2022: Comprehensive impacts of diversified cropping on soil health and sustainability. *Agroecology and Sustainable Food Systems*, **46** (3), 331–363. https://doi.org/10.1080/21683565.2021.2019167

21. Walsh, M.K., P. Backlund, L. Buja, A. DeGaetano, R. Melnick, L. Prokopy, E. Takle, D. Todey, and L. Ziska, 2020: Climate Indicators for Agriculture. USDA Technical Bulletin 1953. U.S. Department of Agriculture, Washington, DC, 70 pp. https://doi.org/10.25675/10217/210930

22. Kucharik, C.J., T. Ramiadantsoa, J. Zhang, and A.R. Ives, 2020: Spatiotemporal trends in crop yields, yield variability, and yield gaps across the USA. *Crop Science*, **60** (4), 2085–2101. https://doi.org/10.1002/csc2.20089

23. Bowling, L.C., K.A. Cherkauer, C.I. Lee, J.L. Beckerman, S. Brouder, J.R. Buzan, O.C. Doering, J.S. Dukes, P.D. Ebner, J.R. Frankenberger, B.M. Gramig, E.J. Kladivko, and J.J. Volenec, 2020: Agricultural impacts of climate change in Indiana and potential adaptations. *Climatic Change*, **163** (4), 2005–2027. https://doi.org/10.1007/s10584-020-02934-9

24. English, B.C., S.A. Smith, R.J. Menard, D.W. Hughes, and M. Gunderson, 2021: Estimated economic impacts of the 2019 Midwest floods. *Economics of Disasters and Climate Change*, **5** (3), 431–448. https://doi.org/10.1007/s41885-021-00095-2

25. Hoell, A., T.W. Ford, M. Woloszyn, J.A. Otkin, and J. Eischeid, 2021: Characteristics and predictability of Midwestern United States drought. *Journal of Hydrometeorology*, **22** (11), 3087–3105. https://doi.org/10.1175/jhm-d-21-0052.1

26. Byun, K., C.M. Chiu, and A.F. Hamlet, 2019: Effects of 21st century climate change on seasonal flow regimes and hydrologic extremes over the Midwest and Great Lakes region of the US. *Science of The Total Environment*, **650**, 1261–1277. https://doi.org/10.1016/j.scitotenv.2018.09.063

27. Grady, K.A., L. Chen, and T.W. Ford, 2021: Projected changes to spring and summer precipitation in the Midwestern United States. *Frontiers in Water*, **3**, 780333. https://doi.org/10.3389/frwa.2021.780333

28. Zhou, W., L.R. Leung, and J. Lu, 2022: Seasonally dependent future changes in the U.S. Midwest hydroclimate and extremes. *Journal of Climate*, **35** (1), 17–27. https://doi.org/10.1175/jcli-d-21-0012.1

29. Hatfield, J.L., M.V.K. Sivakumar, and J.H. Prueger, Eds., 2018: *Agroclimatology: Linking Agriculture to Climate*. Vol. 60. American Society of Agronomy: Crop Science Society of America: Soil Science Society of America. https://doi.org/10.2134/agronmonogr60

30. Hatfield, J.L., L. Wright-Morton, and B. Hall, 2018: Vulnerability of grain crops and croplands in the Midwest to climatic variability and adaptation strategies. *Climatic Change*, **146** (1–2), 263–275. https://doi.org/10.1007/s10584-017-1997-x

31. Kimm, H., K. Guan, C.H. Burroughs, B. Peng, E.A. Ainsworth, C.J. Bernacchi, C.E. Moore, E. Kumagai, X. Yang, J.A. Berry, and G. Wu, 2021: Quantifying high-temperature stress on soybean canopy photosynthesis: The unique role of sun-induced chlorophyll fluorescence. *Global Change Biology*, **27** (11), 2403–2415. https://doi.org/10.1111/gcb.15603

32. Wuebbles, D., J. Angel, K. Petersen, and A.M. Lemke, 2021: An Assessment of the Impacts of Climate Change in Illinois. University of Illinois at Urbana-Champaign. https://doi.org/10.13012/b2idb-1260194_v1

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

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

35. Lark, T.J., S.A. Spawn, M. Bougie, and H.K. Gibbs, 2020: Cropland expansion in the United States produces marginal yields at high costs to wildlife. *Nature Communications*, **11** (1), 4295. https://doi.org/10.1038/s41467-020-18045-z

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

37. Nikiel, C.A. and E.A.B. Eltahir, 2019: Summer climate change in the Midwest and Great Plains due to agricultural development during the twentieth century. *Journal of Climate*, **32** (17), 5583–5599. https://doi.org/10.1175/jcli-d-19-0096.1

38. Wang, S., S. Di Tommaso, J.M. Deines, and D.B. Lobell, 2020: Mapping twenty years of corn and soybean across the US Midwest using the Landsat archive. *Scientific Data*, **7** (1), 307. https://doi.org/10.1038/s41597-020-00646-4

39. Butler, E.E., N.D. Mueller, and P. Huybers, 2018: Peculiarly pleasant weather for US maize. *Proceedings of the National Academy of Sciences of the United States of America*, **115** (47), 11935–11940. https://doi.org/10.1073/pnas.1808035115

40. Partridge, T.F., J.M. Winter, L. Liu, A.D. Kendall, B. Basso, and D.W. Hyndman, 2019: Mid-20th century warming hole boosts US maize yields. *Environmental Research Letters*, **14**, 114008. https://doi.org/10.1088/1748-9326/ab422b

41. Rizzo, G., J.P. Monzon, F.A. Tenorio, R. Howard, K.G. Cassman, and P. Grassini, 2022: Climate and agronomy, not genetics, underpin recent maize yield gains in favorable environments. *Proceedings of the National Academy of Sciences of the United States of America*, **119** (4), e2113629119. https://doi.org/10.1073/pnas.2113629119

42. Jägermeyr, J., C. Müller, A.C. Ruane, J. Elliott, J. Balkovic, O. Castillo, B. Faye, I. Foster, C. Folberth, J.A. Franke, K. Fuchs, J.R. Guarin, J. Heinke, G. Hoogenboom, T. Iizumi, A.K. Jain, D. Kelly, N. Khabarov, S. Lange, T.-S. Lin, W. Liu, O. Mialyk, S. Minoli, E.J. Moyer, M. Okada, M. Phillips, C. Porter, S.S. Rabin, C. Scheer, J.M. Schneider, J.F. Schyns, R. Skalsky, A. Smerald, T. Stella, H. Stephens, H. Webber, F. Zabel, and C. Rosenzweig, 2021: Climate impacts on global agriculture emerge earlier in new generation of climate and crop models. *Nature Food*, **2** (11), 873–885. https://doi.org/10.1038/s43016-021-00400-y

43. Liu, L. and B. Basso, 2020: Impacts of climate variability and adaptation strategies on crop yields and soil organic carbon in the US Midwest. *PLoS One*, **15** (1), 0225433. https://doi.org/10.1371/journal.pone.0225433

44. DeLucia, E.H., S. Chen, K. Guan, B. Peng, Y. Li, N. Gomez-Casanovas, I.B. Kantola, C.J. Bernacchi, Y. Huang, S.P. Long, and D.R. Ort, 2019: Are we approaching a water ceiling to maize yields in the United States? *Ecosphere*, **10** (6), 02773. https://doi.org/10.1002/ecs2.2773

45. Rigden, A.J., N.D. Mueller, N.M. Holbrook, N. Pillai, and P. Huybers, 2020: Combined influence of soil moisture and atmospheric evaporative demand is important for accurately predicting US maize yields. *Nature Food*, **1**, 127–133. https://doi.org/10.1038/s43016-020-0028-7

46. Nocco, M.A., R.A. Smail, and C.J. Kucharik, 2019: Observation of irrigation-induced climate change in the Midwest United States. *Global Change Biology*, **25** (10), 3472–3484. https://doi.org/10.1111/gcb.14725

47. Nickles, K., A. Relling, A. García Guerra, F. Fluharty, and A. Parker, 2020: 70 cows housed in muddy environmental conditions during late gestation have lesser body weight and body condition score compared with cows housed on wood chips. *Journal of Animal Science*, **98** (Supplement_4), 48. https://doi.org/10.1093/jas/skaa278.088

48. Nickles, K., A. Relling, A. García Guerra, F. Fluharty, and A. Parker, 2021: 87 beef heifers housed in muddy environmental conditions lose body weight and body condition but meet gestational requirements for fetal growth. *Journal of Animal Science*, **99** (Supplement_3), 46. https://doi.org/10.1093/jas/skab235.081

49. Nickles, K., A.E. Relling, A. Garcia-Guerra, F.L. Fluharty, and A.J. Parker, 2021: 39 muddy environmental conditions cause conceptus free live weight loss but not a decrease in calf birth weight when compared with cows housed on wood chips. *Journal of Animal Science*, **99** (Supplement_1), 31–31. https://doi.org/10.1093/jas/skab054.054

50. Rojas-Downing, M.M., A.P. Nejadhashemi, T. Harrigan, and S.A. Woznicki, 2017: Climate change and livestock: Impacts, adaptation, and mitigation. *Climate Risk Management*, **16**, 145–163. https://doi.org/10.1016/j.crm.2017.02.001

51. Crist, S., J. Mori, and R.L. Smith, 2020: Flooding on beef and swine farms: A scoping review of effects in the Midwestern United States. *Preventive Veterinary Medicine*, **184**, 105158. https://doi.org/10.1016/j.prevetmed.2020.105158

52. Hristov, A.N., A.T. Degaetano, C.A. Rotz, E. Hoberg, R.H. Skinner, T. Felix, H. Li, P.H. Patterson, G. Roth, M. Hall, T.L. Ott, L.H. Baumgard, W. Staniar, R.M. Hulet, C.J. Dell, A.F. Brito, and D.Y. Hollinger, 2018: Climate change effects on livestock in the Northeast US and strategies for adaptation. *Climatic Change*, **146** (1), 33–45. https://doi.org/10.1007/s10584-017-2023-z

53. Feliciano, R.J., G. Boué, and J.-M. Membré, 2020: Overview of the potential impacts of climate change on the microbial safety of the dairy industry. *Foods*, **9** (12). https://doi.org/10.3390/foods9121794

54. Gunn, K.M., M.A. Holly, T.L. Veith, A.R. Buda, R. Prasad, C.A. Rotz, K.J. Soder, and A.M.K. Stoner, 2019: Projected heat stress challenges and abatement opportunities for U.S. milk production. *PLoS ONE*, **14** (3), e0214665. https://doi.org/10.1371/journal.pone.0214665

55. Veltman, K., C.A. Rotz, L. Chase, J. Cooper, C.E. Forest, P.A. Ingraham, R.C. Izaurralde, C.D. Jones, R.E. Nicholas, M.D. Ruark, W. Salas, G. Thoma, and O. Jolliet, 2021: Assessing and reducing the environmental impact of dairy production systems in the northern US in a changing climate. *Agricultural Systems*, **192**, 103170. https://doi.org/10.1016/j.agsy.2021.103170

56. Andresen, J.A. and W.J. Baule, 2020: Ch. 16. Perennial systems (temperate fruit trees and grapes). In: *Agroclimatology: Linking Agriculture to Climate*. Hatfield, J.L., M.V. Sivakumar, and J.H. Prueger, Eds. American Society of Agronomy: Crop Science Society of America: Soil Science Society of America, 425–452. https://doi.org/10.2134/agronmonogr60.2016.0016

57. NASS, 2019: 2017 Census of Agriculture: Specialty Crops. AC-17-S-8. U.S. Department of Agriculture, National Agricultural Statistics Service. https://www.nass.usda.gov/publications/agcensus/2017/online_resources/specialty_crops/scrops.pdf

58. Kistner, E., O. Kellner, J. Andresen, D. Todey, and L.W. Morton, 2018: Vulnerability of specialty crops to short-term climatic variability and adaptation strategies in the Midwestern USA. *Climatic Change*, **146** (1), 145–158. https://doi.org/10.1007/s10584-017-2066-1

59. Khalifa, S.A.M., M.H. Elashal, N. Yosri, M. Du, S.G. Musharraf, L. Nahar, S.D. Sarker, Z. Guo, W. Cao, X. Zou, A.A. Abd El-Wahed, J. Xiao, H.A. Omar, M.-E.F. Hegazy, and H.R. El-Seedi, 2021: Bee pollen: Current status and therapeutic potential. *Nutrients*, **13** (6), 1876. https://doi.org/10.3390/nu13061876

60. Reilly, J.R., D.R. Artz, D. Biddinger, K. Bobiwash, N.K. Boyle, C. Brittain, J. Brokaw, J.W. Campbell, J. Daniels, E. Elle, J.D. Ellis, S.J. Fleischer, J. Gibbs, R.L. Gillespie, K.B. Gundersen, L. Gut, G. Hoffman, N. Joshi, O. Lundin, K. Mason, C.M. McGrady, S.S. Peterson, T.L. Pitts-Singer, S. Rao, N. Rothwell, L. Rowe, K.L. Ward, N.M. Williams, J.K. Wilson, R. Isaacs, and R. Winfree, 2020: Crop production in the USA is frequently limited by a lack of pollinators. *Proceedings of the Royal Society B: Biological Sciences*, **287** (1931), 20200922. https://doi.org/10.1098/rspb.2020.0922

61. Soroye, P., T. Newbold, and J. Kerr, 2020: Climate change contributes to widespread declines among bumble bees across continents. *Science*, **367** (6478), 685–688. https://doi.org/10.1126/science.aax8591

62. Kammerer, M., S.C. Goslee, M.R. Douglas, J.F. Tooker, and C.M. Grozinger, 2021: Wild bees as winners and losers: Relative impacts of landscape composition, quality, and climate. *Global Change Biology*, **27** (6), 1250–1265. https://doi.org/10.1111/gcb.15485

63. Bebber, D.P., M.A.T. Ramotowski, and S.J. Gurr, 2013: Crop pests and pathogens move polewards in a warming world. *Nature Climate Change*, **3** (11), 985–988. https://doi.org/10.1038/nclimate1990

64. Britt, K.E., T.P. Kuhar, W. Cranshaw, C.T. McCullough, S.V. Taylor, B.R. Arends, H. Burrack, M. Pulkoski, D. Owens, T.A. Tolosa, S. Zebelo, K.A. Kesheimer, O.S. Ajayi, M. Samuel-Foo, J.A. Davis, N. Arey, H. Doughty, J. Jones, M. Bolt, B.J. Fritz, J.F. Grant, J. Cosner, and M. Schreiner, 2021: Pest management needs and limitations for corn earworm (Lepidoptera: Noctuidae), an emergent key pest of hemp in the United States. *Journal of Integrated Pest Management*, **12** (1), 34. https://doi.org/10.1093/jipm/pmab030

65. IPCC Secretariat, 2021: Scientific Review of the Impact of Climate Change on Plant Pests–A Global Challenge to Prevent and Mitigate Plant Pest Risks in Agriculture, Forestry and Ecosystems. 978-92-5-134435-4. FAO on behalf of the IPPC Secretariat, Rome, Italy. https://doi.org/10.4060/cb4769en

66. Kistner, E.J., 2017: Climate change impacts on the potential distribution and abundance of the brown marmorated stink bug (Hemiptera: Pentatomidae) with special reference to North America and Europe. *Environmental Entomology*, **46** (6), 1212–1224. https://doi.org/10.1093/ee/nvx157

67. Kistner-Thomas, E.J., 2019: The potential global distribution and voltinism of the Japanese beetle (Coleoptera: Scarabaeidae) under current and future climates. *Journal of Insect Science*, **19** (2). https://doi.org/10.1093/jisesa/iez023

68. Taylor, R.A.J., D.A. Herms, J. Cardina, and R.H. Moore, 2018: Climate change and pest management: Unanticipated consequences of trophic dislocation. *Agronomy*, **8** (1), 7. https://doi.org/10.3390/agronomy8010007

69. Kiefer, M.T., J.A. Andresen, D.G. McCullough, W.J. Baule, and M. Notaro, 2021: Extreme minimum temperatures in the Great Lakes region of the United States: A climatology with implications for insect mortality. *International Journal of Climatology*, **42** (7), 3596–3615. https://doi.org/10.1002/joc.7434

70. Landau, C.A., A.G. Hager, and M.M. Williams II, 2021: Diminishing weed control exacerbates maize yield loss to adverse weather. *Global Change Biology*, **27** (23), 6156–6165. https://doi.org/10.1111/gcb.15857

71. Fall, M.L., J.F. Willbur, D.L. Smith, A.M. Byrne, and M.I. Chilvers, 2018: Spatiotemporal distribution pattern of *Sclerotinia sclerotiorum* apothecia is modulated by canopy closure and soil temperature in an irrigated soybean field. *Plant Disease*, **102** (9), 1794–1802. https://doi.org/10.1094/pdis-11-17-1821-re

72. Komoto, K., L. Soldo, Y. Tang, M.I. Chilvers, K. Dahlin, G. Guentchev, L. Rill, and J.A. Winkler, 2021: Climatology of persistent high relative humidity: An example for the Lower Peninsula of Michigan, USA. *International Journal of Climatology*, **41** (S1), 2517–2536. https://doi.org/10.1002/joc.6861

73. Crane-Droesch, A., E. Marshall, S. Rosch, A. Riddle, J. Cooper, and S. Wallander, 2019: Climate Change and Agricultural Risk Management into the 21st Century. ERR-266. U.S. Department of Agriculture, Economic Research Service. https://www.ers.usda.gov/webdocs/publications/93547/err-266.pdf?v=9203.7

74. Diffenbaugh, N.S., F.V. Davenport, and M. Burke, 2021: Historical warming has increased U.S. crop insurance losses. *Environmental Research Letters*, **16** (8), 084025. https://doi.org/10.1088/1748-9326/ac1223

75. Reyes, J.J. and E. Elias, 2019: Spatio-temporal variation of crop loss in the United States from 2001 to 2016. *Environmental Research Letters*, **14** (7), 074017. https://doi.org/10.1088/1748-9326/ab1ac9

76. Maxwell, J.T., G.L. Harley, and S.M. Robeson, 2016: On the declining relationship between tree growth and climate in the Midwest United States: The fading drought signal. *Climatic Change*, **138** (1), 127–142. https://doi.org/10.1007/s10584-016-1720-3

77. Thaler, E.A., I.J. Larsen, and Q. Yu, 2021: The extent of soil loss across the US Corn Belt. *Proceedings of the National Academy of Sciences of the United States of America*, **118** (8), e1922375118. https://doi.org/10.1073/pnas.1922375118

78. Basara, J.B., J.I. Christian, R.A. Wakefield, J.A. Otkin, E.H. Hunt, and D.P. Brown, 2019: The evolution, propagation, and spread of flash drought in the Central United States during 2012. *Environmental Research Letters*, **14** (8), 084025. https://doi.org/10.1088/1748-9326/ab2cc0

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

80. FAO, 2023: Economic and Policy Analysis of Climate Change: EX-ACT and Climate-Smart Agriculture (CSA). Food and Agriculture Organization of the United Nations, accessed September 22, 2023. https://www.fao.org/in-action/epic/ex-act-tool/overview/ex-act-and-csa/en/

81. Chandra, A., K.E. McNamara, and P. Dargusch, 2018: Climate-smart agriculture: Perspectives and framings. *Climate Policy*, **18** (4), 526–541. https://doi.org/10.1080/14693062.2017.1316968

82. Deines, J.M., K. Guan, B. Lopez, Q. Zhou, C.S. White, S. Wang, and D.B. Lobell, 2023: Recent cover crop adoption is associated with small maize and soybean yield losses in the United States. *Global Change Biology*, **29** (3), 794–807. https://doi.org/10.1111/gcb.16489

83. Qin, Z., K. Guan, W. Zhou, B. Peng, M.B. Villamil, Z. Jin, J. Tang, R. Grant, L. Gentry, A.J. Margenot, G. Bollero, and Z. Li, 2021: Assessing the impacts of cover crops on maize and soybean yield in the U.S. Midwestern agroecosystems. *Field Crops Research*, **273**, 108264. https://doi.org/10.1016/j.fcr.2021.108264

84. Basso, B., G. Shuai, J. Zhang, and G.P. Robertson, 2019: Yield stability analysis reveals sources of large-scale nitrogen loss from the US Midwest. *Scientific Reports*, **9** (1), 5774. https://doi.org/10.1038/s41598-019-42271-1

85. Maestrini, B. and B. Basso, 2021: Subfield crop yields and temporal stability in thousands of US Midwest fields. *Precision Agriculture*, **22** (6), 1749–1767. https://doi.org/10.1007/s11119-021-09810-1

86. Basso, B., R.A. Martinez-Feria, L. Rill, and J.T. Ritchie, 2021: Contrasting long-term temperature trends reveal minor changes in projected potential evapotranspiration in the US Midwest. *Nature Communications*, **12** (1), 1476. https://doi.org/10.1038/s41467-021-21763-7

87. Baule, W.J. 2022: Climatic Variability and Change in the Midwestern United States: Implications for Nitrogen Leaching in Agricultural Systems. Doctor of Philosophy in Geography, Michigan State University. https://lter.kbs.msu.edu/pub/4046

88. Khanna, M., D. Rajagopal, and D. Zilberman, 2021: Lessons learned from US experience with biofuels: Comparing the hype with the evidence. *Review of Environmental Economics and Policy*, **15** (1), 67–86. https://doi.org/10.1086/713026

89. Chen, H., J.M. Samet, P.A. Bromberg, and H. Tong, 2021: Cardiovascular health impacts of wildfire smoke exposure. *Particle and Fibre Toxicology*, **18** (1), 2. https://doi.org/10.1186/s12989-020-00394-8

90. Field, J.L., T.L. Richard, E.A.H. Smithwick, H. Cai, M.S. Laser, D.S. LeBauer, S.P. Long, K. Paustian, Z. Qin, J.J. Sheehan, P. Smith, M.Q. Wang, and L.R. Lynd, 2020: Robust paths to net greenhouse gas mitigation and negative emissions via advanced biofuels. *Proceedings of the National Academy of Sciences of the United States of America*, **117** (36), 21968–21977. https://doi.org/10.1073/pnas.1920877117

91. Moore, K.J., C.L. Kling, and D.R. Raman, 2020: A Midwest USA perspective on von Cossel et al.'s prospects of bioenergy cropping systems for a more social-ecologically sound bioeconomy. *Agronomy*, **10** (11). https://doi.org/10.3390/agronomy10111658

92. Foley, J.A., N. Ramankutty, K.A. Brauman, E.S. Cassidy, J.S. Gerber, M. Johnston, N.D. Mueller, C. O'Connell, D.K. Ray, P.C. West, C. Balzer, E.M. Bennett, S.R. Carpenter, J. Hill, C. Monfreda, S. Polasky, J. Rockström, J. Sheehan, S. Siebert, D. Tilman, and D.P.M. Zaks, 2011: Solutions for a cultivated planet. *Nature*, **478** (7369), 337–342. https://doi.org/10.1038/nature10452

93. Reo, N.J. and L.A. Ogden, 2018: Anishnaabe Aki: An indigenous perspective on the global threat of invasive species. *Sustainability Science*, **13**, 1443–1452. https://doi.org/10.1007/s11625-018-0571-4

94. DOI, FWS, DOC, and USCB, 2016: National Survey of Fishing, Hunting, and Wildlife-Associated Recreation. U.S. Department of the Interior, U.S. Fish and Wildlife Service, U.S. Department of Commerce, and U.S. Census Bureau. https://www.census.gov/content/dam/Census/library/publications/2018/demo/fhw16-nat.pdf

95. White, M.P., I. Alcock, J. Grellier, B.W. Wheeler, T. Hartig, S.L. Warber, A. Bone, M.H. Depledge, and L.E. Fleming, 2019: Spending at least 120 minutes a week in nature is associated with good health and wellbeing. *Scientific Reports*, **9** (1), 7730. https://doi.org/10.1038/s41598-019-44097-3

96. Mitchell, R. and F. Popham, 2008: Effect of exposure to natural environment on health inequalities: An observational population study. *The Lancet*, **372** (9650), 1655–1660. https://doi.org/10.1016/s0140-6736(08)61689-x

97. Paukert, C., J.D. Olden, A.J. Lynch, D.D. Breshears, R.C. Chambers, C. Chu, M. Daly, K.L. Dibble, J. Falke, D. Issak, P. Jacobson, O.P. Jensen, and D. Munroe, 2021: Climate change effects on North American fish and fisheries to inform adaptation strategies. *Fisheries*, **46** (9), 449–464. https://doi.org/10.1002/fsh.10668

98. Hansen, G.J.A., T.D. Ahrenstorff, B.J. Bethke, J.D. Dumke, J. Hirsch, K.E. Kovalenko, J.F. LeDuc, R.P. Maki, H.M. Rantala, and T. Wagner, 2020: Walleye growth declines following zebra mussel and *Bythotrephes* invasion. *Biological Invasions*, **22**, 1481–1495. https://doi.org/10.1007/s10530-020-02198-5

99. Höök, T.O., C.J. Foley, P. Collingsworth, L. Dorworth, B. Fisher, J.T. Hoverman, E. LaRue, M. Pyron, and J. Tank, 2020: An assessment of the potential impacts of climate change on freshwater habitats and biota of Indiana, USA. *Climatic Change*, **163** (4), 1897–1916. https://doi.org/10.1007/s10584-019-02502-w

100. Jacobson, P.C., G.J.A. Hansen, B.J. Bethke, and T.K. Cross, 2017: Disentangling the effects of a century of eutrophication and climate warming on freshwater lake fish assemblages. *PLoS One*, **12** (8), 0182667. https://doi.org/10.1371/journal.pone.0182667

101. Murdoch, A., C. Mantyka-Pringle, and S. Sharma, 2020: The interactive effects of climate change and land use on boreal stream fish communities. *Science of The Total Environment*, **700**, 134518. https://doi.org/10.1016/j.scitotenv.2019.134518

102. Hansen, G.J.A., J.S. Read, J.F. Hansen, and L.A. Winslow, 2017: Projected shifts in fish species dominance in Wisconsin lakes under climate change. *Global Change Biology*, **23** (4), 1463–1476. https://doi.org/10.1111/gcb.13462

103. Hansen, G.J.A., J. Ruzich, C.A. Krabbenhoft, H. Kundel, S. Mahlum, C.I. Rounds, A.O. Van Pelt, L.D. Eslinger, D.E. Logsdon, and D.A. Isermann, 2022: It's complicated and it depends: A review of the effects of ecosystem changes on walleye and yellow perch populations in North America. *North American Journal of Fisheries Management*, **42** (3), 484–506. https://doi.org/10.1002/nafm.10741

104. Hansen, G.J.A., L.A. Winslow, J.S. Read, M. Treml, P.J. Schmalz, and S.R. Carpenter, 2019: Water clarity and temperature effects on walleye safe harvest: An empirical test of the safe operating space concept. *Ecosphere*, **10** (5), 02737. https://doi.org/10.1002/ecs2.2737

105. Till, A., A.L. Rypel, A. Bray, and S.B. Fey, 2019: Fish die-offs are concurrent with thermal extremes in north temperate lakes. *Nature Climate Change*, **9**, 637–641. https://doi.org/10.1038/s41558-019-0520-y

106. Death, R.G., I.C. Fuller, and M.G. Macklin, 2015: Resetting the river template: The potential for climate-related extreme floods to transform river geomorphology and ecology. *Freshwater Biology*, **60** (12), 2477–2496. https://doi.org/10.1111/fwb.12639

107. Choi, C., P. Berry, and A. Smith, 2021: The climate benefits, co-benefits, and trade-offs of green infrastructure: A systematic literature review. *Journal of Environmental Management*, **291**, 112583. https://doi.org/10.1016/j.jenvman.2021.112583

108. Demaria, E.M.C., R.N. Palmer, and J.K. Roundy, 2016: Regional climate change projections of streamflow characteristics in the Northeast and Midwest U.S. *Journal of Hydrology: Regional Studies*, **5**, 309–323. https://doi.org/10.1016/j.ejrh.2015.11.007

109. Tsang, Y., D.M. Infante, L. Wang, D. Krueger, and D. Wieferich, 2021: Conserving stream fishes with changing climate: Assessing fish responses to changes in habitat over a large region. *Science of The Total Environment*, **755** (2), 142503. https://doi.org/10.1016/j.scitotenv.2020.142503

110. Mitro, M.G., J.D. Lyons, J.S. Stewart, P.K. Cunningham, and J.D.T. Griffin, 2019: Projected changes in brook trout and brown trout distribution in Wisconsin streams in the mid-twenty-first century in response to climate change. *Hydrobiologia*, **840** (1), 215–226. https://doi.org/10.1007/s10750-019-04020-3

111. Usinowicz, J., J. Qiu, and A. Kamarainen, 2017: Flashiness and flooding of two lakes in the Upper Midwest during a century of urbanization and climate change. *Ecosystems*, **20**, 601–615. https://doi.org/10.1007/s10021-016-0042-7

112. Palmer, R.N., K.H. Nislow, P. McIntyre, M. Ocana, K. Kahl, K. Lutz, B. Backiel, A. Ericson, E. Lotter, S. Pfiefle, and M. Saleeba, 2020: Slowing the Flow for Climate Resilience: Reducing Vulnerability to Extreme Flood and Drought Events. University of Massachusetts, Northeast Climate Adaptation Science Center, Amherst, MA. https://necasc.umass.edu/sites/default/files/styles/desktop_x1_1400px_/public/2020-00/Slow-the-Flow-_schematic2.jpg?itok=BoxKBGx6

113. Zhang, X., T.J. Lark, C.M. Clark, Y. Yuan, and S.D. LeDuc, 2021: Grassland-to-cropland conversion increased soil, nutrient, and carbon losses in the US Midwest between 2008 and 2016. *Environmental Research Letters*, **16**, 054018. https://doi.org/10.1088/1748-9326/abecbe

114. Jarzyna, M.A., B. Zuckerberg, A.O. Finley, and W.F. Porter, 2016: Synergistic effects of climate and land cover: Grassland birds are more vulnerable to climate change. *Landscape Ecology*, **31**, 2275–2290. https://doi.org/10.1007/s10980-016-0399-1

115. Zuckerberg, B., C.A. Ribic, and L.A. McCauley, 2018: Effects of temperature and precipitation on grassland bird nesting success as mediated by patch size. *Conservation Biology*, **32** (4), 872–882. https://doi.org/10.1111/cobi.13089

116. Patterson, T.A., R. Grundel, J.D.K. Dzurisin, R.L. Knutson, and J.J. Hellmann, 2020: Evidence of an extreme weather-induced phenological mismatch and a local extirpation of the endangered Karner blue butterfly. *Conservation Science and Practice*, **2** (1), 147. https://doi.org/10.1111/csp2.147

117. Zylstra, E.R., L. Ries, N. Neupane, S.P. Saunders, M.I. Ramírez, E. Rendón-Salinas, K.S. Oberhauser, M.T. Farr, and E.F. Zipkin, 2021: Changes in climate drive recent monarch butterfly dynamics. *Nature Ecology & Evolution*, **5**, 1441–1452. https://doi.org/10.1038/s41559-021-01504-1

118. Alstad, A.O., E.I. Damschen, T.J. Givnish, J.A. Harrington, M.K. Leach, D.A. Rogers, and D.M. Waller, 2016: The pace of plant community change is accelerating in remnant prairies. *Science Advances*, **2** (2), e1500975. https://doi.org/10.1126/sciadv.1500975

119. Henn, J.J. and E.I. Damschen, 2022: Grassland management actions influence soil conditions and plant community responses to winter climate change. *Ecosphere*, **13** (10), e4270. https://doi.org/10.1002/ecs2.4270

120. Ratcliffe, H., M. Ahlering, D. Carlson, S. Vacek, A. Allstadt, and L.E. Dee, 2022: Invasive species do not exploit early growing seasons in burned tallgrass prairies. *Ecological Applications*, **32** (7), e2641. https://doi.org/10.1002/eap.2641

121. Frelich, L., C.G. Lorimer, and M.C. Stambaugh, 2021: Ch. 7. History and future of fire in hardwood and conifer forests of the Great Lakes-Northeastern Forest Region, USA. In: *Fire Ecology and Management: Past, Present, and Future of US Forested Ecosystems. Managing Forest Ecosystems*. Greenberg, C.H. and B. Collins, Eds. Springer, Cham, Switzerland, 243–285. https://doi.org/10.1007/978-3-030-73267-7_7

122. Gao, P., A.J. Terando, J.A. Kupfer, J. Morgan Varner, M.C. Stambaugh, T.L. Lei, and J. Kevin Hiers, 2021: Robust projections of future fire probability for the conterminous United States. *Science of The Total Environment*, **789**, 147872. https://doi.org/10.1016/j.scitotenv.2021.147872

123. Stambaugh, M.C., B.O. Knapp, and D.C. Dey, 2021: Ch. 5. Fire ecology and management of forest ecosystems in the Western Central Hardwoods and Prairie-Forest Border. In: *Fire Ecology and Management: Past, Present, and Future of US Forested Ecosystems*. Greenberg, C.H. and B. Collins, Eds. Springer, Cham, Switzerland, 149–199. https://doi.org/10.1007/978-3-030-73267-7_5

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

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

126. Christian, J.I., J.B. Basara, E.D. Hunt, J.A. Otkin, J.C. Furtado, V. Mishra, X. Xiao, and R.M. Randall, 2021: Global distribution, trends, and drivers of flash drought occurrence. *Nature Communications*, **12**, 6330. https://doi.org/10.1038/s41467-021-26692-z

127. Wood, J.D., B.O. Knapp, R.M. Muzika, M.C. Stambaugh, and L. Gu, 2018: The importance of drought–pathogen interactions in driving oak mortality events in the Ozark border region. *Environmental Research Letters*, **13** (1), 015004. https://doi.org/10.1088/1748-9326/aa94fa

128. De Jager, N.R., M. Van Appledorn, T.J. Fox, J.J. Rohweder, L.J. Guyon, A.R. Meier, R.J. Cosgriff, and B.J. Vandermyde, 2019: Spatially explicit modelling of floodplain forest succession: Interactions among flood inundation, forest successional processes, and other disturbances in the Upper Mississippi River floodplain, USA. *Ecological Modelling*, **405**, 15–32. https://doi.org/10.1016/j.ecolmodel.2019.05.002

129. King, D.J., G.L. Harley, J.T. Maxwell, K.J. Heeter, B.J. Vandermyde, and R.J. Cosgriff, 2021: Floodplain forest structure and the recent decline of *Carya illinoinensis* (Wangenh.) K. Koch (Northern pecan) at its northern latitudinal range margin, Upper Mississippi River System, USA. *Forest Ecology and Management*, **496**, 119454. https://doi.org/10.1016/j.foreco.2021.119454

130. Klooster, W.S., K.J.K. Gandhi, L.C. Long, K.I. Perry, K.B. Rice, and D.A. Herms, 2018: Ecological impacts of emerald ash borer in forests at the epicenter of the invasion in North America. *Forests*, **9** (5), 250. https://doi.org/10.3390/f9050250

131. Phillips, R.P., L. Brandt, P.D. Polly, P. Zollner, M.R. Saunders, K. Clay, L. Iverson, and S. Fei, 2020: An integrated assessment of the potential impacts of climate change on Indiana forests. *Climatic Change*, **163**, 1917–1931. https://doi.org/10.1007/s10584-018-2326-8

132. Tribal Adaptation Menu Team, 2019: Dibaginjigaadeg Anishinaabe Ezhitwaad: A Tribal Climate Adaptation Menu. Great Lakes Indian Fish and Wildlife Commission, Odanah, WI, 54 pp. https://forestadaptation.org/tribal-climate-adaptation-menu

133. Contosta, A.R., N.J. Casson, S. Garlick, S.J. Nelson, M.P. Ayres, E.A. Burakowski, J. Campbell, I. Creed, C. Eimers, C. Evans, I. Fernandez, C. Fuss, T. Huntington, K. Patel, R. Sanders-DeMott, K. Son, P. Templer, and C. Thornbrugh, 2019: Northern forest winters have lost cold, snowy conditions that are important for ecosystems and human communities. *Ecological Applications*, **29** (7), 01974. https://doi.org/10.1002/eap.1974

134. Contosta, A.R., N.J. Casson, S.J. Nelson, and S. Garlick, 2020: Defining frigid winter illuminates its loss across seasonally snow-covered areas of eastern North America. *Environmental Research Letters*, **15** (3), 034020. https://doi.org/10.1088/1748-9326/ab54f3

135. Zuckerberg, B. and J.N. Pauli, 2018: Conserving and managing the subnivium. *Conservation Biology*, **32** (4), 774–781. https://doi.org/10.1111/cobi.13091

136. Marks-Marino, D., 2019: 1854 Treaty Authority. Northern Arizona University, Institute for Tribal Environmental Professionals. http://www7.nau.edu/itep/main/tcc/Tribes/gl_trAuth

137. Moore, S., 2012: Grand Portage Band of Lake Superior Chippewa: Creative Solutions for a Changing Environment. Northern Arizona University, Institute for Tribal Environmental Professionals, Climate Change Program. http://www7.nau.edu/itep/main/tcc/Tribes/gl_gpchippewa

138. Teitelbaum, C.S., A.P.K. Sirén, E. Coffel, J.R. Foster, J.L. Frair, J.W. Hinton, R.M. Horton, D.W. Kramer, C. Lesk, C. Raymond, D.W. Wattles, K.A. Zeller, and T.L. Morelli, 2021: Habitat use as indicator of adaptive capacity to climate change. *Diversity and Distributions*, **27** (4), 655–667. https://doi.org/10.1111/ddi.13223

139. Weiskopf, S.R., O.E. Ledee, and L.M. Thompson, 2019: Climate change effects on deer and moose in the Midwest. *The Journal of Wildlife Management*, **83** (4), 769–781. https://doi.org/10.1002/jwmg.21649

140. Billiot, S., S. Kwon, and C.E. Burnette, 2019: Repeated disasters and chronic environmental changes impede generational transmission of Indigenous knowledge. *Journal of Family Strengths*, **19** (1), 11. https://digitalcommons.library.tmc.edu/jfs/vol19/iss1/11

141. Bond, M.O., B.J. Anderson, T.H.A. Henare, and P.M. Wehi, 2019: Effects of climatically shifting species distributions on biocultural relationships. *People and Nature*, **1** (1), 87–102. https://doi.org/10.1002/pan3.15

142. Daigle, J.J., N. Michelle, D.J. Ranco, and M.R. Emery, 2019: Traditional lifeways and storytelling: Tools for adaptation and resilience to ecosystem change. *Human Ecology*, **47** (5), 777–784. https://doi.org/10.1007/s10745-019-00113-8

143. Pearson, J., G. Jackson, and K.E. McNamara, 2023: Climate-driven losses to Indigenous and local knowledge and cultural heritage. *The Anthropocene Review*, **10** (2), 343–366. https://doi.org/10.1177/20530196211005482

144. Panci, H., M. Montano, A. Shultz, T. Bartnick, and K. Stone, 2018: Climate Change Vulnerability Assessment: Integrating Scientific and Traditional Ecological Knowledge. Version 1. Coleman, J., E. Chiriboga, A.M. Soltis, and J. Gilbert, Eds. Great Lakes Indian Fish and Wildlife Commission. https://glifwc.org/ClimateChange/GLIFWC_Climate_Change_Vulnerability_Assessment_Version1_April2018.pdf

145. Dooper, S., K. Proudman, A. Osielski, S. Swanz, and A. Zaman, 2018: Assessing Potential Non-Economic Loss & Damage from Climate Change: Partnership with the Bad River Band of the Lake Superior Chippewa Indians. University of Michigan, Ann Arbor, MI. https://hdl.handle.net/2027.42/150173

146. Marks-Marino, D., 2019: The Bad River Band of Lake Superior Chippewa (Ojibwe). Northern Arizona University, Institute for Tribal Environmental Professionals, Climate Change Program. http://www7.nau.edu/itep/main/tcc/tribes/gl_badriver

147. Stoffle, R.W., M.J. Evans, C.S. Sittler, D.L. Berry, and K. Van Vlack, 2022: Climate change and Odawa cultural plants in Sleeping Bear Dunes National Lake Shore. *Climatic Change*. https://doi.org/10.21203/rs.3.rs-869301/v1

148. Hatfield, S.C., E. Marino, K.P. Whyte, K.D. Dello, and P.W. Mote, 2018: Indian time: Time, seasonality, and culture in Traditional Ecological Knowledge of climate change. *Ecological Processes*, **7**, 25. https://doi.org/10.1186/s13717-018-0136-6

149. Embke, H.S., T.D. Beard Jr., A.J. Lynch, and M.J.V. Zanden, 2020: Fishing for food: Quantifying recreational fisheries harvest in Wisconsin lakes. *Fisheries*, **45** (12), 647–655. https://doi.org/10.1002/fsh.10486

150. Filazzola, A., K. Blagrave, M.A. Imrit, and S. Sharma, 2020: Climate change drives increases in extreme events for lake ice in the Northern Hemisphere. *Geophysical Research Letters*, **47** (18), 2020GL089608. https://doi.org/10.1029/2020gl089608

151. Knoll, L.B., S. Sharma, B.A. Denfeld, G. Flaim, Y. Hori, J.J. Magnuson, D. Straile, and G.A. Weyhenmeyer, 2019: Consequences of lake and river ice loss on cultural ecosystem services. *Limnology and Oceanography Letters*, **4** (5), 119–131. https://doi.org/10.1002/lol2.10116

152. Sharma, S., K. Blagrave, S.R. Watson, C.M. O'Reilly, R. Batt, J.J. Magnuson, T. Clemens, B.A. Denfeld, G. Flaim, L. Grinberga, Y. Hori, A. Laas, L.B. Knoll, D. Straile, N. Takamura, and G.A. Weyhenmeyer, 2020: Increased winter drownings in ice-covered regions with warmer winters. *PLoS ONE*, **15** (11), e0241222. https://doi.org/10.1371/journal.pone.0241222

153. Ontl, T.A., C. Swanston, L.A. Brandt, P.R. Butler, A.W. D'Amato, S.D. Handler, M.K. Janowiak, and P.D. Shannon, 2018: Adaptation pathways: Ecoregion and land ownership influences on climate adaptation decision-making in forest management. *Climatic Change*, **146** (1), 75–88. https://doi.org/10.1007/s10584-017-1983-3

154. White, M.A., M.W. Cornett, K. Frerker, and J.R. Etterson, 2020: Partnerships to take on climate change: Adaptation forestry and conifer strongholds projects in the Northwoods, Minnesota, USA. *Journal of Forestry*, **118** (3), 219–232. https://doi.org/10.1093/jofore/fvaa005

155. Muller, J.J., L.M. Nagel, and B.J. Palik, 2021: Comparing long-term projected outcomes of adaptive silvicultural approaches aimed at climate change in red pine forests of northern Minnesota, USA. *Canadian Journal of Forest Research*, **51** (12), 1875–1887. https://doi.org/10.1139/cjfr-2021-0097

156. Tingley, R.W., C. Paukert, G.G. Sass, P.C. Jacobson, G.J.A. Hansen, A.J. Lynch, and P.D. Shannon, 2019: Adapting to climate change: Guidance for the management of inland glacial lake fisheries. *Lake and Reservoir Management*, **35** (4), 435–452. https://doi.org/10.1080/10402381.2019.1678535

157. Magee, M.R., C.L. Hein, J.R. Walsh, P.D. Shannon, M.J. Vander Zanden, T.B. Campbell, G.J.A. Hansen, J. Hauxwell, G.D. LaLiberte, T.P. Parks, G.G. Sass, C.W. Swanston, and M.K. Janowiak, 2019: Scientific advances and adaptation strategies for Wisconsin lakes facing climate change. *Lake and Reservoir Management*, **35** (4), 364–381. https://doi.org/10.1080/10402381.2019.1622612

158. IPBES, 2019: *Summary for Policymakers of the Global Assessment Report on Biodiversity and Ecosystem Services of the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services*. Díaz, S., J. Settele, E.S. Brondízio, H.T. Ngo, M. Guèze, J. Agard, A. Arneth, P. Balvanera, K.A. Brauman, S.H.M. Butchart, K.M.A. Chan, L.A. Garibaldi, K. Ichii, J. Liu, S.M. Subramanian, G.F. Midgley, P. Miloslavich, Z. Molnár, D. Obura, A. Pfaff, S. Polasky, A. Purvis, J. Razzaque, B. Reyers, R. Roy Chowdhury, Y.J. Shin, I.J. Visseren-Hamakers, K.J. Willis, and C.N. Zayas, Eds. IPBES Secretariat, Bonn, Germany, 56 pp. https://www.ipbes.net/sites/default/files/inline/files/ipbes_global_assessment_report_summary_for_policymakers.pdf

159. Seddon, N., A. Chausson, P. Berry, C.A.J. Girardin, A. Smith, and B. Turner, 2020: Understanding the value and limits of nature-based solutions to climate change and other global challenges. *Philosophical Transactions of the Royal Society B: Biological Sciences*, **375** (1794), 20190120. https://doi.org/10.1098/rstb.2019.0120

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

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

162. Johnson, K.A., O.E.J. Wing, P.D. Bates, J. Fargione, T. Kroeger, W.D. Larson, C.C. Sampson, and A.M. Smith, 2020: A benefit–cost analysis of floodplain land acquisition for US flood damage reduction. *Nature Sustainability*, **3** (1), 56–62. https://doi.org/10.1038/s41893-019-0437-5

163. Cheng, F.Y., K.J. Van Meter, D.K. Byrnes, and N.B. Basu, 2020: Maximizing US nitrate removal through wetland protection and restoration. *Nature*, **588** (7839), 625–630. https://doi.org/10.1038/s41586-020-03042-5

164. Johnson, T., J. Butcher, S. Santell, S. Schwartz, S. Julius, and S. LeDuc, 2022: A review of climate change effects on practices for mitigating water quality impacts. *Journal of Water and Climate Change*, **13** (4), 1684–1705. https://doi.org/10.2166/wcc.2022.363

165. Anderegg, W.R.L., A.T. Trugman, G. Badgley, C.M. Anderson, A. Bartuska, P. Ciais, D. Cullenward, C.B. Field, J. Freeman, S.J. Goetz, J.A. Hicke, D. Huntzinger, R.B. Jackson, J. Nickerson, S. Pacala, and J.T. Randerson, 2020: Climate-driven risks to the climate mitigation potential of forests. *Science*, **368** (6497), 7005. https://doi.org/10.1126/science.aaz7005

166. Bossio, D.A., S.C. Cook-Patton, P.W. Ellis, J. Fargione, J. Sanderman, P. Smith, S. Wood, R.J. Zomer, M. Unger, I.M. Emmer, and B.W. Griscom, 2020: The role of soil carbon in natural climate solutions. *Nature Sustainability*, **3**, 391–398. https://doi.org/10.1038/s41893-020-0491-z

167. Fargione, J.E., S. Bassett, T. Boucher, S.D. Bridgham, R.T. Conant, S.C. Cook-patton, P.W. Ellis, A. Falcucci, J.W. Fourqurean, T. Gopalakrishna, H. Gu, B. Henderson, M.D. Hurteau, K.D. Kroeger, T. Kroeger, T.J. Lark, S.M. Leavitt, G. Lomax, R.I. McDonald, J.P. Megonigal, D.A. Miteva, C.J. Richardson, J. Sanderman, D. Shoch, S.A. Spawn, J.W. Veldman, C.A. WIlliams, P.B. Woodbury, C. Zganjar, M. Baranski, R.A. Houghton, E. Landis, E. McGlynn, W.H. Schlesinger, J.V. Siikamakiariana, E. Sutton-Grierand, and B.W. Griscom, 2018: Natural climate solutions for the United States. *Science Advances*, **4** (11), 1869. https://doi.org/10.1126/sciadv.aat1869

168. Griscom, B.W., J. Adams, P.W. Ellis, R.A. Houghton, G. Lomax, D.A. Miteva, W.H. Schlesinger, D. Shoch, J.V. Siikamäki, P. Smith, P. Woodbury, C. Zganjar, A. Blackman, J. Campari, R.T. Conant, C. Delgado, P. Elias, T. Gopalakrishna, M.R. Hamsik, M. Herrero, J. Kiesecker, E. Landis, L. Laestadius, S.M. Leavitt, S. Minnemeyer, S. Polasky, P. Potapov, F.E. Putz, J. Sanderman, M. Silvius, E. Wollenberg, and J. Fargione, 2017: Natural climate solutions. *Proceedings of the National Academy of Sciences of the United States of America*, **114** (44), 11645–11650. https://doi.org/10.1073/pnas.1710465114

169. Michigan DNR, 2023: DNR State Forecast Carbon Projects. Michigan Department of Natural Resources, accessed April 27, 2023. https://www.michigan.gov/dnr/buy-and-apply/carbon

170. Reich, P.B., S.E. Hobbie, T.D. Lee, R. Rich, M.A. Pastore, and K. Worm, 2020: Synergistic effects of four climate change drivers on terrestrial carbon cycling. *Nature Geoscience*, **13**, 787–793. https://doi.org/10.1038/s41561-020-00657-1

171. Krause, L., K.J. McCullough, E.S. Kane, R.K. Kolka, R.A. Chimner, and E.A. Lilleskov, 2021: Impacts of historical ditching on peat volume and carbon in northern Minnesota USA peatlands. *Journal of Environmental Management*, **296**, 113090. https://doi.org/10.1016/j.jenvman.2021.113090

172. Prince, H., 1997: *Wetlands of the American Midwest: A Historical Geography of Changing Attitudes*. University of Chicago Press, 410 pp. https://press.uchicago.edu/ucp/books/book/chicago/W/bo3633450.html

173. Naidu, D.G.T. and S. Bagchi, 2021: Greening of the earth does not compensate for rising soil heterotrophic respiration under climate change. *Global Change Biology*, **27** (10), 2029–2038. https://doi.org/10.1111/gcb.15531

174. Hanson, P.J., N.A. Griffiths, C.M. Iversen, R.J. Norby, S.D. Sebestyen, J.R. Phillips, J.P. Chanton, R.K. Kolka, A. Malhotra, K.C. Oleheiser, J.M. Warren, X. Shi, X. Yang, J. Mao, and D.M. Ricciuto, 2020: Rapid net carbon loss from a whole-ecosystem warmed peatland. *AGU Advances*, **1** (3), e2020AV000163. https://doi.org/10.1029/2020av000163

175. Stults, M., S. Petersen, J. Bell, W. Baule, E. Nasser, E. Gibbons, and M. Fougerat, 2016: Climate Change Vulnerability Assessment and Adaptation Plan: 1854 Ceded Territory Including the Bois Forte, Fond du Lac, and Grand Portage Reservations. 1854 Ceded Territory, Duluth, MN, 146 pp. https://www.1854treatyauthority.org/images/ClimateAdaptationPlan_Final-July_2016-optimized(1).pdf

176. CTKW, 2014: Guidelines for Considering Traditional Knowledges (TKs) in Climate Change Initiatives. Climate and Traditional Knowledges Workgroup. https://climatetkw.wordpress.com

177. Koski, J., J. Vanator, M. Montano, J. Ballinger, V. Gagnon, J. Lackey, E. Ravindran, and J.L. Jock, 2021: Guidance Document on Traditional Ecological Knowledge Pursuant to the Great Lakes Water Quality Agreement. U.S. Caucus of the Traditional Ecological Knowledge, 34 pp. https://www.bia.gov/sites/default/files/dup/assets/bia/wstreg/Guidance_Document_on_TEK_Pursuant_to_the_Great_Lakes_Water_Quality_Agreement.pdf

178. Chin, N., K. Byun, A.F. Hamlet, and K.A. Cherkauer, 2018: Assessing potential winter weather response to climate change and implications for tourism in the U.S. Great Lakes and Midwest. *Journal of Hydrology: Regional Studies*, **19**, 42–56. https://doi.org/10.1016/j.ejrh.2018.06.005

179. Sampson, N.R., C.E. Price, J. Kassem, J. Doan, and J. Hussein, 2019: "We're just sitting ducks": Recurrent household flooding as an underreported environmental health threat in Detroit's changing climate. *International Journal of Environmental Research and Public Health*, **16** (1), 6. https://doi.org/10.3390/ijerph16010006

180. Bernstein, A.S., S. Sun, K.R. Weinberger, K.R. Spangler, P.E. Sheffield, and G.A. Wellenius, 2022: Warm season and emergency department visits to U.S. children's hospitals. *Environmental Health Perspectives*, **130** (1), 017001. https://doi.org/10.1289/ehp8083

181. Liu, J., L.P. Clark, M.J. Bechle, A. Hajat, S.Y. Kim, A.L. Robinson, L. Sheppard, A.A. Szpiro, and J.D. Marshall, 2021: Disparities in air pollution exposure in the United States by race/ethnicity and income, 1990–2010. *Environmental Health Perspectives*, **129** (12), 127005. https://doi.org/10.1289/ehp8584

182. National Academies of Sciences, Engineering, and Medicine, 2022: *Communities, Climate Change, and Health Equity: Proceedings of a Workshop–In Brief*. The National Academies Press, Washington, DC, 12 pp. https://doi.org/10.17226/26435

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

184. Muñoz, C.E. and E. Tate, 2016: Unequal recovery? Federal resource distribution after a Midwest flood disaster. *International Journal of Environmental Research and Public Health*, **13** (5), 507. https://doi.org/10.3390/ijerph13050507

185. Hsiao, V., T. Chandereng, R.L. Lankton, J.A. Huebner, J.J. Baltus, G.E. Flood, S.M. Dean, A.J. Tevaarwek, and D.F. Schneider, 2021: Disparities in telemedicine access: A cross-sectional study of a newly established infrastructure during the COVID-19 pandemic. *Applied Clinical Informatics*, **12** (3), 445–458. https://doi.org/10.1055/s-0041-1730026

186. ALA, 2022: State of the Air 2022. American Lung Association. https://www.lung.org/getmedia/74b3d3d3-88d1-4335-95d8-c4e47d0282c1/sota-2022.pdf

187. Dedoussi, I.C., S.D. Eastham, E. Monier, and S.R.H. Barrett, 2020: Premature mortality related to United States cross-state air pollution. *Nature*, **578**, 261–265. https://doi.org/10.1038/s41586-020-1983-8

188. Fann, N.L., C.G. Nolte, M.C. Sarofim, J. Martinich, and N.J. Nassikas, 2021: Associations between simulated future changes in climate, air quality, and human health. *JAMA Network Open*, **4** (1), e2032064. https://doi.org/10.1001/jamanetworkopen.2020.32064

189. Nassikas, N., K. Spangler, N. Fann, C.G. Nolte, P. Dolwick, T.L. Spero, P. Sheffield, and G.A. Wellenius, 2021: Ozone-related asthma emergency department visits in the US in a warming climate. *Environmental Research*, **183**, 109206. https://doi.org/10.1016/j.envres.2020.109206

190. Limaye, V.S., W. Max, J. Constible, and K. Knowlton, 2019: Estimating the health-related costs of 10 climate-sensitive U.S. events during 2012. *GeoHealth*, **3** (9), 245–265. https://doi.org/10.1029/2019gh000202

191. EPA, 2017: Multi-Model Framework for Quantitative Sectoral Impacts Analysis: A Technical Report for the Fourth National Climate Assessment. EPA 430-R-17-001. U.S. Environmental Protection Agency, Washington, DC. https://www.epa.gov/cira/multi-model-framework-quantitative-sectoral-impacts-analysis

192. Scott, J.H., A.M. Brough, J.W. Gilbertson-Day, K. Gregory, and C. Moran, 2020: Wildfire Risk to Communities: Spatial Datasets of Wildfire Risk for Populated Areas in the United States. Forest Service Research Data Archive, Fort Collins, CO. https://doi.org/10.2737/rds-2020-0060

193. Brey, S.J., M. Ruminski, S.A. Atwood, and E.V. Fischer, 2018: Connecting smoke plumes to sources using Hazard Mapping System (HMS) smoke and fire location data over North America. *Atmospheric Chemistry and Physics*, **18** (3), 1745–1761. https://doi.org/10.5194/acp-18-1745-2018

194. Sorensen, C., J.A. House, K. O'Dell, S.J. Brey, B. Ford, J.R. Pierce, E.V. Fischer, J. Lemery, and J.L. Crooks, 2021: Associations between wildfire-related $PM_{2.5}$ and intensive care unit admissions in the United States, 2006–2015. *GeoHealth*, **5** (5), 2021GH000385. https://doi.org/10.1029/2021gh000385

195. Mills, D., R. Jones, C. Wobus, J. Ekstrom, L. Jantarasami, A.S. Juliana, and A. Crimmins, 2018: Projecting age-stratified risk of exposure to inland flooding and wildfire smoke in the United States under two climate scenarios. *Environmental Health Perspectives*, **126** (4), 047007. https://doi.org/10.1289/ehp2594

196. Neumann, J.E., S.C. Anenberg, K.R. Weinberger, M. Amend, S. Gulati, A. Crimmins, H. Roman, N. Fann, and P.L. Kinney, 2019: Estimates of present and future asthma emergency department visits associated with exposure to oak, birch, and grass pollen in the United States. *GeoHealth*, **3** (1), 11–27. https://doi.org/10.1029/2018gh000153

197. Patel, S., C. Kaplan, A. Galor, and N. Kumar, 2021: The role of temperature change, ambient temperature, and relative humidity in allergic conjunctivitis in a US veteran population. *American Journal of Ophthalmology*, **230**, 243–255. https://doi.org/10.1016/j.ajo.2021.04.035

198. Anenberg, S.C., K.R. Weinberger, H. Roman, J.E. Neumann, A. Crimmins, N. Fann, J. Martinich, and P.L. Kinney, 2017: Impacts of oak pollen on allergic asthma in the United States and potential influence of future climate change. *GeoHealth*, **1** (3), 80–92. https://doi.org/10.1002/2017gh000055

199. Eguiluz-Gracia, I., A.G. Mathioudakis, S. Bartel, S.J.H. Vijverberg, E. Fuertes, P. Comberiati, Y.S. Cai, P.V. Tomazic, Z. Diamant, J. Vestbo, C. Galan, and B. Hoffmann, 2020: The need for clean air: The way air pollution and climate change affect allergic rhinitis and asthma. *Allergy*, **75** (9), 2170–2184. https://doi.org/10.1111/all.14177

200. AAFA, 2020: Asthma Disparities in America: A Roadmap to Reducing Burden on Racial and Ethnic Minorities. Asthma and Allergy Foundation of America. https://aafa.org/asthmadisparities

201. Olds, H.T., S.R. Corsi, D.K. Dila, K.M. Halmo, M.J. Bootsma, and S.L. McLellan, 2018: High levels of sewage contamination released from urban areas after storm events: A quantitative survey with sewage specific bacterial indicators. *PLoS Medicine*, **15** (7), 1002614. https://doi.org/10.1371/journal.pmed.1002614

202. Shirzaei, M., M. Khoshmanesh, C. Ojha, S. Werth, H. Kerner, G. Carlson, S.F. Sherpa, G. Zhai, and J.-C. Lee, 2021: Persistent impact of spring floods on crop loss in U.S. Midwest. *Weather and Climate Extremes*, **34**, 100392. https://doi.org/10.1016/j.wace.2021.100392

203. Uejio, C.K., M. Christenson, C. Moran, and M. Gorelick, 2017: Drinking-water treatment, climate change, and childhood gastrointestinal illness projections for northern Wisconsin (USA) communities drinking untreated groundwater. *Hydrogeology Journal*, **25** (4), 969–979. https://doi.org/10.1007/s10040-016-1521-9

204. Hoppe, B.O., K.K. Raab, K.A. Blumenfeld, and J. Lundy, 2018: Vulnerability assessment of future flood impacts for populations on private wells: Utilizing climate projection data for public health adaptation planning. *Climatic Change*, **148**, 533–546. https://doi.org/10.1007/s10584-018-2207-1

205. Alkishe, A. and A.T. Peterson, 2022: Climate change influences on the geographic distributional potential of the spotted fever vectors *Amblyomma maculatum* and *Dermacentor andersoni*. *PeerJ*, **10**, e13279. https://doi.org/10.7717/peerj.13279

206. Sonenshine, D.E., 2018: Range expansion of tick disease vectors in North America: Implications for spread of tick-borne disease. *International Journal of Environmental Research and Public Health*, **15** (3), 478. https://doi.org/10.3390/ijerph15030478

207. Hauser, N., K.C. Conlon, A. Desai, and L.N. Kobziar, 2021: Climate change and infections on the move in North America. *Infection and Drug Resistance*, **14**, 5711–5723. https://doi.org/10.2147/idr.s305077

208. Sagurova, I., A. Ludwig, N.H. Ogden, Y. Pelcat, G. Dueymes, and P. Gachon, 2019: Predicted northward expansion of the geographic range of the tick vector *Amblyomma americanum* in North America under future climate conditions. *Environmental Health Perspectives*, **127** (10), 107014. https://doi.org/10.1289/ehp5668

209. Khan, S.U., N.H. Ogden, A.A. Fazil, P.H. Gachon, G.U. Dueymes, A.L. Greer, and V. Ng, 2020: Current and projected distributions of *Aedes aegypti* and *Ae. albopictus* in Canada and the U.S. *Environmental Health Perspectives*, **128** (5), 057007. https://doi.org/10.1289/ehp5899

210. Belova, A., D. Mills, R. Hall, A. Juliana, A. Crimmins, C. Barker, and R. Jones, 2017: Impacts of increasing temperature on the future incidence of West Nile neuroinvasive disease in the United States. *American Journal of Climate Change*, **6**, 166–216. https://doi.org/10.4236/ajcc.2017.61010

211. Hoppe, B.O., L. Prussia, C. Manning, K.K. Raab, and K.V. Jones-Casey, 2023: "It's hard to give hope sometimes": Climate change, mental health, and the challenges for mental health professionals. *Ecopsychology*, **15** (1), 13–25. https://doi.org/10.1089/eco.2022.0032

212. Bjornestad, A., C. Cuthbertson, and J. Hendricks, 2021: An analysis of suicide risk factors among farmers in the Midwestern United States. *International Journal of Environmental Research and Public Health*, **18** (7), 3563. https://doi.org/10.3390/ijerph18073563

213. Cianconi, P., S. Betrò, and L. Janiri, 2020: The impact of climate change on mental health: A systematic descriptive review. *Frontiers in Psychiatry*, **11**, 74. https://doi.org/10.3389/fpsyt.2020.00074

214. Thoma, M.V., N. Rohleder, and S.L. Rohner, 2021: Clinical ecopsychology: The mental health impacts and underlying pathways of the climate and environmental crisis. *Frontiers in Psychiatry*, **12**, 675936. https://doi.org/10.3389/fpsyt.2021.675936

215. Berman, J.D., M.R. Ramirez, J.E. Bell, R. Bilotta, F. Gerr, and N.B. Fethke, 2021: The association between drought conditions and increased occupational psychosocial stress among U.S. farmers: An occupational cohort study. *Science of The Total Environment*, **798**, 149245. https://doi.org/10.1016/j.scitotenv.2021.149245

216. Liang, Y., B. Janssen, C. Casteel, M. Nonnenmann, and D.S. Rohlman, 2021: Agricultural cooperatives in mental health: Farmers' perspectives on potential influence. *Journal of Agromedicine*, **27** (2), 143–153. https://doi.org/10.1080/1059924x.2021.2004962

217. Nuako, A., J. Liu, G. Pham, N. Smock, A. James, T. Baker, L. Bierut, G. Colditz, and L.-S. Chen, 2022: Quantifying rural disparity in healthcare utilization in the United States: Analysis of a large midwestern healthcare system. *PLoS ONE*, **17** (2), e0263718. https://doi.org/10.1371/journal.pone.0263718

218. Kirby, J.B., S.H. Zuvekas, A.E. Borsky, and Q. Ngo-Metzger, 2019: Rural residents with mental health needs have fewer care visits than urban counterparts. *Health Affairs*, **38** (12), 2057–2060. https://doi.org/10.1377/hlthaff.2019.00369

219. Schultz, K., S. Farmer, S. Harrell, and C. Hostetter, 2021: Closing the gap: Increasing community mental health services in rural Indiana. *Community Mental Health Journal*, **57**, 684–700. https://doi.org/10.1007/s10597-020-00737-x

220. Hoppe, B.O., K.K. Raab, E.E. Waldhart, E.D. Waage, M.L. Varien, and J.E. Davis, 2022: Advancing Health & Disaster Resiliency in Minnesota: Co-producing Climate & Health Information for the Emergency Management Sector. Minnesota Department of Health, Minnesota Climate and Health Program, St. Paul, MN. https://www.lrl.mn.gov/docs/2022/other/221077.pdf

221. Martinich, J. and A. Crimmins, 2019: Climate damages and adaptation potential across diverse sectors of the United States. *Nature Climate Change*, **9** (5), 397–404. https://doi.org/10.1038/s41558-019-0444-6

222. Hsiang, S., R. Kopp, A. Jina, J. Rising, M. Delgado, S. Mohan, D.J. Rasmussen, R. Muir-Wood, P. Wilson, M. Oppenheimer, K. Larsen, and T. Houser, 2017: Estimating economic damage from climate change in the United States. *Science*, **356** (6345), 1362–1369. https://doi.org/10.1126/science.aal4369

223. Bikomeye, J.C., S. Namin, C. Anyanwu, C.S. Rublee, J. Ferschinger, K. Leinbach, P. Lindquist, A. Hoppe, L. Hoffman, J. Hegarty, D. Sperber, and K.M.M. Beyer, 2021: Resilience and equity in a time of crises: Investing in public urban greenspace is now more essential than ever in the US and beyond. *International Journal of Environmental Research and Public Health*, **18** (16), 8420. https://doi.org/10.3390/ijerph18168420

224. Dalbotten, D.M., E. Ito, S. Eriksson, H. Pellerin, L. Greensky, C. Kowalczak, and A. Berthelote, 2017: Gidakiimanaanawigamig's circle of learning: A model for partnership between Tribal community and research university. *Interdisciplinary Journal of Partnership Studies*, **4** (3). https://doi.org/10.24926/ijps.v4i3.176

225. Ebi, K.L., J. Vanos, J.W. Baldwin, J.E. Bell, D.M. Hondula, N.A. Errett, K. Hayes, C.E. Reid, S. Saha, J. Spector, and P. Berry, 2021: Extreme weather and climate change: Population health and health system implications. *Annual Review of Public Health*, **42** (1), 293–315. https://doi.org/10.1146/annurev-publhealth-012420-105026

226. Houghton, A. and C. Castillo-Salgado, 2019: Associations between green building design strategies and community health resilience to extreme heat events: A systematic review of the evidence. *International Journal of Environmental Research and Public Health*, **16** (4), 663. https://doi.org/10.3390/ijerph16040663

227. NCEH, 2022: Climate and Health: A Guide for Cross-Sector Collaboration. Centers for Disease Control and Prevention, National Center for Environmental Health. https://www.cdc.gov/climateandhealth/docs/crosssectorclimateandhealth.pdf

228. Lookadoo, R.E. and J.E. Bell, 2020: Public health policy actions to address health issues associated with drought in a changing climate. *The Journal of Law, Medicine & Ethics*, **48** (4), 653–663. https://doi.org/10.1177/1073110520979372

229. MNHSEM, 2019: Minnesota State Hazard Mitigation Plan. Minnesota Homeland Security and Emergency Management. https://dps.mn.gov/divisions/hsem/hazard-mitigation/documents/2019-mn-hmp-only.pdf

230. FEMA, 2021: 2022–2026 FEMA Strategic Plan: Building the FEMA Our Nation Needs and Deserves. U.S. Department of Homeland Security, Federal Emergency Management Agency. https://www.fema.gov/about/strategic-plan

231. National Research Council, 2012: *A Framework for K-12 Science Education: Practices, Crosscutting Concepts, and Core Ideas*. The National Academies Press, Washington, DC, 400 pp. https://doi.org/10.17226/13165

232. NGSS, 2023: Next Generation of Science Standards [Website], accessed May 3, 2023. https://www.nextgenscience.org/

233. NSTA, 2014: National Science Teaching Association [Website], accessed May 3, 2023. https://www.nsta.org/science-standards

234. Muhich, T.E. and R.B. Rood, 2022: CCE for me: Students demand high-quality climate change course offerings. *The Science Teacher*, **90** (1). https://www.nsta.org/science-teacher/science-teacher-septemberoctober-2022/cce-me

235. Midwest CASC, n.d.: Midwest Climate Adaptation Science Center. U.S. Geological Survey, accessed August 14, 2023. https://www.usgs.gov/programs/climate-adaptation-science-centers/midwest-casc

236. ASCE, 2021: A Comprehensive Assessment of America's Infrastructure: 2021 Report Card for America's Infrastructure. American Society of Civil Engineers. https://infrastructurereportcard.org/

237. de Abreu, V.H.S., A.S. Santos, and T.G.M. Monteiro, 2022: Climate change impacts on the road transport infrastructure: A systematic review on adaptation measures. *Sustainability*, **14** (14), 8864. https://doi.org/10.3390/su14148864

238. Neumann, J.E., P. Chinowsky, J. Helman, M. Black, C. Fant, K. Strzepek, and J. Martinich, 2021: Climate effects on US infrastructure: The economics of adaptation for rail, roads, and coastal development. *Climatic Change*, **167** (3), 44. https://doi.org/10.1007/s10584-021-03179-w

239. Khatami, D. and B. Shafei, 2021: Impact of climate conditions on deteriorating reinforced concrete bridges in the US Midwest region. *Journal of Performance of Constructed Facilities*, **35** (1), 04020129. https://doi.org/10.1061/(asce)cf.1943-5509.0001528

240. Drum, R.G., J. Noel, J. Kovatch, L. Yeghiazarian, H. Stone, J. Stark, P. Kirshen, E. Best, E. Emery, J. Trimboli, J. Arnold, and D. Raff, 2017: Ohio River Basin–Formulating Climate Change Mitigation/Adaptation Strategies Through Regional Collaboration with the ORB Alliance, May 2017. Civil Works Technical Report, CWTS 2017-01. U.S. Army Corps of Engineers, Institute for Water Resources, Alexandria, VA. https://biotech.law.lsu.edu/blog/USACE-Ohio-River-Basin-CC-Report_MAY-2017.pdf

241. English, G. and D.C. Hackston, 2013: Environmental and Social Impacts of Marine Transport in the Great Lakes St. Lawrence Seaway Region: Executive Summary. Research and Traffic Group. https://greatlakes-seaway.com/wp-content/uploads/2019/10/Impacts-Comparison-ExSum.pdf

242. GLERL, 2022: The Great Lakes Dashboard. National Oceanic and Atmospheric Administration, Office of Oceanic and Atmospheric Research, Great Lakes Environmental Research Laboratory, Ann Arbor, MI. https://www.glerl.noaa.gov/data/dashboard/GLD_HTML5.html

243. Environment Canada and EPA, 2009: Nearshore areas of the Great Lakes, 2009. In: *State of the Lakes Ecosystem Conference 2008*. Environment Canada and U.S. Environmental Protection Agency. https://binational.net/wp-content/uploads/2014/05/SOGL_2009_nearshore_en.pdf

244. Larson, J.H., A.S. Trebitz, A.D. Steinman, M.J. Wiley, M.C. Mazur, V. Pebbles, H.A. Braun, and P.W. Seelbach, 2013: Great Lakes rivermouth ecosystems: Scientific synthesis and management implications. *Journal of Great Lakes Research*, **39** (3), 513–524. https://doi.org/10.1016/j.jglr.2013.06.002

245. Ruswick, T., S. Burkholder, B. Davis, and M. Moffitt, 2021: Healthy Port futures: Rethinking sediments for rivermouth landscapes. *Landscape Architecture Frontiers*, **9** (3), 98–112. https://doi.org/10.15302/j-laf-1-040027

246. LCPA, 2022: More than a Port. Toledo-Lucas County Port Authority. https://www.toledoport.org/about/about-the-port/

247. Burkholder, S., B. Davis, and T. Ruswick, 2022: Ashtabula. Healthy Port Futures. https://healthyportfutures.com/project/ashtabula/

248. Craig, M.T., S. Cohen, J. Macknick, C. Draxl, O.J. Guerra, M. Sengupta, S.E. Haupt, B.M. Hodge, and C. Brancucci, 2018: A review of the potential impacts of climate change on bulk power system planning and operations in the United States. *Renewable and Sustainable Energy Reviews*, **98**, 255–267. https://doi.org/10.1016/j.rser.2018.09.022

249. Bartos, M., M. Chester, N. Johnson, B. Gorman, D. Eisenberg, I. Linkov, and M. Bates, 2016: Impacts of rising air temperatures on electric transmission ampacity and peak electricity load in the United States. *Environmental Research Letters*, **11** (11), 114008. https://doi.org/10.1088/1748-9326/11/11/114008

250. EIA, 2023: Electricity Data Browser. U.S. Energy Information Administration, accessed May 3, 2023. https://www.eia.gov/electricity/data/browser/

251. Austin, J. and A. Hitch, 2020: A Vital Midwest: The Path to a New Prosperity. Chicago Council on Global Affairs. https://globalaffairs.org/sites/default/files/2020-11/ccga_vital_midwest_fullissue_final_0.pdf

252. Lopez, A., A. Levine, and G. Maclaurin. 2019: U.S. Wind Siting Regulation and Zoning Ordinances. U.S. Department of Energy, National Renewable Energy Laboratory. https://doi.org/10.25984/1784284

253. Willner, S.N., A. Levermann, F. Zhao, and K. Frieler, 2018: Adaptation required to preserve future high-end river flood risk at present levels. *Science Advances*, **4** (1), 1914. https://doi.org/10.1126/sciadv.aao1914

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

255. Moftakhari, H.R., A. AghaKouchak, B.F. Sanders, M. Allaire, and R.A. Matthew, 2018: What is nuisance flooding? Defining and monitoring an emerging challenge. *Water Resources Research*, **54** (7), 4218–4227. https://doi.org/10.1029/2018wr022828

256. Boustan, L.P., M.E. Kahn, P.W. Rhode, and M.L. Yanguas, 2017: The Effect of Natural Disasters on Economic Activity in US Counties: A Century of Data. Working Paper 23410. National Bureau of Economic Research, Cambridge, MA. https://doi.org/10.3386/w23410

257. Strouse, N., R.P. Herman, S.K. Sinha, and E.D. Roos, 2021: Climate Risks and Opportunities in the Great Lakes Region. Environmental Consulting and Technology, Inc., 78 pp. https://cdn.ymaws.com/www.chicagowilderness.org/resource/resmgr/publications/climaterisksgljan2021.pdf

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

259. Pinter, N., 2021: True stories of managed retreat from rising waters. *Issues in Science and Technology*, **37** (4), 64–73. https://issues.org/true-stories-managed-retreat-rising-waters-pinter/

260. GAO, 2020: National Flood Insurance Program: Fiscal Exposure Persists Despite Property Acquisitions. GAO-20-508. U.S. Government Accountability Office. https://www.gao.gov/products/gao-20-508

261. Pinter, N. and J.C. Rees, 2021: Assessing managed flood retreat and community relocation in the Midwest USA. *Natural Hazards*, **107**, 497–518. https://doi.org/10.1007/s11069-021-04592-1

262. GSA, 2023: Bipartisan Infrastructure Law (BIL) Maps Dashboard. General Services Administration, accessed May 4, 2023. https://d2d.gsa.gov/report/bipartisan-infrastructure-law-bil-maps-dashboard

263. Higgins, P., T. Male, and S.K. Sinha, 2021: Paying for Water Quality Improvements and Resilience in the Great Lakes: Focus on Green Stormwater Infrastructure. Environmental Consulting & Technology, Inc., 22 pp. https://www.risc.solutions/wp-content/uploads/2021/07/Paying-for-Water-Quality-Improvements-and-Resilience-in-the-Great-Lakes-A-Toolkit-for-Green-Stormwater-Infrastructure.pdf

264. Sinha, S.K., R. Pettit, J. Ridgway, J. Eidson, J. Silfen, G. Peralta, and G. Cannito, 2017: Public Private Partnerships and Finance of Large-scale Green Infrastructure in the Great Lakes Basin. Environmental Consulting & Technology, Inc., 46 pp. https://www.risc.solutions/wp-content/uploads/2020/11/Assessing-Market-Size-for-Large-Scale-Green-Infrastructure-Adoption.pdf

265. USCM and C2ES, 2022: Cities Advancing Climate Action: Leveraging Federal Funds for Local Impact: A Resource Guide. U.S. Conference of Mayors and Center for Climate and Energy Solutions. https://www.c2es.org/wp-content/uploads/2022/01/cities-advancing-climate-cation-leveraging-federal-funds-for-impact.pdf

266. Sharma, A., P. Conry, H.J.S. Fernando, A.F. Hamlet, J.J. Hellmann, and F. Chen, 2016: Green and cool roofs to mitigate urban heat island effects in the Chicago metropolitan area: Evaluation with a regional climate model. *Environmental Research Letters*, **11** (6), 064004. https://doi.org/10.1088/1748-9326/11/6/064004

267. Höök, T., C. Foley, P. Collingsworth, L. Dorworth, B. Fisher, J. Hoverman, E. LaRue, M. Pyron, J. Tank, M. Widhalm, and J. Dukes, 2018: Aquatic Ecosystems in a Shifting Indiana Climate: A Report from the Indiana Climate Change Impacts Assessment. Aquatic Ecosystems Reports, Paper 1. Purdue University, Purdue Climate Change Research Center. https://doi.org/10.5703/1288284316782

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

269. Kovacs, T. and K. Barrett, 2020: Michigan Climate Assessment 2019: Considering Michigan's Future in a Changing Climate. Michigan Climate Assessment, 1. Eastern Michigan University, Environmental Science and Society, 186 pp. https://commons.emich.edu/michigan_climate2019/1/

270. Zeng, X., P. Broxton, and N. Dawson, 2018: Snowpack change from 1982 to 2016 over conterminous United States. *Geophysical Research Letters*, **45** (23), 12940–12947. https://doi.org/10.1029/2018gl079621

271. Ashley, W.S., A.M. Haberlie, and V.A. Gensini, 2020: Reduced frequency and size of late-twenty-first-century snowstorms over North America. *Nature Climate Change*, **10** (6), 539–544. https://doi.org/10.1038/s41558-020-0774-4

272. Chen, H., J. Sun, and W. Lin, 2020: Anthropogenic influence would increase intense snowfall events over parts of the Northern Hemisphere in the future. *Environmental Research Letters*, **15** (11), 114022. https://doi.org/10.1088/1748-9326/abbc93

273. Dierauer, J.R. and C. Zhu, 2020: Drought in the twenty-first century in a water-rich region: Modeling study of the Wabash River watershed, USA. *Water*, **12** (1), 181. https://doi.org/10.3390/w12010181

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

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

276. Gautam, S., C. Costello, C. Baffaut, A. Thompson, and E.J. Sadler, 2021: Projection of future drought and extreme events occurrence in Goodwater Creek Experimental Watershed, Midwestern US. *Hydrological Sciences Journal*, **66** (6), 1045–1058. https://doi.org/10.1080/02626667.2021.1906878

277. Wu, W.-Y., M.-H. Lo, Y. Wada, J.S. Famiglietti, J.T. Reager, P.J.F. Yeh, A. Ducharne, and Z.-L. Yang, 2020: Divergent effects of climate change on future groundwater availability in key mid-latitude aquifers. *Nature Communications*, **11** (1), 3710. https://doi.org/10.1038/s41467-020-17581-y

278. Hare, D.K., A.M. Helton, Z.C. Johnson, J.W. Lane, and M.A. Briggs, 2021: Continental-scale analysis of shallow and deep groundwater contributions to streams. *Nature Communications*, **12** (1), 1450. https://doi.org/10.1038/s41467-021-21651-0

279. USGS, 2021: Principal Aquifers of the United States. U.S. Geological Survey, accessed October 4, 2022. https://www.usgs.gov/mission-areas/water-resources/science/principal-aquifers-united-states#overview

280. Ho, J.C. and A.M. Michalak, 2020: Exploring temperature and precipitation impacts on harmful algal blooms across continental U.S. lakes. *Limnology and Oceanography*, **65** (5), 992–1009. https://doi.org/10.1002/lno.11365

281. Wilkinson, G.M., J.A. Walter, C.D. Buelo, and M.L. Pace, 2022: No evidence of widespread algal bloom intensification in hundreds of lakes. *Frontiers in Ecology and the Environment*, **20** (1), 16–21. https://doi.org/10.1002/fee.2421

282. ECCC and EPA, 2022: State of the Great Lakes 2022 Report: An Overview of the Status and Trends of the Great Lakes Ecosystem. EPA 905-R-22-001. Environment and Climate Change Canada and U.S. Environmental Protection Agency. https://binational.net/wp-content/uploads/2022/07/State-of-the-Great-Lakes-2022-Report.pdf

283. O'Reilly, C.M., S. Sharma, D.K. Gray, S.E. Hampton, J.S. Read, R.J. Rowley, P. Schneider, J.D. Lenters, P.B. McIntyre, B.M. Kraemer, G.A. Weyhenmeyer, D. Straile, B. Dong, R. Adrian, M.G. Allan, O. Anneville, L. Arvola, J. Austin, J.L. Bailey, J.S. Baron, J.D. Brookes, E. de Eyto, M.T. Dokulil, D.P. Hamilton, K. Havens, A.L. Hetherington, S.N. Higgins, S. Hook, L.R. Izmest'eva, K.D. Joehnk, K. Kangur, P. Kasprzak, M. Kumagai, E. Kuusisto, G. Leshkevich, D.M. Livingstone, S. MacIntyre, L. May, J.M. Melack, D.C. Mueller-Navarra, M. Naumenko, P. Noges, T. Noges, R.P. North, P.-D. Plisnier, A. Rigosi, A. Rimmer, M. Rogora, L.G. Rudstam, J.A. Rusak, N. Salmaso, N.R. Samal, D.E. Schindler, S.G. Schladow, M. Schmid, S.R. Schmidt, E. Silow, M.E. Soylu, K. Teubner, P. Verburg, A. Voutilainen, A. Watkinson, C.E. Williamson, and G. Zhang, 2015: Rapid and highly variable warming of lake surface waters around the globe. *Geophysical Research Letters*, **42** (24), 10773–10781. https://doi.org/10.1002/2015gl066235

284. Gronewold, A.D. and R.B. Rood, 2019: Recent water level changes across Earth's largest lake system and implications for future variability. *Journal of Great Lakes Research*, **45** (1), 1–3. https://doi.org/10.1016/j.jglr.2018.10.012

285. Gronewold, A.D., H.X. Do, Y. Mei, and C.A. Stow, 2021: A tug-of-war within the hydrologic cycle of a continental freshwater basin. *Geophysical Research Letters*, **48** (4), e2020GL090374. https://doi.org/10.1029/2020gl090374

286. Millerd, F., 2011: The potential impact of climate change on Great Lakes international shipping. *Climatic Change*, **104** (3), 629–652. https://doi.org/10.1007/s10584-010-9872-z

287. Theuerkauf, E.J. and K.N. Braun, 2021: Rapid water level rise drives unprecedented coastal habitat loss along the Great Lakes of North America. *Journal of Great Lakes Research*, **47** (4), 945–954. https://doi.org/10.1016/j.jglr.2021.05.004

288. Huang, C., E. Anderson, Y. Liu, G. Ma, G. Mann, and P. Xue, 2022: Evaluating essential processes and forecast requirements for meteotsunami-induced coastal flooding. *Natural Hazards*, **110** (3), 1693–1718. https://doi.org/10.1007/s11069-021-05007-x

289. Xue, P., X. Ye, J.S. Pal, P.Y. Chu, M.B. Kayastha, and C. Huang, 2022: Climate projections over the Great Lakes region: Using two-way coupling of a regional climate model with a 3-D lake model. *Geoscientific Model Development*, **15** (11), 4425–4446. https://doi.org/10.5194/gmd-15-4425-2022

290. McKenna Jr, J.E., 2019: The Laurentian Great Lakes: A case study in ecological disturbance and climate change. *Fisheries Management and Ecology*, **26** (6), 486–499. https://doi.org/10.1111/fme.12317

291. Mason, L.A., C.M. Riseng, A.D. Gronewold, E.S. Rutherford, J. Wang, A. Clites, S.D.P. Smith, and P.B. McIntyre, 2016: Fine-scale spatial variation in ice cover and surface temperature trends across the surface of the Laurentian Great Lakes. *Climatic Change*, **138** (1), 71–83. https://doi.org/10.1007/s10584-016-1721-2

292. U.S. Federal Government, 2022: Case Studies [Webpage], accessed September 6, 2022. https://toolkit.climate.gov/case-studies

293. NIDIS, 2023: What Is NIDIS? National Integrated Drought Information System, accessed April 27, 2023. https://www.drought.gov/about

294. NIDIS and NOAA, 2021: 2021–2024 Midwest Drought Early Warning System Strategic Action Plan. National Integrated Drought Information System and National Oceanic and Atmospheric Administration. https://www.drought.gov/documents/2021-2024-midwest-drought-early-warning-system-strategic-action-plan

295. NOAA, 2022: Runoff Risk Decision Support. National Oceanic and Atmospheric Administration, accessed October 7, 2022. https://www.noaa.gov/runoff-risk-decision-support

296. Lu, C., J. Zhang, H. Tian, W.G. Crumpton, M.J. Helmers, W.-J. Cai, C.S. Hopkinson, and S.E. Lohrenz, 2020: Increased extreme precipitation challenges nitrogen load management to the Gulf of Mexico. *Communications Earth & Environment*, **1** (1), 21. https://doi.org/10.1038/s43247-020-00020-7

297. Tewari, M., C.M. Kishtawal, V.W. Moriarty, P. Ray, T. Singh, L. Zhang, L. Treinish, and K. Tewari, 2022: Improved seasonal prediction of harmful algal blooms in Lake Erie using large-scale climate indices. *Communications Earth & Environment*, **3** (1), 195. https://doi.org/10.1038/s43247-022-00510-w

298. NOAA, 2023: NOAA Great Lakes Region. National Oceanic and Atmospheric Administration, accessed May 5, 2023. https://www.noaa.gov/regional-collaboration-network/regions-great-lakes

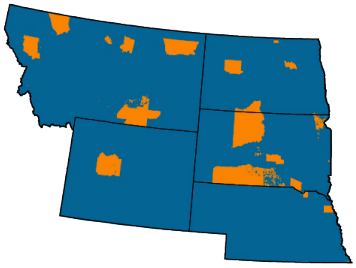
299. Makra, E. and N. Gardiner, 2021: Climate Action Plan for the Chicago Region. Metropolitan Mayors Caucus, National Oceanic and Atmospheric Administration, and U.S. Climate Resilience Toolkit. https://mayorscaucus.org/wp-content/uploads/2021/06/RegionalCAP_primary_and_appendices_062321-02.pdf

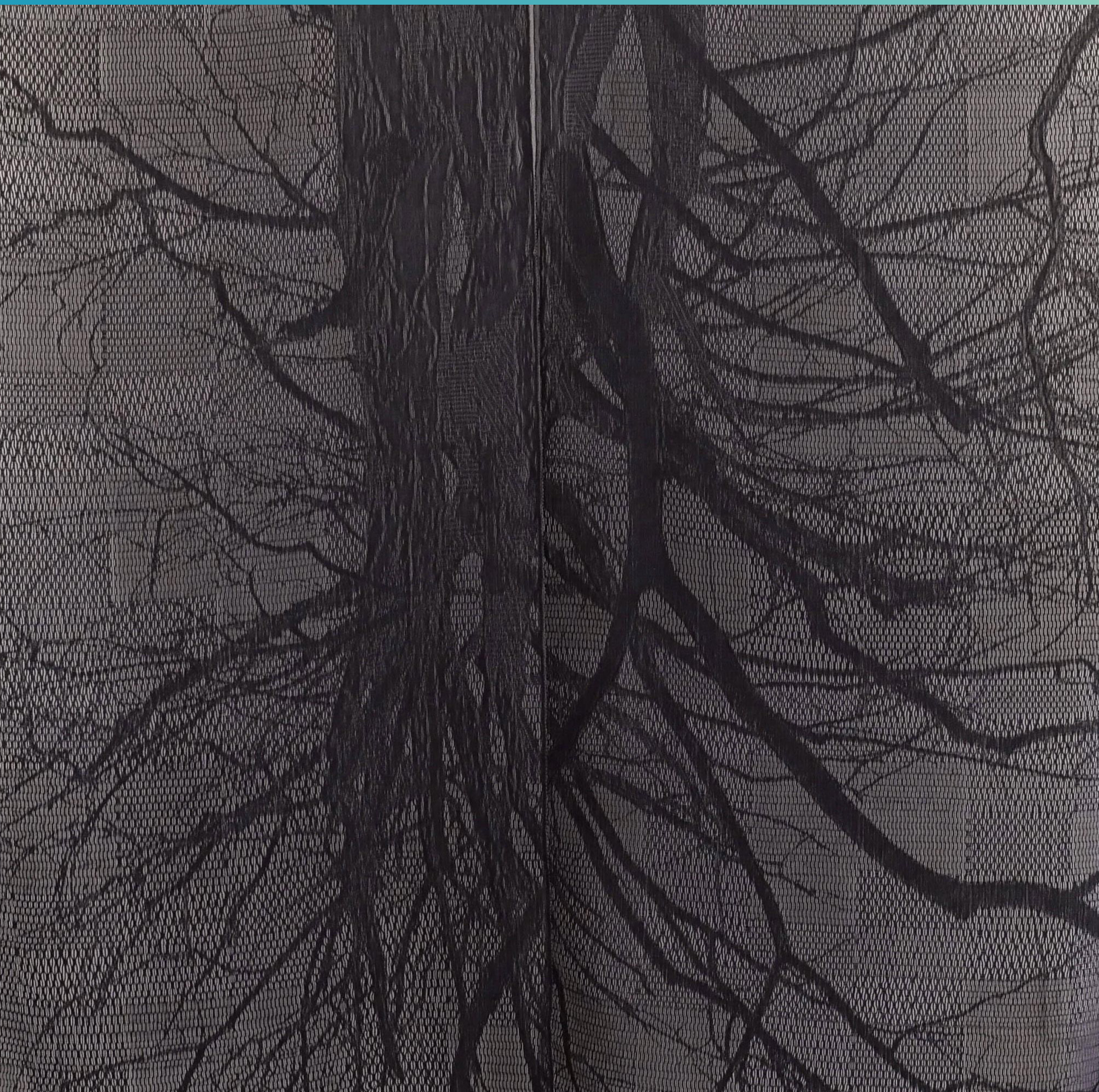
300. WICCI, 2021: Wisconsin's Changing Climate: Impacts and Solutions for a Warmer Climate. 2021 Assessment Report. University of Wisconsin-Madison, Wisconsin Initiative on Climate Change Impacts and the Wisconsin Department of Natural Resources, Madison, WI. https://wicci.wisc.edu/2021-assessment-report/

301. Seglenieks, F. and A. Temgoua, 2022: Future water levels of the Great Lakes under 1.5°C to 3°C warmer climates. *Journal of Great Lakes Research*, **48** (4), 865–875. https://doi.org/10.1016/j.jglr.2022.05.012

Fifth National Climate Assessment: Chapter 25

Northern Great Plains





Chapter 25. Northern Great Plains

Authors and Contributors

Federal Coordinating Lead Author

Douglas R. Kluck, NOAA National Centers for Environmental Information

Chapter Lead Author

Corrine N. Knapp, University of Wyoming

Agency Chapter Lead Author

Glenn Guntenspergen, US Geological Survey

Chapter Authors

Marissa A. Ahlering, The Nature Conservancy
Nicole M. Aimone, Federal Emergency Management Agency
Aparna Bamzai-Dodson, US Geological Survey, North Central Climate Adaptation Science Center
Andrea Basche, University of Nebraska
Robert G. Byron, Montana Health Professionals for a Healthy Climate
Otakuye Conroy-Ben, Arizona State University
Mark N. Haggerty, Center for American Progress
Tonya R. Haigh, University of Nebraska
Carter Johnson, South Dakota State University
Barbara Mayes Boustead, NOAA National Weather Service
Nathaniel D. Mueller, Colorado State University
Jacqueline P. Ott, USDA Forest Service, Rocky Mountain Research Station
Ginger B. Paige, University of Wyoming
Karen R. Ryberg, US Geological Survey
Gregor W. Schuurman, US National Park Service
Stefan G. Tangen, Great Plains Tribal Water Alliance, North Central Climate Adaptation Science Center

Technical Contributors

Cari Cullen, Center for Disaster Philanthropy
Avery W. Driscoll, Colorado State University
Syed Huq, Rosebud Sioux Tribe
Alison Long, The Nature Conservancy
Danika L. Mosher, Colorado State University, North Central Climate Adaptation Science Center
Kyle Nehring, University of Wyoming
Ruth Plenty Sweetgrass-She Kills, Nueta Hidatsa Sahnish College
Anthony Prenni, US National Park Service
Kelli F. Roemer, Montana State University
Kristin Smith, Headwaters Economics
Philimon D. Two Eagle, Rosebud Sioux Tribe

Review Editor

Alex Basaraba, Adaptation International

Cover Art

Tali Weinberg

Recommended Citation

Knapp, C.N., D.R. Kluck, G. Guntenspergen, M.A. Ahlering, N.M. Aimone, A. Bamzai-Dodson, A. Basche, R.G. Byron, O. Conroy-Ben, M.N. Haggerty, T.R. Haigh, C. Johnson, B. Mayes Boustead, N.D. Mueller, J.P. Ott, G.B. Paige, K.R. Ryberg, G.W. Schuurman, and S.G. Tangen, 2023: Ch. 25. Northern Great Plains. In: *Fifth National Climate Assessment*. Crimmins, A.R., C.W. Avery, D.R. Easterling, K.E. Kunkel, B.C. Stewart, and T.K. Maycock, Eds. U.S. Global Change Research Program, Washington, DC, USA. https://doi.org/10.7930/NCA5.2023.CH25

Table of Contents

Introduction 6

Key Message 25.1
Climate Change Is Compounding the Impacts of Extreme Events 8
Temperatures and Precipitation 8
Hail 10
Flooding 10
Drought 11
Wildfire 13

Key Message 25.2
Human and Ecological Health Face Rising Threats from Climate-Related Hazards 14
Mental Health 14
Physical Health 14
Compound Health Impacts of Climate Events 15
Ecological Health 15

Key Message 25.3
Resource- and Land-Based Livelihoods Are at Risk 17
Food and Agriculture 17
Tourism and Recreation 19
Energy 19
Community Infrastructure and Quality of Life 20

Key Message 25.4
Climate Response Involves Navigating Complex Trade-Offs and Tensions 21
Tensions: Navigating Barriers to Mitigation and Adaptation 21
Box 25.1. Rural Capacity and Funding 22
Trade-Offs: Land-Use Conversion 22

Key Message 25.5
Communities Are Building the Capacity to Adapt and Transform 24
Box 25.2. Prairie Pothole Wetlands and Climate Adaptation Challenges 25
Box 25.3. Climate Adaptation Successes 26
Adaptations in Agriculture 28
Adaptation to Flooding 29
Adaptations in Indigenous Communities 29
Public Land Adaptation 30
Rural Community Adaptation 32

Traceable Accounts 33
Process Description 33
Key Message 25.1 33
Key Message 25.2 35
Key Message 25.3 36
Key Message 25.4 38
Key Message 25.5 40

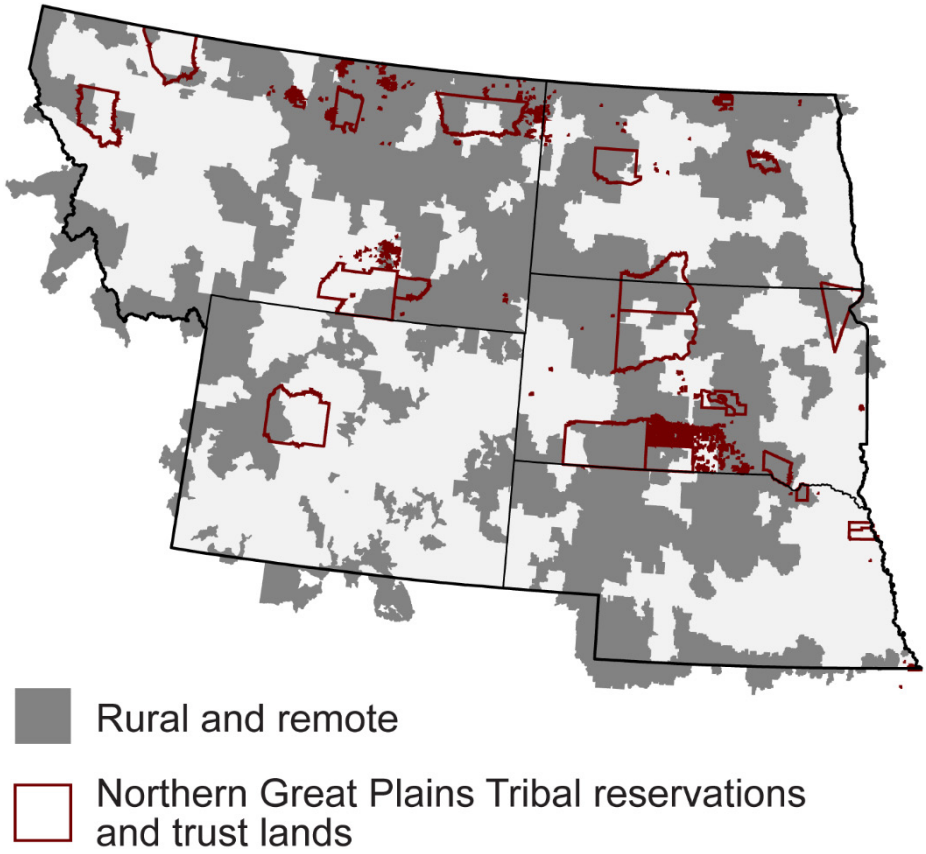
References 41

Introduction

The Northern Great Plains region, which includes Montana, Nebraska, North Dakota, South Dakota, and Wyoming (Figure 25.1), has a wealth of natural resources supporting economies, sense of place, and leisure activities. Climate change impacts on individuals and communities will differ, and it is critical to consider equity dimensions (Ch. 20). Economic dependence on crops, rangelands, and recreation makes residents with land-based livelihoods vulnerable to climate-related changes in weather, as well as flows of water, nutrients, and wildlife across the landscape.[1,2,3] This region is largely rural, and its intact natural areas, farms, and wildlands serve as habitat for resident and migrating species, which are threatened by changing water scarcity. The region is an energy and food exporter and vulnerable to policy decisions and markets outside the region. Historical processes may lead to unequal distribution of harms, with Indigenous communities, service and energy workers, and rural residents more sensitive to impacts. Values related to place, community, and stewardship are strong. Residents of small towns express strong place attachment in comparison with their urban counterparts.[4] The region's population grew by 10% between 2008 and 2020. Ten metropolitan counties accounted for two-thirds of growth, while 75% of the region's rural counties lost population.[5] Among rural counties, energy-dependent and tourism-focused counties both grew by 14%,[6] and farm-dependent communities experienced a 3% decline in population over the same period.[7,8] An indication that more people are willing to move to the region due to climate conditions was the influx of remote workers from large cities during the COVID-19 pandemic.[9]

This region also has many vibrant Indigenous communities with a rich cultural heritage (Figure 25.1). There is increased environmental action from Indigenous communities to protect waters and lands, to navigate climate change, and to maintain cultural continuity.[10] Culturally appropriate adaptation strategies, such as the restoration of buffalo, which serve a valuable ecological role and reestablish historic relationships to landscapes, are rooted in this region.[11] "Buffalo" is the preferred term of Indigenous communities based on their culture and history; this term is used in reference to Indigenous actions while acknowledging that the scientific name of the species is American bison (*Bison bison*). Although the share of the non-White population remains small in absolute numbers, the region is becoming more culturally diverse. The Indigenous and Hispanic populations grew by 20% and 42%, respectively, between 2010 and 2019, and in 2019, Indigenous and Hispanic populations accounted for 4% and 7% of the total population.[8]

Tribal Lands and Rurality Measures

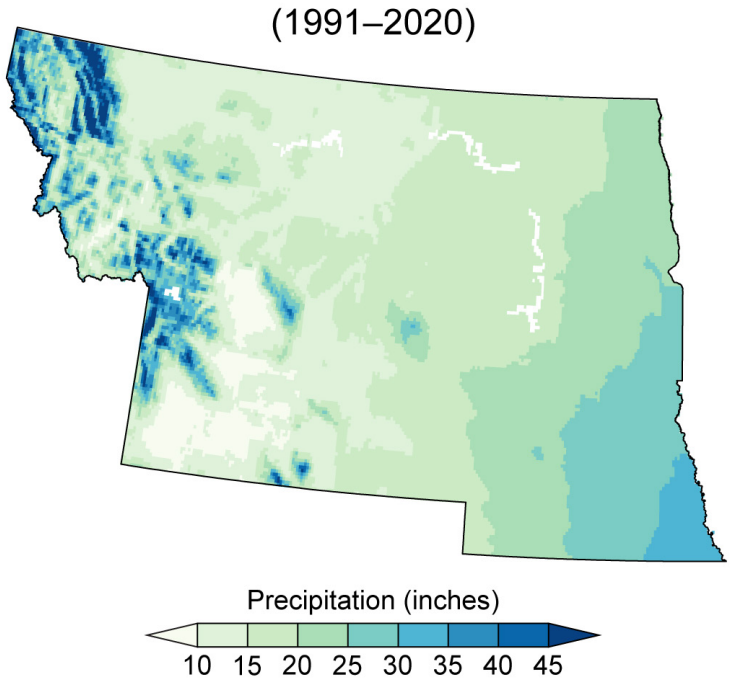


Rural areas, including those controlled by Indigenous Peoples, are often under-resourced and therefore less resilient to climate change.

Figure 25.1. Tribal reservations and American Indian trust lands (red outlines) overlap rural areas (dark gray; as defined by the USDA) across the Northern Great Plains. Rural and historically marginalized communities are often under-resourced and lack capacity to prepare for and recover from climate-driven natural disasters, making large portions of the Northern Great Plains less resilient to climate change.[12] White sections represent areas that fail to meet the criteria for "remote from urban" as defined by the USDA.[13] Figure credit: University of Wyoming, Center for American Progress, NOAA NCEI, and CISESS NC.

The Northern Great Plains region is known for its climate extremes and variability, but climate change is intensifying these characteristics.[14,15,16,17,18] The region has strong east–west precipitation (Figure 25.2) and north–south temperature gradients (Figure 25.3). Moving east to west across the region, the landscape becomes drier and elevation increases, forming three distinct areas: the humid eastern plains, semiarid high plains, and mountainous west. This complexity makes it challenging to summarize climate impacts across the region, but there are some common changes. Climate extremes in this region are expected to continue, compounded by climate change (KM 25.1). Human and ecological health will be impacted by these compounding hazards (KM 25.2). Human communities reflect the dependence on natural resources, historical policy legacies, and market forces that left a patchwork of land ownership and use (such as crop versus range, energy development, and recreation; Figure 25.8), and these livelihoods are at risk (KM 25.3). Climate change response will involve navigating complex tensions and trade-offs (KM 25.4), but communities are already building their capacity to adapt and transform (KM 25.5).

Average Precipitation for the Northern Great Plains



The region has distinct east–west precipitation gradients.

Figure 25.2. The map shows annual precipitation averaged over 1991–2020. Distinct precipitation gradients are evident from east to west and with elevation. These gradients highlight the complexity of the climate across the Northern Great Plains. White areas are large water bodies. Figure credit: USGS, University of Wyoming, NOAA NCEI, and CISESS NC.

Key Message 25.1

Climate Change Is Compounding the Impacts of Extreme Events

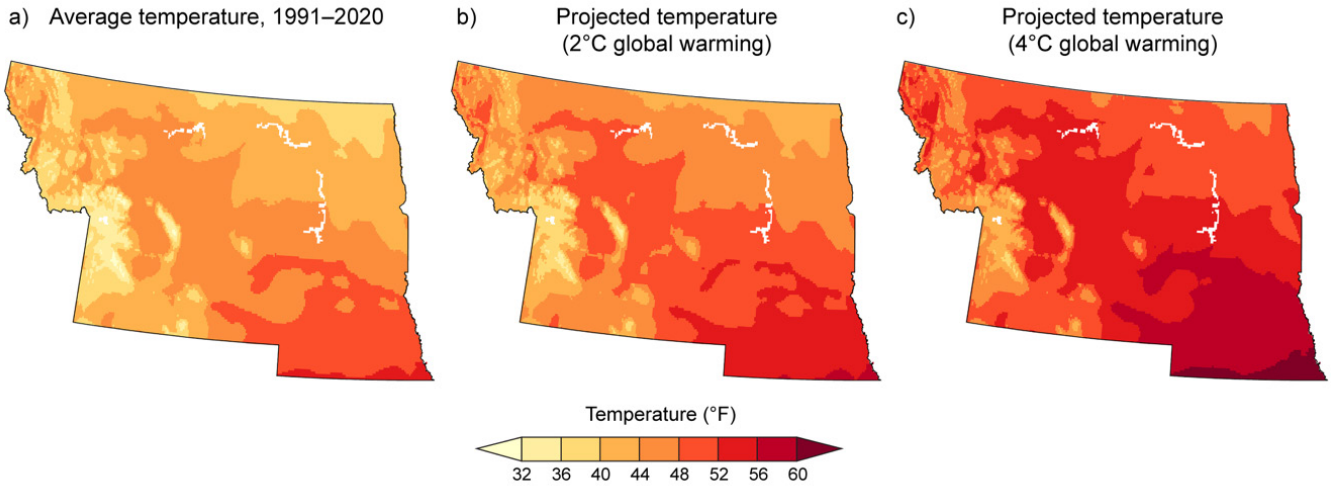
The Northern Great Plains region is experiencing unprecedented extremes related to changes in climate, including severe droughts (*likely*, *high confidence*), increases in hail frequency and size (*medium confidence*), floods (*very likely*, *high confidence*), and wildfire (*likely*, *high confidence*). Rising temperatures across the region are expected to lead to increased evapotranspiration (*very likely*, *very high confidence*), as well as greater variability in precipitation (*very likely*, *high confidence*).

Temperatures and Precipitation

Given the frequency of extremes and weather variability in the region, it is challenging to quantify long-term climate change trends. Even so, significant temperature trends and projections are clear (Figure 25.3). Since 1900, annual average temperature has increased in the region by 1.6°–2.6°F, with the largest increase in North Dakota and the smallest increase in southern Nebraska. Warming has occurred in all seasons but is most pronounced in winter. Summers have warmed little in North Dakota, South Dakota, and Nebraska. However, warm nights (minimum temperature of 70°F or higher), which were once rare, have become more common in Montana and Wyoming. The region has experienced fewer very cold days (maximum temperature of 0°F or lower) than the long-term average (1900–2020) for several decades. For

instance, the number of very cold days has been below the long-term average in Montana since 1985, in Nebraska since 1990, and in Wyoming, North Dakota, and South Dakota since 2000.[14,15,16,17,18] Decreasing snowpack will alter surface water availability for irrigation and may increase pressure on groundwater resources.[3,19] Overall aridity has increased and is projected to continue to do so because of increases in potential evapotranspiration, suggesting that the demarcation line between the humid East and arid West, traditionally defined by the 100th meridian, is moving eastward.[20,21]

Temperature for the Northern Great Plains



Distinctive gradients of temperature will hold with projected warming.

Figure 25.3. The maps show temperature averages for 1991–2020 (**a**) and projected temperature for global warming of 2°C (3.6°F; **b**) and 4°C (7.2°F; **c**) above preindustrial levels for the Northern Great Plains region. Current and projected values demonstrate distinctive gradients of temperature from southeast to northwest, with implications for climate impacts and effective adaptation. White areas are large water bodies. Figure credit: USGS, NOAA NCEI, CISESS NC, and University of Wyoming. See figure metadata for additional contributors.

All states in the Northern Great Plains region recorded their wettest five-year period between 1995 and 2019.[14,15,16,17,18] Total annual precipitation will be relatively stable across the region (Figure 4.3), but shifts in the form and timing of precipitation are expected. More intense precipitation events highlighting the projected increased variability in precipitation are expected to occur in all seasons, especially in the spring (Figure 2.12).[22] Temporal and spatial variability continues to be a dominant factor with precipitation and temperature.

Much of the runoff in the Northern Great Plains region contributes to the Missouri River and eventually the Gulf of Mexico, but portions contribute to the Columbia River, Colorado River, and Red River of the North basins. Much of the increasing streamflow in North Dakota shown in Figure 25.4 occurs in the Red River of the North basin and has prompted an approximately $3.2 billion (in 2022 dollars) infrastructure project to divert flood water around Fargo, North Dakota, and Moorhead, Minnesota.[23] The upper Colorado River basin (Colorado, Wyoming, Utah, and New Mexico), with headwaters in the western Northern Great Plains region, has been experiencing extensive drought for the last 20 years. Flows in the upper Colorado River basin, which account for about 90% of the streamflow of the entire basin,[24] have decreased over the past 20 years.[25,26] Increases in evaporative demand (the loss of water from Earth's surface to the atmosphere; Figure 25.5) have decreased runoff efficiencies, meaning that less rain and melted snow end up reaching the streams that feed the Colorado River.[27] Model-based analysis shows that continued warming is expected to further reduce flows in the upper Colorado River basin.[26]

Hail

The region is prone to damaging hailstorms; southeastern Wyoming and the southwestern part of the Nebraska Panhandle lie in "hail alley," the most hail-prone area in the United States.[17,18] Changes in low-level moisture, convective instability, melting level height, and wind shear will create shifts in hail occurrence.[28] From 1979 to 2017, the number of days favorable to significant (2 inches or greater diameter) hail in the central and eastern United States increased by 2 to 4 days each year.[29]

Research on the response of severe convection to climate change has focused on a very high scenario (RCP8.5).[30,31,32,33] Hail size, frequency of large hail, and length of hail season are projected to increase through the rest of this century in the Northern Great Plains.[33] By 2071–2100, under a very high scenario (RCP8.5), projections for the Northern Great Plains show a 27% increase in moderate-size (0.79–1.4 inches) hail days, a 49% increase in large (1.4–2.0 inches) hail days, and a 302% increase in very large (2 inches and larger) hail days, with increases in hail coverage of 73%, 157%, and 882% for moderate, large, and very large hail, respectively.[33] Projections also indicate a lengthened hail season.[33] The largest increases in hail risk anywhere in the United States are in this region and in July.[33] Projections by late this century using the SRES (Special Report Emissions Scenarios) A2 scenario (a scenario with increasing greenhouse gas emissions, similar to those in RCP8.5) indicate more hail days and an increase in the potential size, with a correspondent increase in accumulated kinetic energy and damage potential.[34] Comparing intermediate (RCP4.5) and very high (RCP8.5) scenario projections for severe convection indicates that the projected trends for RCP4.5 are in the same direction with lower amplitude compared to RCP8.5.[35]

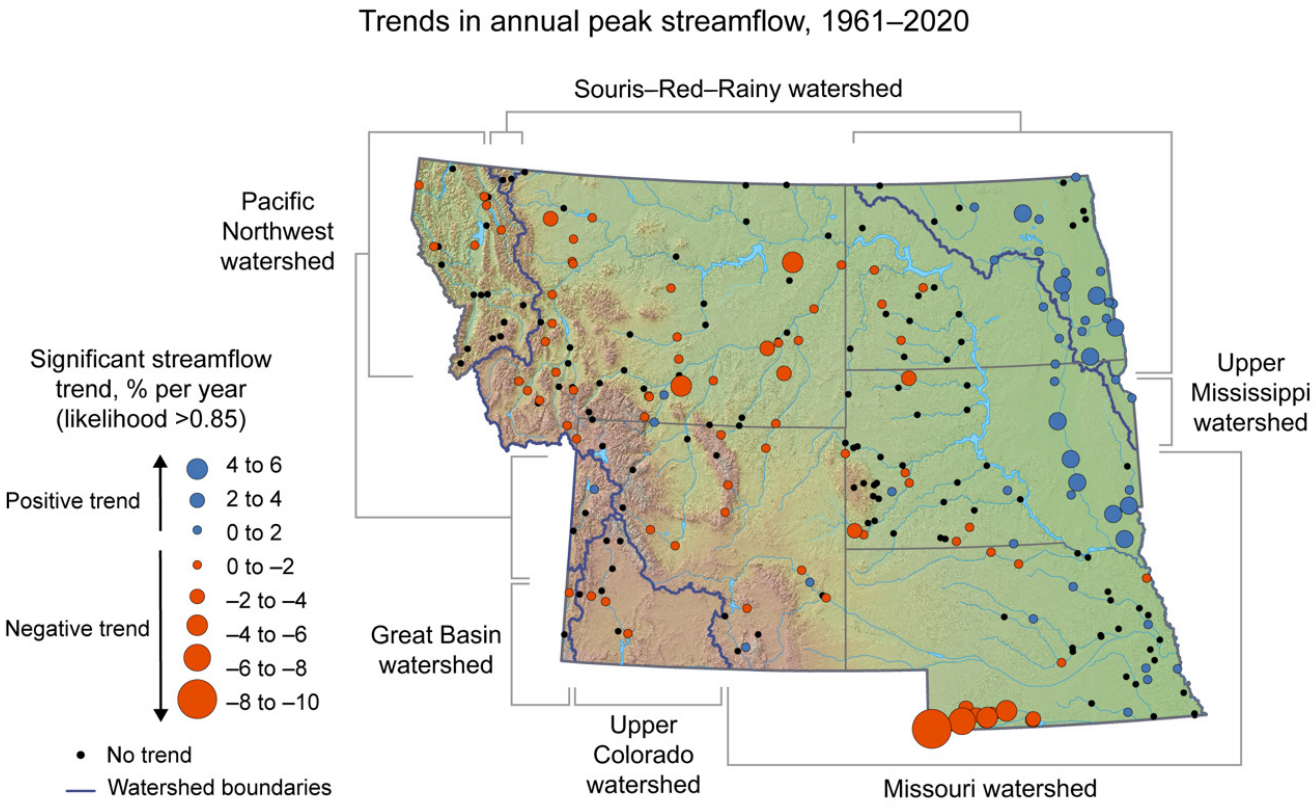
Flooding

Precipitation changes do not have a one-to-one relation with flooding. Many factors influence floods, including short- and long-term antecedent moisture conditions, presence of frozen soils, snowpack accumulation, rain-on-snow events, storm tracks, and rainfall rates.[36,37,38,39]

The Missouri River transects the region through 10 US states and 28 Tribal territories and is emblematic of the complex intergovernmental relations that will become increasingly important under climate change.[40] Record floods along the Missouri River and its tributaries in 2011 and 2019 caused evacuations, cost billions in damages,[41] and created interstate closures. Research suggests that recent large floods were caused by natural variability within the system;[42] however, model simulations suggest that climate change will reduce runoff in the upper Missouri basin.

Trends in annual peak streamflow, a proxy for flooding, differ across the 100th meridian divide (Figure 25.4). Observations show that annual peak streamflow is decreasing in the west and increasing in the east.[43] With few exceptions, the eastern Dakotas are an area of increasing peak streamflow (and flooding), while the western Dakotas, Montana, and Wyoming have decreasing peak streamflow. With 2° to 4°C (3.6° to 7.2°F) of global warming, the Northern Great Plains would expect to see some of the highest increases in annual flooding damage costs in the contiguous US due to climate change.[44]

Water Resource Regions and Rivers



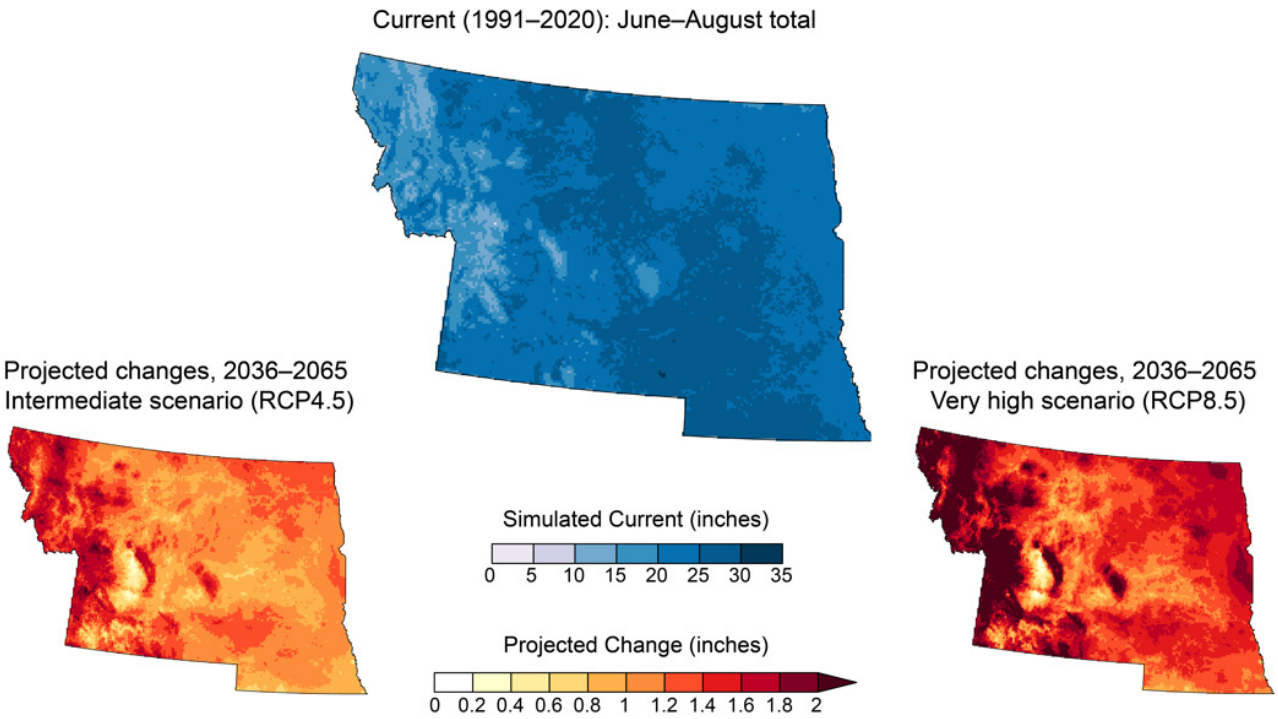
Annual peak streamflow—a proxy for flooding—has been rising in eastern portions of the region and declining in the west.

Figure 25.4. This map of the water resource regions and rivers within the region shows distinct east–west differences in trends in annual peak streamflow for 1961–2020, expressed as percent per year, where the size of the dot is relative to the size of the trend. Red dots are downward trends, and blue dots are upward trends. A likelihood-based approach is used to report these trend results. When a trend is identified, the trend likelihood value (likelihood = 1 – p-value/2) associated with the trend is between 0.85 and 1.0. In other words, the chance of the trend occurring in the specified direction is at least 85 out of 100. Smaller black dots are sites for which there were sufficient data for trend analysis but likelihood was less than 0.85; that is, these sites do not exhibit a substantial trend in either direction. Figure credit: USGS, NOAA NCEI, and CISESS NC.

Drought

Drought is projected to increase in the region, with localized droughts increasing by 2040 and more widespread regional droughts by 2070, under intermediate (RCP4.5), high (RCP6.0), and very high (RCP8.5) scenarios across wet or dry global climate models.[22,45] After precipitation, the most significant component of the water budget is evapotranspiration—the moisture transfer from Earth's surface and plants to the atmosphere.[46] Projected warming is expected to increase evapotranspiration (Figure 25.5), which may lead to drier soils later in the growing season (Figure 25.6).[47,48,49] Summer drought will be more probable than spring drought.[22,50] Multiple future climate scenarios indicate future increases in moderate, severe, and extreme drought, occurring approximately 10% and 20% more frequently by 2050 and 2100, respectively.[45] Recent droughts in the upper Missouri River basin between 2000 and 2010 were the most severe in the instrumental record,[51] and flash droughts are a growing concern.[52,53]

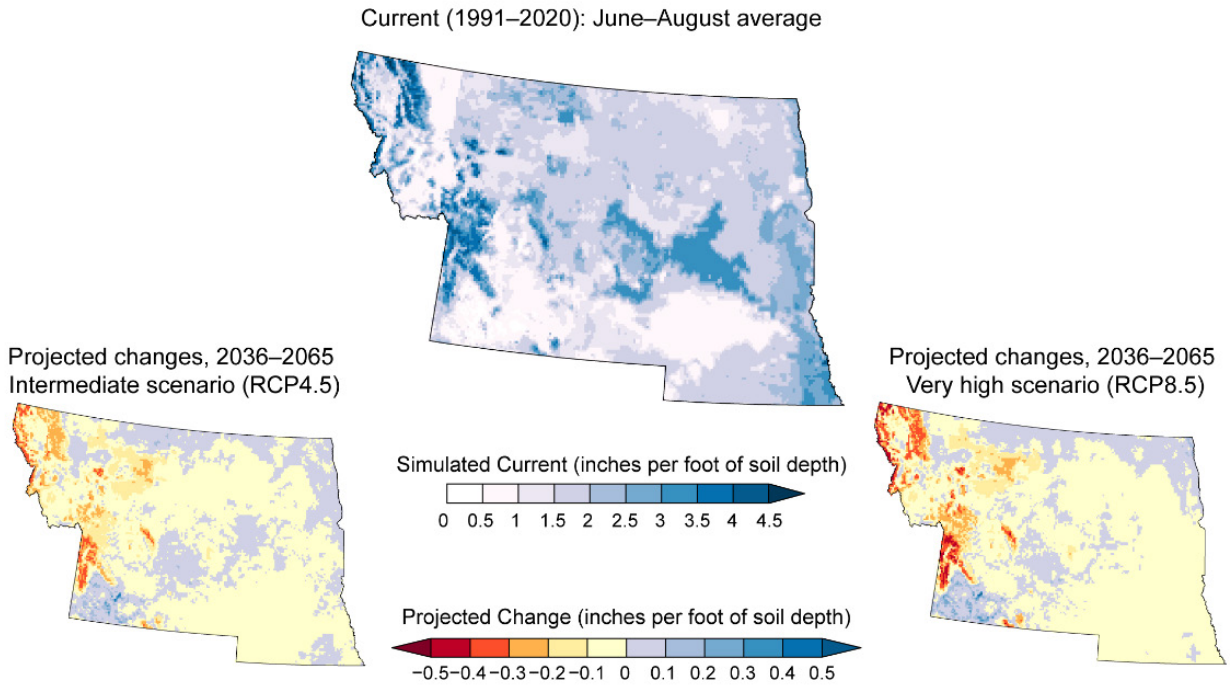
Current and Projected Potential Evapotranspiration



Warming is expected to increase evapotranspiration.

Figure 25.5. Figure shows (**center**) simulated current evapotranspiration and its projected change for the summer months under (**left**) intermediate and (**right**) very high scenarios. Data presented were obtained from Variable Infiltration Capacity models driven by the Coupled Model Intercomparison Project Phase 5 and Localized Constructed Analogs downscaling methods. Potential evaporative demands in the summer months (June, July, and August) increase regionally, especially in western areas under moderate climate change, and in both western and eastern areas under severe climate change. An increase in potential evapotranspiration typically drives a decrease in surface soil moisture (4-inch depth; Figure 25.6). Figure credit: USDA Forest Service, NOAA NCEI, and CISESS NC. See figure metadata for additional contributors.

Current and Projected Soil Moisture



Warming may not always lead to declines in soil moisture that would cause water stress in crops and natural plants.

Figure 25.6. Figure shows (**center**) simulated current soil moisture and its projected change for the summer months under (**left**) intermediate and (**right**) very high scenarios. Data presented were obtained from Variable Infiltration Capacity models driven by the Coupled Model Intercomparison Project Phase 5 and Localized Constructed Analogs downscaling methods. Soil moisture is expected to decrease slightly throughout the region in the summer months, with the largest decreases in the western mountain ranges of Montana. An increase in southwestern Wyoming is projected under both intermediate and very high scenarios. Snow water equivalent is decreasing at higher elevations in the Northern Great Plains (Figure 4.5) and can contribute to lower soil moisture in these areas. Declines in soil moisture can lead to crop, forest, and rangeland plant water stress, reduce plant growth, and increase ecosystems' susceptibility to fire. Figure credit: USDA Forest Service, NOAA NCEI, and CISESS NC. See figure metadata for additional contributors.

Wildfire

Driven by increased temperature and decreased relative humidity, fire potential in this region is projected to increase under future climate change (HadCM3-HRM3 model), especially in summer and autumn, with fire seasons becoming longer.[54] Increased evapotranspiration and drought risk raise the probability of large fire occurrence.[55,56] The number of large grassland wildfires in the four semiarid ecoregional grasslands of the Northern Great Plains increased by 213%, from 128 between 1985 and 1995 to 273 between 2005 and 2014, with total area burned increasing in the western ecoregions of the region by 350% but decreasing in eastern ecoregions by 75% or more.[57] Wildfire numbers and fire-season length increased from the 1970s to the 2000s by 889% and 85 days, respectively, in western Montana and Wyoming forests, with most ignited by lightning strikes rather than humans.[58] Historically, snow cover prevented winter wildfires and increased fuel moisture conditions during snowmelt followed by spring precipitation.[59,60] However, early spring snowmelt has been correlated with increased fire activity.[58] From 1950 to 2010, the number of snow-cover days declined within the region,[60] increasing wildfire activity due to drying fuels, which can lead to changes in flash flooding and debris flow (Focus on Western Wildfires).

Key Message 25.2

Human and Ecological Health Face Rising Threats from Climate-Related Hazards

Climate-related hazards, such as drought, wildfire, and flooding, are already harming the physical, mental, and spiritual health of Northern Great Plains region residents (*virtually certain*, *high confidence*), as well as the ecology of the region (*very likely*, *medium confidence*). As the climate continues to change, it is expected to have increasing and cascading negative effects on human health and on the lands, waters, and species on which people depend (*very likely*, *medium confidence*).

Mental Health

Climate change adversely affects mental and spiritual health in multiple ways (Ch. 15).[61,62] Although this issue affects the entire country, it is especially relevant in the Northern Great Plains, where three states are among the top 10 in highest suicide rates per capita in the Nation.[63] Suicide rates are particularly high in rural and Indigenous populations,[64] in part because of remoteness from care and the limited number of mental health professionals.[65,66] Based on geographically broad-based studies, climate change is projected to amplify these risks.[67,68] Climate anxiety, also called eco-anxiety (a feeling of doom about future climate change), is already prominent among farmers and ranchers in the region.[69] Solastalgia—the distress specifically caused by environmental change while still in a home environment[70,71]—is indicative of more subtle but potentially wider-reaching mental health impacts. Solastalgia is most often associated with Indigenous communities, who share collective ancestral ties to the lands and natural resources where they live or previously lived and which are inextricably linked to their identities, cultures, and livelihoods, as well as their physical and spiritual well-being.[72] However, solastalgia can also affect others who are connected to the land, such as ranchers and farmers.[73]

Direct impacts such as crop failure, increased disease, and biodiversity loss can lead to increased loss of Traditional Knowledge and language, further influencing the mental health of Indigenous Peoples.[61,74] Despair related to the loss of environmental, cultural, and human health is widespread among Crow Tribal elders, adversely affecting mental and spiritual health, and is exacerbated by a sense of inability to address the root causes of climate change.[75,76]

Physical Health

Climate change is impacting the physical health of the region's inhabitants in a number of ways. Wildfire is projected to increase in the region (KM 25.1), with correspondent health and property implications (Chs. 14, 15; Focus on Western Wildfires).[61] One study suggests that although the total number of premature deaths attributable to wildfire smoke is higher in states with greater population density, Montana has the highest per capita rate of such deaths in the country.[77] In addition, heat is responsible for more climate-related deaths than any other factor in the United States.[78] Although the Northern Great Plains region lacks the extreme temperature increases experienced in some other regions, people in this region are still at risk given the large number of outdoor workers and recreationists.[79] Rising temperatures, as well as other climate impacts, are expected to increase the risk of some vector-borne diseases, such as West Nile virus.[80,81,82] Flood risk patterns in the United States are inequitable on a county basis, with some of the counties in this region at increased risk, including some that encompass or are adjacent to Tribal reservations.[83] Shifts in precipitation and increased flooding (KM 25.1) are expected to raise the risk of water-borne diseases such as *Campylobacter* infection.[84]

Compound Health Impacts of Climate Events

Multiple climate pressures frequently act simultaneously, leading to compounding health-related outcomes (Ch. 15).[61,85,86] The impacts of floods resulting from earlier snowmelt combined with more intense precipitation events can be worsened by loss of ground cover from past wildfires,[87] putting people at risk of water-borne diseases, trauma and increased mental health issues, and economic losses. Wildfires are more common during hotter months when drought is more common,[55,56] exposing people to compounding risks and stress from smoke, heat, and poor water quality.[88,89]

Ecological Health

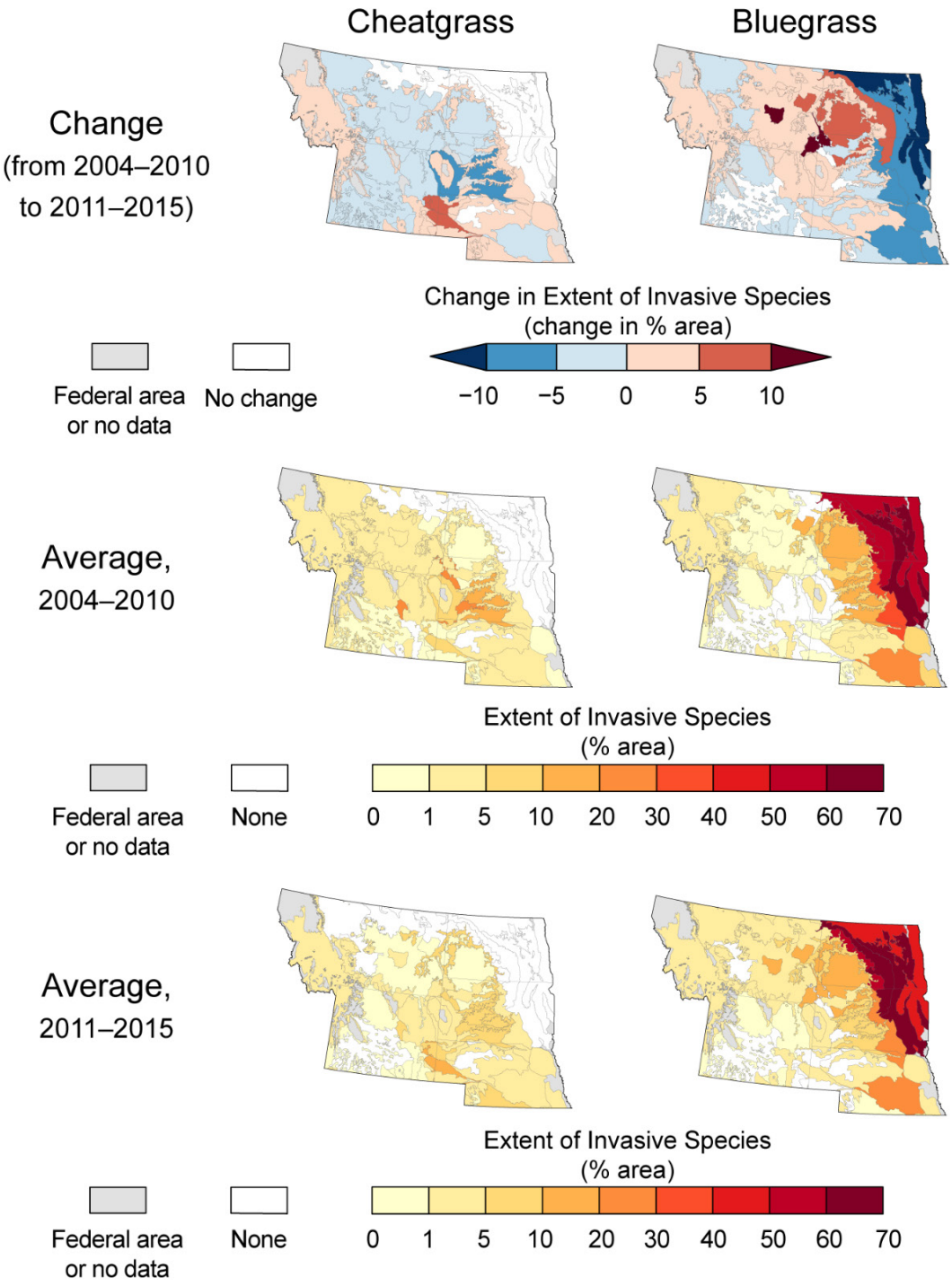
Water Quality

Excess contributions of nutrients, such as nitrogen and phosphorus from agricultural runoff or point sources such as wastewater treatment plants, can cause water quality issues, which are expected to be exacerbated by climate change.[90,91] Nutrient loads (the total amount of a nutrient transported past a single location over a set period of time) can increase after droughts, when sediment is flushed in subsequent runoff events.[92] Nutrient runoff from agricultural land spikes after heavy rain and contributes to harmful algal blooms and transport of nutrients to the Gulf of Mexico (KM 25.5).[93,94,95] Climate change has long been hypothesized as a driver of harmful algal blooms;[96] supporting these hypotheses with observations has been challenging because of gaps in monitoring, lack of long-term algae data, and changes in laboratory and remote-sensing methods.[97,98]

Cascading Impacts to Biodiversity Loss

Climate change compounds existing threats to biodiversity (Ch. 8). Within the Northern Great Plains, conversion of perennial grasslands to monocultures of annual crops results in a loss of biodiversity.[99] Invasive species are also a contributor to biodiversity loss in the region,[100,101] and the dominant invasive species of concern varies from east to west (Figure 25.7). The region is a hotspot for grassland bird diversity and encompasses the entire breeding season range for many of the most vulnerable species;[102,103] based on projections under a scenario with 5.4°F (3.0°C) warming above preindustrial levels, more than 80% of grassland bird species will be vulnerable to climate-related threats during the breeding season.[104] Both native pollinators and honeybees are important components of the region's ecosystems. The region supports approximately 40% of US honeybee colonies in the summer.[105] Over the last 15 years, pollinators have been experiencing declines.[106] Although not directly linked to climate change, changes in land-use patterns related to biofuel policies and loss of Conservation Reserve Program (CRP) lands are potentially contributing to these declines.[105,107] The CRP program pays farmers to take marginal land out of agricultural production for 10 years and plant perennial cover to reduce soil erosion and provide other ecosystem benefits. Recent modeling, however, indicates that targeting where CRP lands are planted on the landscape could improve the benefits to pollinators.[108] Finally, natural resource managers have identified a number of management strategies to help reduce biodiversity loss in the face of climate change, but for many taxa and ecological communities, there are still knowledge gaps.[109,110]

Invasive Species as Bioindicators of Ecological Condition



Invasive cool-season grasses are reducing biodiversity in the Northern Great Plains.

Figure 25.7. Acreage in the Northern Great Plains region where at least 50% of the soil surface is covered by two representative invasive plant species: cheatgrass (*Bromus tectorum*; **left**) in the western part of the region, and Kentucky bluegrass or Canada bluegrass (*Poa pratensis* or *Poa compressa*; **right**) in the eastern part of the region. The figure shows acreage for 2004–2010 (**center**) and 2011–2015 (**bottom**), as well as the change in extent of invasion between those two periods (**top**). These invasive grasses already pose a threat to the biodiversity of the region, and climate change is predicted to increase invasive species challenges for this region. Figure credits: (center left, bottom left, center right, bottom right) adapted from NRCS 2018;[111] (top left, top right) The Nature Conservancy, NOAA NCEI, and CISESS NC.

Key Message 25.3

Resource- and Land-Based Livelihoods Are at Risk

The Northern Great Plains region is heavily reliant on agriculture and resource-based economies, placing livelihoods at risk from the impacts of climate change and related policy. Agriculture and recreation will see some positive effects but primarily negative effects related to changing temperature and precipitation regimes (*likely*, *medium confidence*). Energy-sector livelihoods will be affected as emissions-reductions policies drive shifts away from fossil fuel sources (*likely*, *high confidence*). Climate change is expected to test the adaptive resilience of the region's residents, in particular rural, Indigenous, and low-income immigrant populations (*likely*, *medium confidence*).

Food and Agriculture

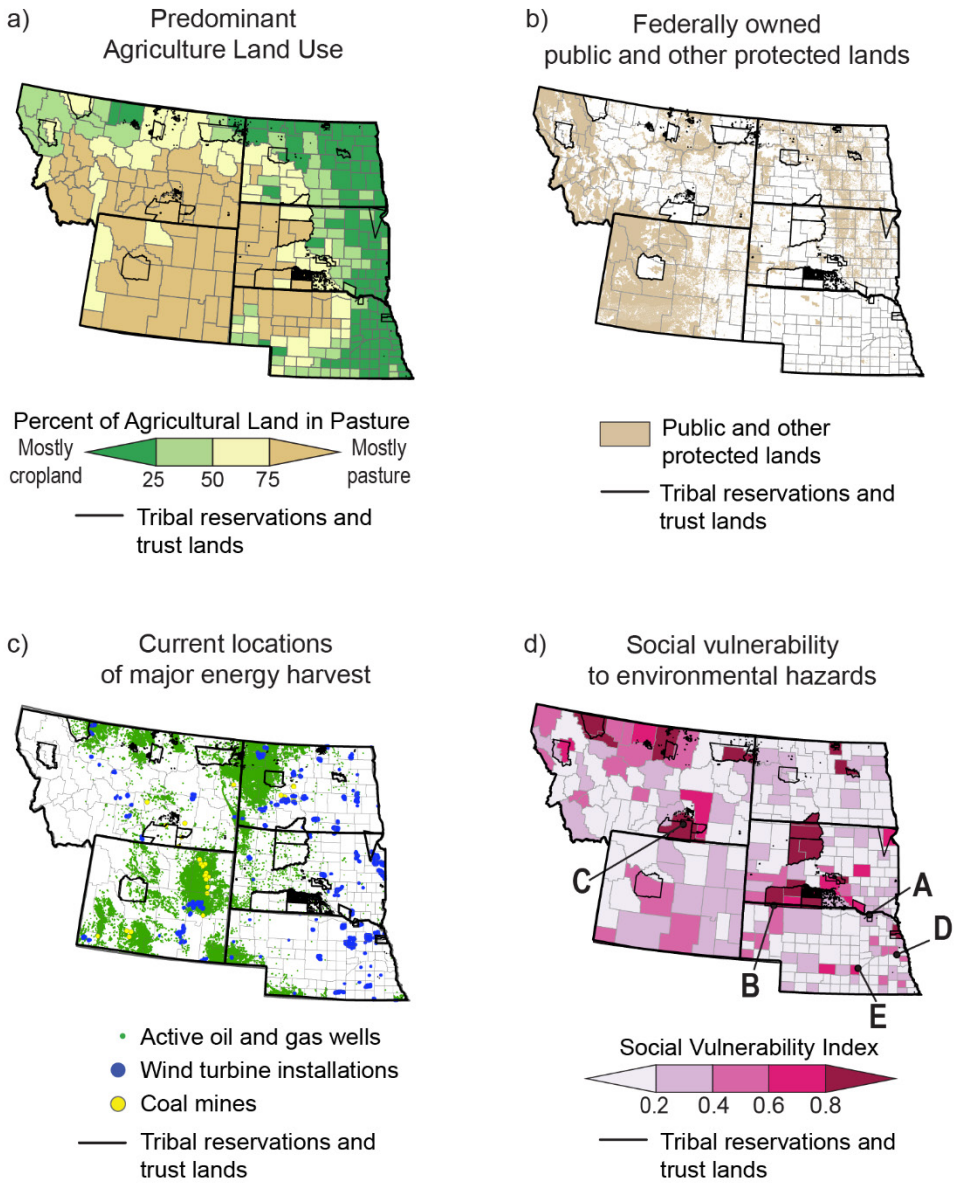
Farming (referring to all forms of agricultural production, including livestock operations) accounts for 6% of total earnings in the region, compared to 0.4% of total earnings nationally.[112] Although growing seasons and frost-free periods are lengthening,[113,114] other factors may stress crop production.[49] Negative crop yield impacts are anticipated from rising temperatures, which increase the potential for heat and moisture stress during reproductive periods, as well as the potential for increased weed competition and pest expansion.[3] Although row crop agriculture generally occurs where greater average annual precipitation occurs (Figures 25.2, 25.8a), farmers are expanding and intensifying croplands into less productive lands in the region[99,115,116] as climate change alters growing conditions. Although crop yield decline from increased evapotranspiration may be somewhat offset by soil moisture trends, soil moisture is projected to slightly decline on an annual basis across much of the region (KM 25.1).[117,118] Overwintering crops like winter wheat are expected to benefit from reduced exposure to frost days under climate change, but reduced ground insulation from declining snow cover may offset some of this gain.[119] Additionally, higher carbon dioxide concentrations are expected to benefit the productivity of many crops.[120]

The net effect of climate change on specific crop yields is uncertain and will depend on interacting effects of temperature, moisture, carbon dioxide, and ozone, as well as adaptation through shifts in cultivars, crop mix, and management practices.[120,121,122] For example, climate change was listed as a primary challenge to both dryland and irrigated agriculture in the 2022 Blackfeet Agricultural Resource Management Plan (ARMP), due to earlier snowmelt, increased evapotranspiration, and less water available for irrigation. Recent extreme events indicate potential future impacts to livelihoods of individuals throughout the agricultural value chain.[123] Climate change negatively impacts the ability of regional Indigenous communities to grow and use traditional foods, medicines, and plants due to species movements and shifts in growing and harvesting seasons. Two significant examples are the Lakota staples wild turnips and chokecherries.[124,125] In 2017, above-normal temperatures in late summer and fall delayed the harvest of berries and medicinal plants.[126]

Northern Great Plains rangeland productivity may see less harm from climate change than other livestock-producing regions.[127,128] Rising temperatures and elevated carbon dioxide levels are projected to increase growing-season length and carbon assimilation by plants, thus increasing aboveground net primary productivity (atmospheric carbon converted into aboveground plant matter)[129,130,131] but decreasing nutritional quality.[132,133] However, drought-induced water limitation would produce the opposite response by reducing biomass production, concentrating nutrients, and enhancing forage quality.[134] While the northern part of the region could see more frequent forage surpluses under both intermediate (RCP4.5) and very high (RCP8.5) scenarios, the southern part of the region (e.g., Nebraska) may experience more frequent forage deficits.[1] Drought years have had a smaller impact on cattle numbers in the Northern Great Plains than

in other regions,[135] and single-year droughts have only minimally impacted management or livelihoods.[136] However, ranchers face increasing challenges managing livestock health due to heat stress, parasites, and pathogens, as well as managing shifts in forage species, including invasive weeds.[137,138] Tribal producers may be more vulnerable to these stresses, as they tend to operate smaller farms and ranches on lands that have highly fractionated ownership, compared to non-Indigenous producers.[139] While cattle production has moved northward overall,[1] additional stressors to rangeland-based livelihoods exist in the region, including conversion to cropland,[140] rising land prices, and land ownership concentration trends.[141,142,143]

Geography of Land Use and Social Vulnerability



The Northern Great Plains region shows wide geographical variations in land use and social vulnerability.

Figure 25.8. The figure shows the geography of resource- and land-based livelihoods and vulnerabilities. Tribal reservation and trust lands are outlined on all maps. Panel (**a**) displays the predominant use of each county's agricultural land as either pasture or cropland. Pasture is common throughout much of the region, with cropland prev-

alent in the eastern portion of the region. Panel (**b**) shows federally owned public lands, including lands managed by the National Park Service, Bureau of Land Management, Bureau of Reclamation, US Forest Service, US Fish and Wildlife Service, Department of Defense, Department of Energy, and other federal agencies. In addition to public lands, private protected areas voluntarily provided to the database are also included but make up a very small minority of the overall public and other protected land area. The amount of federally owned public land increases in the more arid western portion of the region. Panel (**c**) displays locations of major energy sources in the region. Surface coal mines, oil and gas wells, and wind turbine installations are located throughout the region. Panel (**d**) shows county-level Social Vulnerability Index (SoVI) scores, with higher scores closer to 1 indicating higher levels of social vulnerability to environmental hazards.[144] Capital letters in panel (d) display locations of recent extreme climate events highlighted in the "Community Infrastructure and Quality of Life" section below (A, D, and E highlight examples of flood impacts, B highlights storm damage, and C provides an example of drought impacts). Figure credit: University of Nebraska, USDA Forest Service, NOAA NCEI, and CISESS NC.

Tourism and Recreation

The region's public and private lands provide tourism revenue, as well as benefits to residents' quality of life (Figure 25.8b).[145,146] Climate-related trends and extremes are expected to affect ecosystem services, wildlife, and tourism, with associated economic impacts.[147,148] Higher temperatures in the Yellowstone River in August 2016 are blamed for a fish kill that triggered the closure of the river to fishing and other uses, decreasing income for local and regional businesses.[149] Water-based activities are particularly vulnerable to drought and face increased conflicts with other water uses.[150] In 2017, Montana lost approximately 800,000 visitors and $289 million (in 2022 dollars) of tourism- and recreation- related income due to drought.[151] Visitors also shortened their stays due to smoke and fires.[150] Warmer winter temperatures in recent decades are correlated with mountain pine beetle outbreaks in western Montana but were not significantly correlated with mountain pine beetle outbreaks in other forests within the region, such as the Black Hills.[152] A 2017 drought decreased pheasant populations, affecting tourism income; its impact on wildlife populations also reduced Tribal-guided hunting opportunities and may have affected the competitiveness of culturally significant plants.[126] The length of winter sports seasons is expected to decrease[153] and thus negatively affect recreation economies in Montana, Wyoming, and South Dakota.[154] However, there may be improved opportunities for spring and autumn "shoulder season" recreation and both positive and negative effects on wildlife-based activities.[150]

Energy

Energy revenue in the region supports local services, infrastructure, and income that includes per capita payments for some Tribal members.[155] Energy revenue can also create risks in the region stemming from short-term revenue volatility and long-term dependence.[156] The region has an extensive number of oil and gas wells, numerous surface coal mines, and increasing wind turbine installations (Figure 25.8c). The region's share of employees working in fossil fuel extraction is four times greater (1.8% of all jobs) than in the Nation as a whole (0.4% of all jobs).[5] Energy-related livelihoods are affected by climate change due to changes in power generation, transmission, and consumption, as well as shifts in demands for particular types of energy sources.

Climate change impacts and mitigation efforts are expected to change energy demand in the Northern Great Plains seasonally. Higher summer temperatures and heatwaves are expected to increase energy demand in the Northern Great Plains and throughout the country, while in the region, higher winter temperatures and fewer cold snaps are expected to reduce energy demand for heating (Ch. 5).[157,158] Increased energy demands from outside the region will place increased demands on regional energy resources and electricity supply.[159] Lower winter electricity demands may potentially lower annual household energy costs in this region,[157] but increased electrification of the grid may increase costs to utility ratepayers as natural gas utilization declines.[160] Finally, climate change, especially climate extremes, may also stress energy infrastructure (e.g. rail, pipelines, distribution lines, transmission lines; Ch. 5).[161,162]

Energy-related livelihoods are also affected by shifts in the type of energy harvested. Energy extraction and generation in the region respond to external market and policy drivers.[163,164,165] For example, coal extraction has declined since 2011 due to air quality regulations, competition with lower-cost natural gas and renewables, and climate policy in states and utilities outside the region.[155] Tribal and other rural communities dependent on coal extraction for revenue and jobs have experienced losses to both as markets shift away from these resources.[166] Energy transition policy is heterogenous at the state level, and states in the region have pursued efforts to protect coal assets rather than help communities transition from coal.[155,167,168] In response to the demand for oil and gas, communities engaged in oil and natural gas extraction in the Northern Great Plains region grew faster than the regional average (14% compared to 6%),[8] and oil and natural gas extraction is expected to remain at or near current levels through 2030.[169] Renewable energy production is on the rise in the Northern Great Plains, with the region supplying 12% of the total US electricity generation from wind, biomass, and solar sources.[163,170] Wind electricity generation tripled in the region between 2011 and 2021 and was often co-located alongside row crop agriculture (Figure 25.8).[159,170] A growing number of Tribal entities are leading the Nation's renewable energy transition by installing renewable energy projects, including the Pine Ridge Indian Reservation in South Dakota (solar), the Oceti Sakowin Power Authority (wind), and the Confederated Salish and Kootenai Tribes in Montana (hydroelectric).[171,172,173] The Inflation Reduction Act of 2022 (IRA) is expected to accelerate deployment of renewable energy sources,[169] and the region may benefit from investments in hydrogen hubs; carbon capture, utilization, and storage; and advanced nuclear reactors (Ch. 5).[174] Without the IRA and other climate mitigation policies, additional energy produced by new renewable energy sources is expected to only meet the increased energy demand by 2050 rather than replace the current usage levels of petroleum and natural gas.[163]

Community Infrastructure and Quality of Life

Tribal lands, governments, and peoples are integral to the energy, agriculture, and recreation sectors. Immigrant populations are tied to agriculture in the region through their role in meatpacking, dairy, and other key industries. These communities face social vulnerability to harm from environmental hazards (Figure 25.8d). Communities across the region have experienced damages to infrastructure, businesses, homes, and livelihoods due to extreme events, including drought (2017, 2021), hailstorms (2018), flooding (2019, 2022), and wildfire (2021).[41] For example, after the 2019 Nebraska floods, community-level impacts included damage to homes, lack of water and sanitation services, and increased levels of anxiety and stress.[175] The effect of floods on the Santee Sioux Tribe included interruptions to power and drinking water supplies, wastewater backups, and destruction of many bridges and buildings (Figure 25.8d, point A).[176]

Future extreme events will disproportionately affect communities in the Northern Great Plains region that have greater exposure and sensitivity to hazards and fewer resources to prepare, respond, and adapt compared to larger cities.[12] For example, two storms damaged nearly 600 homes on the Pine Ridge Indian Reservation in July 2018, half of which were not repaired one year later (Figure 25.8d, point B). In 2019, the region experienced widespread flooding and damaged roads,[177] stranding many residents without access to basic needs. Many communities were disconnected from major highways, and infrastructure repairs are still underway. In drought years, communities dependent on surface water, such as those across the Crow Reservation, are seeing water resources and adaptation options become increasingly scarce (Figure 25.8d, point C).[166]

The lack of resilient infrastructure combined with regional climate impacts has created extreme water insecurity for Indigenous communities.[178] In the region, $159 million (in 2022 dollars) would be needed to bring either sewer or water access to 175 Tribal communities. Further, there are upwards of 18,000 homes within the region in need of sanitation (water and sewer) repair.[179]

Finally, regional residents living in housing or locations that are vulnerable face potential harms due to climate change. States in the region have a higher percentage of mobile and manufactured homes (e.g., 12.3% in Wyoming and 10.4% in Montana) compared to the US average (5.5%).[8] Mobile and manufactured homes are physically more vulnerable to extreme heat, flooding, and wildfires, exacerbating impacts from disasters.[180] Homes in floodplains are disproportionately occupied by renters and non-White populations. In Nebraska, Hispanic residents are overrepresented in floodplain areas (18% compared to 9% of residents in non-floodplain areas),[181] which resulted in disproportionate impacts to their housing security during the 2019 flooding in areas like Fremont and Grand Island, Nebraska (Figure 25.8d, points D and E).

Key Message 25.4

Climate Response Involves Navigating Complex Trade-Offs and Tensions

Climate change is creating new, and exacerbating existing, tensions and trade-offs between land use, water availability, ecosystem services, and other considerations in the region, leading to decisions that are expected to benefit some and set back others (*very high confidence*). Decision-makers are navigating a complicated landscape of shifting demographics, policy and regulatory tensions, and barriers to action (*high confidence*). Changes in temperature and precipitation averages, extremes, and seasonality will alter the productivity of working lands, resulting in land-use shifts to alternative crops or conversion to grasslands (*likely, medium confidence*). Shifts in energy demand, production, and policy will change land-use needs for energy infrastructure (*likely, medium confidence*).

Communities across the Northern Great Plains region experience complex tensions and trade-offs between land use, water availability, ecosystem services, and other factors, all exacerbated by the impacts of climate change. For example, higher temperatures and a longer growing season make the region attractive for climate-driven human migration[9] and increased forage production,[1] which in turn increase the demand for water resources. However, shifts in precipitation and reductions in snowpack will alter the quantity and timing of available water.[60] These tensions culminate in difficult decisions about how best to manage water quantity and quality and balance trade-offs between consumptive and ecological uses. Chapter 18 highlights frameworks for understanding complex systems, cascading effects, and decision-making under uncertainty.

Tensions: Navigating Barriers to Mitigation and Adaptation

Decision-makers are increasingly aware of current and projected climate change impacts, and communities are trying to adapt and mitigate. However, there are cultural, structural, and institutional barriers that prevent effective action in the Northern Great Plains region. States within the region currently rely on fossil fuel economies, creating resistance to energy transition and economic diversification.[155,156,182] For example, Wyoming has passed legislation designed to hamper the retirement of coal plants and to ensure a continued market for coal generation.[167] Other examples of barriers include less research funding than other regions;[183] lowered capacity to adapt (Box 25.1); varying perceptions of climate change;[184] and a confusing, and occasionally contradictory, set of water regulations and rights around surface water storage (e.g., implementation of artificial beaver dams to retain water on the landscape).[185,186] These factors limit transition planning and undermine community-level resilience.[168]

Integration of climate change into K–12 science education standards in the Northern Great Plains region varies greatly, with several states in the region failing to link human activities to climate change.[187] Acceptance of the human link to climate change is lower than the national average among adults in the

Northern Great Plains region, with particularly low acceptance among agricultural producers and agricultural interest groups.[188,189] This lack of acceptance highlights barriers to collective understanding and climate change response in the region and is matched by a stronger evidence base for actions that emphasize adaptation and resilience rather than mitigation (KM 25.5).

The employment, income, and public revenue impacts of the transition away from fossil fuels will vary by geography.[190,191] Declines in coal demand have, and will continue to have, negative effects on rural coal-dependent states and communities, such as Rosebud and Big Horn Counties in Montana.[155,156,192] The public revenue gains from renewable energy could be substantial but uneven, reflecting both the impact of facility siting on regional economic opportunity and the impacts of tax policy on the ability of state and local governments to capture and retain tax revenue.[155,193,194] Specifically, state taxation and expenditure limits preempt governments from generating revenue from diversified economic growth,[195] including from renewable energy, and tax incentives designed to lower costs for renewable energy projects can undermine the revenue benefits of an energy transition.[196] Tribal communities in this region also face barriers to developing and benefiting from renewable energy on Tribal lands, including a dependence on federal agencies for permitting, limited access to private finance, and an inability to access federal incentives, which makes private investment on Tribal lands less attractive.[197,198] Decision-makers and communities in the region have increased efforts to incorporate multiple values and ways of knowing (e.g., Indigenous Knowledge, local experience, and empirical science) into planning and action (KM 25.5).

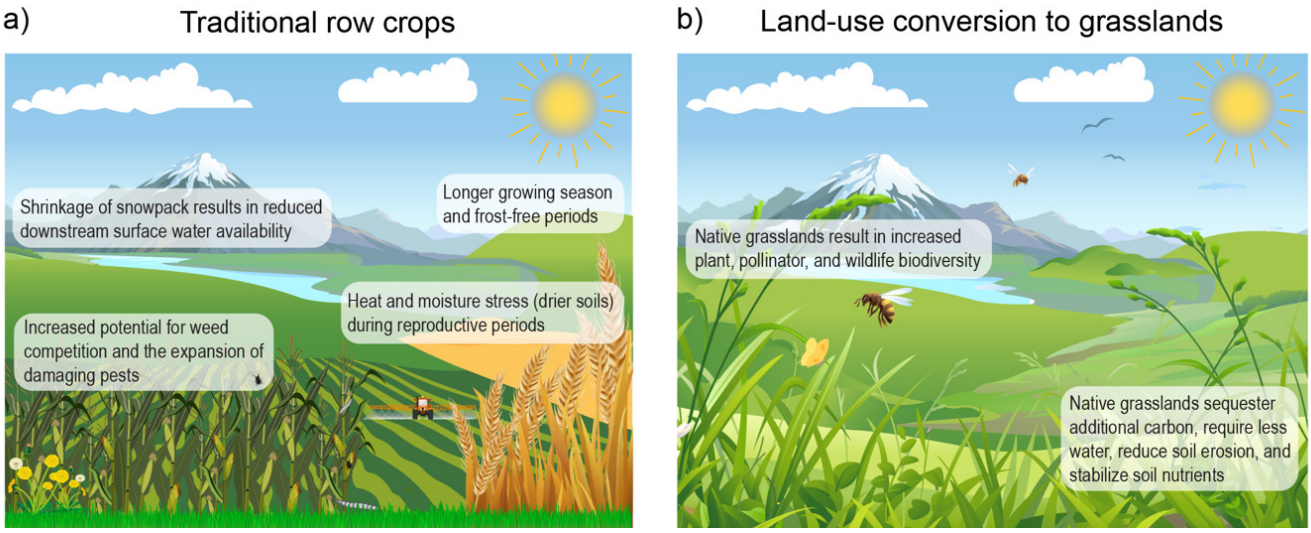
Box 25.1. Rural Capacity and Funding

With $1.28 trillion (in 2022 dollars) in funding, the Infrastructure Investment and Jobs Act is one of the largest investments in infrastructure, community resilience, and climate response in US history.[199] To successfully plan for and finance climate mitigation and adaptation projects, communities require capacity, staffing, resources, and expertise to apply for funding; fulfill reporting requirements; and design, build, and maintain infrastructure projects over the long term.[200] States where capacity to support these efforts is limited receive fewer federal resilience grants, and federal programs that create a need for capacity to apply for and manage grants can erode local capacity that could be utilized for other purposes, thereby discouraging participation.[201] Federal funding agencies can utilize maps of capacity at the local-government level to identify and support communities that lack staff and expertise to compete for climate mitigation and adaptation, community resilience, and economic development resources. Montana, Nebraska, North Dakota, and South Dakota rank among the 10 states where the greatest share of communities have a Rural Capacity Index lower than the national medium.[202] Key Message 20.3 further describes the role of governance and policy in risk, adaptation, and equity.

Trade-Offs: Land-Use Conversion

To counterbalance the potentially negative effects of a warmer future climate and drier soils, a shift to more water-conservative and nutrient-retentive land cover may be needed, such as from row crops to grassland (Figure 25.9). This would enhance ecosystem services such as wildlife, flood retention, nutrient stabilization, and carbon sequestration.[203,204] While this would increase resilience, it would also require many social and infrastructure adjustments and investments, including identifying seed sources for native species. Crops and services produced would shift from grain to forage, animal products, native plant seed, biofuel from grass, increased hunting on private land, and carbon credits. This would disadvantage companies that currently serve the high-input needs of conventional farmers but result in smaller loans for grassland producers due to less costly equipment, smaller seed purchases, and less grain shipped overseas.

Land-Use Conversion as a Strategy for Climate Adaptation



Land-use conversion offers one strategy for adapting to climate change.

Figure 25.9. Climate stressors interact with regional land-use decisions in complex ways. Recent and historical land-use decisions (**left**) are altering the productivity of working lands. Potential alternative land-use decisions (**right**) have the potential to increase resilience against climate change. By converting agriculture to grassland in areas that will become marginal for production, landowners and resource managers can conserve water and enhance ecosystem services. Figure credit: USGS.

Transitioning away from fossil fuel energy systems is expected to result in the abandonment or reduction of fossil fuel energy infrastructure (e.g., pump jacks, well bores), siting of new wind energy generation (e.g., wind turbines), construction of linear transmission CO_2 pipelines, and continued land conversion to biofuels.[165,205] Because renewable energy sources are expected to require larger land areas (3 to 25 times larger) to produce similar amounts of energy as nonrenewables,[206,207] a trade-off exists between providing energy and conserving the few remaining intact grassland tracts in the world.[208,209] Fragmentation of these tracts by energy infrastructure involved in harvesting and transmitting energy can reduce wildlife populations and provide conduits for invasive species.[159] Siting of energy infrastructure on areas already disturbed by row-crop agriculture or other activities may help prevent further fragmentation in some areas but may not be a possibility in the more intact grasslands of the Northern Great Plains that are relatively undisturbed.[159,209,210] Water-use trade-offs are another concern with energy development. Water law can influence the ability of industry to access water rights in low-flow years.[211] For instance, state and federal environmental policy may limit options to generate power from fossil fuel plants that require water for cooling during low-water years, which are projected to become more frequent (KM 25.1). Additionally, legal challenges related to water quantity and quality for endangered fish set up trade-offs between energy, wildlife, and recreation.[212,213]

Another adaptation action, piloted locally on less productive farmland with promising regional mitigation potential, is planting low-input, productive tall grasses, such as switchgrass, as dedicated biofuel energy crops (Figure 25.10).[214] This approach sequesters carbon from the atmosphere,[215,216] and marketing this alternative crop for forage, seed, or biofuels could generate income equal to or exceeding current income.[217] Switchgrass is a native plant that requires little fertilization and is especially resilient to drought. Biofuel feedstocks could be burned to generate electricity or converted to ethanol or bio-oil, syngas, and biochar. Planting grasses would store more carbon in the soil, require fewer inputs of fossil fuel compared to the annual planting of conventional crops, and improve other components of soil health.[218] However, large-scale land-use conversion to biofuel energy crops could disrupt food production processes, reduce biodiversity, and drive water competition.[219]

Marginal Farmland Planted to Switchgrass

Conversion of cropland to production of biofuels such as switchgrass is being piloted in the region as a climate adaptation action.

Figure 25.10. Switchgrass is a highly productive native prairie perennial that is the most promising species for future commercial growth as biofuel (for use as liquid transportation fuels and in electricity production). Photo was taken in 2021 at an experimental farm near South Shore, South Dakota, following two summers of drought, when production of switchgrass hay was 5 tons per acre and was more profitable than the production of corn. Photo credit: ©Arvid Boe, South Dakota State University.

Key Message 25.5

Communities Are Building the Capacity to Adapt and Transform

Adaptation is underway in the Northern Great Plains to address the effects of climate change. Agricultural communities are shifting toward climate adaptation measures such as innovative soil practices, new drought-management tools, and water-use partnerships (*medium confidence*). Several Tribal Nations are leading efforts to incorporate Traditional Knowledge and governance into their adaptation plans (*high confidence*). Resource managers are increasingly relying on tools such as scenario planning to improve the adaptive capacity of natural ecosystems (*medium confidence*).

Effective adaptation accounts for climate change uncertainty as well as the complex interactions and trade-offs within and between ecological and social systems (Ch. 31).[220,221] The failure to carefully navigate the full suite of adaptation options and the consequences of those options can result in maladaptation—increased vulnerability to climate change due to poor or misguided action (Box 25.2)[222] or inequitable distribution of outcomes. Despite these challenges and risks, climate adaptation planning also presents opportunities to build collaborative partnerships and steward ecosystems.[223] The communities, economic sectors, and natural resource practitioners in this region are advancing adaptation solutions (Box 25.3).

Box 25.2. Prairie Pothole Wetlands and Climate Adaptation Challenges

In the eastern Prairie Pothole Region of Minnesota, North Dakota, South Dakota, and Iowa, an increase in rainfall in the spring season has exacerbated problems with excess shallow groundwater in farm fields. Farmers have responded by draining this water with perforated plastic pipes (known as tiles; Figure 25.11)[224,225] buried at the rooting depth of mature corn plants, a practice that improves crop yield.[226] Tiling has increased rapidly in eastern North and South Dakota, particularly in the Red River valley.[227,228,229,230] To date, approximately half of the wetlands in the Northern Great Plains have been drained, disrupting their ecosystem services, such as flood protection, carbon sequestration, and forage and water for livestock.[231,232] Drainage transforms the hydrology of downslope ecosystems, contributing to the widening and sedimentation of rivers,[224,233,234,235] and promotes toxic algal blooms in aquatic systems through transport of nutrients (especially phosphorus and nitrate).[236,237] Additionally, improper placement of tiles may drain water from nearby wetlands.[226] Adaptation actions to regain wetland benefits and respond to climate change include restoring grassland and drained wetlands, redoubling the protection of wetlands with easements, revising vegetation management of wetland watersheds, and discouraging tile drainage in farm fields with wetlands present.[238,239,240,241]

Pattern Field Tiling

Draining agricultural fields through tiling improves crop yields but can harm ecosystems.

Figure 25.11. Pattern field tiling in the Prairie Pothole Region is designed to drain low, wet ground to provide soil space for roots of crops, which can increase yields. Tiling can inadvertently drain wetlands if placed too close to or below the elevation of the wetland bottom. Plastic pipe is buried at each black line visible in the photograph. Photo credit: USFWS.

Box 25.3. Climate Adaptation Successes

Climate adaptation happening in the Northern Great Plains region includes farmers in Nebraska testing new methods to improve soil structure and hydrologic function, Indigenous communities returning buffalo to their lands, ranchers returning less productive farmland to grassland for forage production, and local communities responding to flooding and working to improve flood readiness.

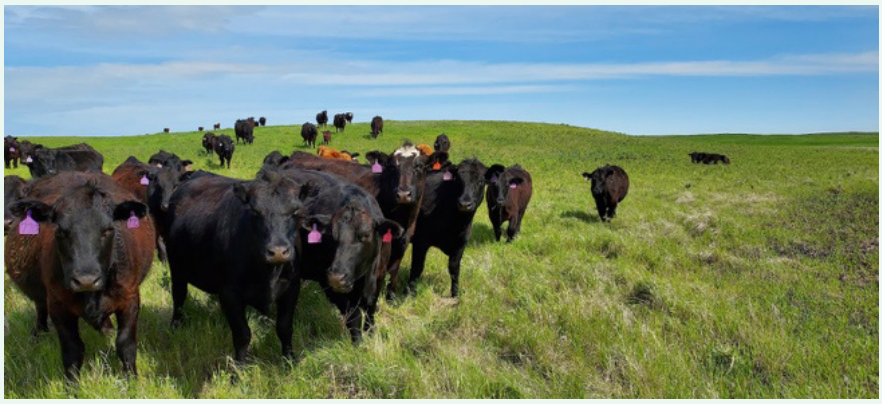
Adaptation Through Soil Health

Restoring soil structure and hydrologic function is a critical adaptation strategy in the Northern Great Plains region. In Nebraska, the Natural Resources Conservation Service has used federal conservation program dollars to support farmers testing soil health management practices, such as incorporating cover crops into annual crop rotations. Partnerships that leverage on-farm trials with outreach and research contribute to growing both the knowledge base and the execution of crop and livestock management practices that support improved soil function. Benefits include water-related outcomes such as increased infiltration and reduced runoff. Photo credit: USDA

Bringing Back the Buffalo

Bringing back the buffalo has been a regional resilience-building strategy for ranchers, Tribal Nations, and others who understand the role it plays in the ecosystem. The buffalo has deep cultural and spiritual significance for Tribal Nations in the region and beyond. The Tanka Fund has been pivotal in this regional effort by connecting ranchers to technical support and resources to increase herd sizes. Similarly, the InterTribal Buffalo Council helps Tribal Nations develop and maintain their own herds. These two entities connect resources to people and Tribal Nations looking to restore the buffalo as the keystone species of grassland ecosystems. Photo credit: NPS

Restoring Native Perennial Land Cover



As climate changes, it may be beneficial to return less productive cropland to native perennial cover that can provide multiple ecosystem services, including climate mitigation through carbon storage, pollinator benefits, and forage production for livestock. Audubon Great Plains, in partnership with government organizations and other nonprofits, is leading a new Conservation Forage Program in North Dakota to help producers achieve this shift in land use to benefit both producer operations and natural resources. Programs such as these that provide technical and financial assistance to producers while also helping to establish the necessary infrastructure for grazing (e.g., fencing, water access) and allow livestock use after vegetation establishment will allow farmers and ranchers flexibility in their operations. Photo credit: ©Reese Lausen

Responding to Increases in River Flooding

Flooding along major rivers is an increasing challenge for rural and Indigenous communities in this region. In March 2019, a 64-unit Tribal housing community with more than 300 Yankton Sioux members on the edge of the Lake Andes National Wildlife Refuge was inundated with floodwaters and cut off from the town of Lake Andes. Subsequent heavy rain events flooded basements and made the road inaccessible until the water over the highway froze in December. On August 12, 2019, the Tribe released a statement: "Our community is literally drowning."[242] The White Swan Recovery Group was created to provide resources for impacted community members and advocate for long-term solutions. The group received training to provide local lead and mold remediation and housing repairs. They continue to explore long-term solutions as the area is subject to frequent flooding; these efforts include advocacy to elevate the highway to protect housing, as well as conversations regarding relocating the community. Photo credit: Marcie Hebert, USFWS

Adaptations in Agriculture

The agricultural community in the Northern Great Plains region is developing innovative climate adaptation solutions to support livelihoods in the region (e.g., Johnson and Knight 2022[243]), many of which also support mitigation by sequestering carbon (Ch. 11). Stakeholders recognize that soil improvements increase flood and drought resilience.[244] Growing evidence from working farms and ranches in the region demonstrates how diversification strategies—such as reduced soil disturbance, increased crop residue, plant cover, and livestock and crop diversity (sometimes referred to as soil health or regenerative practices)—improve soil properties and processes, including water-holding capacity and infiltration, and provide many potential public and private co-benefits, including carbon sequestration.[245,246,247] These properties and processes produce enhanced carbon and nitrogen cycling and soil structure,[240] increased soil microbial communities, and lower pest communities while reducing nutrient inputs and leading to greater yields and profitability.[248,249,250,251,252] There is strong demand for, and proven efficacy around, producer knowledge networks to support transitioning to soil health practices.[253,254] Additionally, reintegrating row crop and livestock production systems could diversify income, increase operation resilience,[246] and restore ecosystem services, including sequestering more carbon in soil; retaining nutrients, especially nitrate; and supporting biodiversity.[108,217,255]

In arid parts of the region, adaptive solutions for irrigated agriculture will be critical. The majority of the region's states assign water rights based on prior appropriation, under which the first person to put water to beneficial use has the right to continue to use that water as long as the water is being used for the same beneficial use. This can slow the ability to acquire new water rights that may be necessary to address climate impacts.[256] The Upper Colorado River Commission (UCRC), as part of the 2019 Drought Contingency Plan,[25] is investigating the feasibility of implementing a demand-management program in the Upper Division states of the basin, including Wyoming. Under this program, water users would be compensated for voluntarily reducing consumptive uses. The conserved or imported water would be stored in federal reservoirs and released when needed to ensure compact compliance under a decision of the UCRC. On a smaller scale, many watershed and irrigation groups are investigating collaborative and shared water management strategies to manage scarce water resources to meet agricultural and ecological water needs, including the Brush Creek Irrigation District[257] and the Popo Agie Watershed Healthy Rivers Initiative[258] in Wyoming, as well as some Montana Tribes.[259] Instead of directly following the prior appropriation doctrines, different approaches to collaboratively manage water resources to meet agriculture and instream needs are being implemented. All of these efforts include and rely on improved hydrologic monitoring and data collection, as well as strong communication and buy-in from stakeholders.

Ranchers are also exploring adaptation strategies that increase livestock production by adjusting range management for a warmer climate.[260] One strategy to improve ranch resilience is through the use of drought planning.[261,262] Drought plans focus on identifying critical time periods for monitoring conditions and making decisions.[263] A planned drought response may involve adjusting the number of cattle, the season of grazing, the length of grazing time in pastures based on precipitation and vegetation growth,[264] or holistic planned grazing strategies that manage for ecosystem health by adapting to changing conditions.[265] A 2017 study found that nearly 60% of ranchers in the region had some type of drought contingency plan;[261] however, adoption of weather and climate data into management decisions has been slow.[136,266] The development of new grassland productivity forecasts may increase adoption by translating climate outlooks into usable information for ranchers.[267] Unique multistakeholder groups are also exploring collaborative adaptive management to understand and reconcile stakeholder experiences and ways of knowing about complex rangeland systems on public lands.[264]

Adaptation to Flooding

In response to significant flooding in 2011 and 2019 in the upper Missouri River basin (UMRB), improved monitoring was implemented to inform water management decisions. Frozen and saturated soil and significant snowpack in the UMRB were major contributors to flooding in those two years. Additionally, the drought west of the Missouri River in 2016–2017 highlighted the problem of sparse soil moisture data inhibiting accurate drought monitoring. As a result, the US Army Corps of Engineers, in collaboration with the state climate offices, is establishing a soil moisture and snowpack monitoring network.[268,269] A total of 529 stations are scheduled for installation between 2021 and 2027 on a 25-square-mile grid at elevations below 5,500 feet. The data from these stations, which include multiple soil moisture and temperature depths, as well as snow depths, will be directly available to NOAA to track and forecast flooding, drought, and other climatic and weather events.

With increased spring precipitation across much of the region, rural and Indigenous communities are adapting to more frequent flooding. Adaptation responses range from individual-scale approaches, such as elevating homes, to policy changes, including changing building codes and zoning regulations. Nebraska's unique river-basin Natural Resources District structure has enabled watershed-scale approaches that bring together multiple jurisdictions and stakeholders to decrease flood risk.[270] More drastic responses considered by some communities include relocating altogether. One increasingly successful adaptation strategy for responding to flood and natural disasters is the grassroots formation of local groups and coalitions to assist communities with disaster recovery and long-term adaptation (e.g., Sioux Empire Community Organizations Active in Disaster in South Dakota, Midwest Housing Resource Network in Nebraska). These groups are a mechanism for local communities to come together in mutual aid to plan for and support each other in response to flooding.

Adaptations in Indigenous Communities

Indigenous Peoples have called the Northern Great Plains region home for centuries, and today several regional Tribal Nations are leading the way in climate adaptation and implementation.[271,272,273] Several other Tribal Nations are leading the effort in water resilience and proactively addressing drought.[274,275,276,277] Indigenous approaches to adaptation combine traditional and contemporary management practices often grounded in spirituality and cultural traditions.[278] The key issues for Tribal climate adaptation in the region are capacity, sustainability, and sovereignty.[197]

The Rosebud Sioux Tribe has several initiatives in progress to build resilience to climate change.[279,280] The Sicangu Climate Crisis Working Group developed a Tribal climate adaptation plan that covers 20 Tribal communities across more than a million acres of Tribal land. The plan incorporates Lakota philosophy and Traditional Knowledge, including historical migrations, astronomy, origin stories, and the Tribes' special relationship with the buffalo. The plan prioritizes data sovereignty, interdepartmental collaboration, and directly supporting Tribal households to prepare for the impacts of climate change.[273] Additionally, the Rosebud Sioux Tribal Water Department has developed a drought adaptation plan and extensive real-time monitoring that enables the management of stream flow and groundwater sources, including the Ogallala Aquifer.[276] One of the major challenges has been the enforcement of the Rosebud water code to address neighboring farmers pumping Tribal-managed groundwater. However, with the removal of the moratorium on Tribal water codes, the Rosebud Sioux Tribe may now have the ability to manage its water as a sovereign nation.[281]

In 2018, the Blackfeet Nation completed a climate adaptation plan, which includes all of the natural resource departments across the Tribal government.[271] This inclusive approach takes more time and coordination but also creates collaborative opportunities by breaking down silos, minimizing redundancy, and maximizing scarce resources. For many Tribal Nations, sustainability is a key issue. This was especially true during

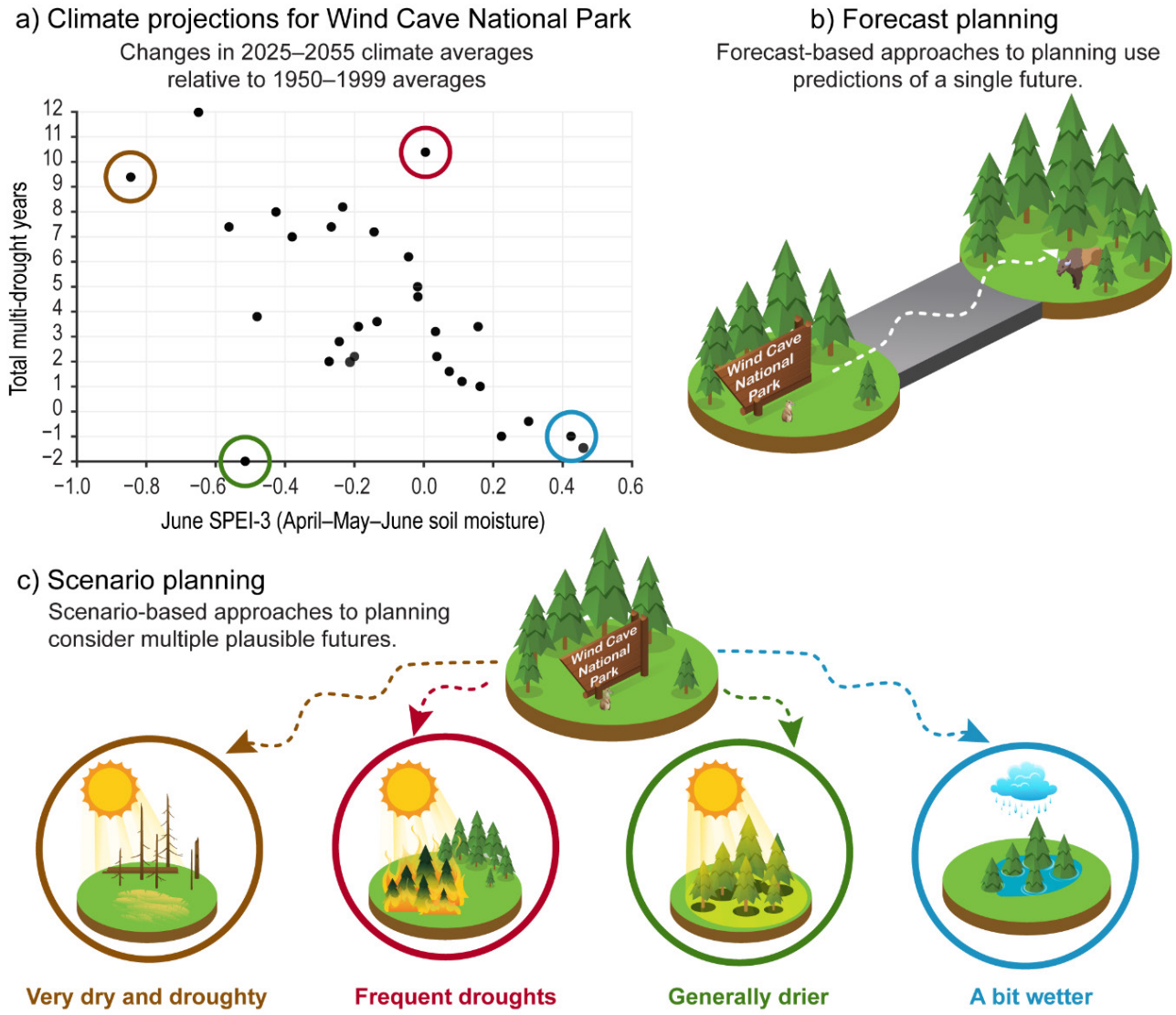
the COVID-19 pandemic and continues to be the reality in rural agricultural regions with smaller tax bases and higher turnover rates in staffing. Implementation includes the Ksik Stakii Project, which aims to protect beaver, restore rivers, and increase natural water storage to reduce vulnerability to drought and flooding.[271,282] A notable capacity-building strategy at Blackfeet is for Tribal resource departments to partner directly with Blackfeet Community College students on research projects. This type of a partnership is particularly important in the Northern Great Plains region, which has the highest concentration of Tribal colleges in the country.

Public Land Adaptation

The National Park Service (NPS) and partners have adapted scenario-based planning to help natural and cultural resource managers and others work with uncertainty and address the ways change might plausibly occur (Ch. 8).[283,284] Adaptation action on public lands in this region is challenged not only by the region's inherent climatic variability but also by the uncertainty in how resources, lifeways, or livelihoods might be affected by climate change and which adaptation responses might be effective (Figure 25.12).

Adaptation of scenario-based planning for public resource stewardship has focused on NPS units within the region—including Knife River Indian Villages National Historic Site, Badlands National Park, Wind Cave National Park, and Devils Tower National Monument.[283,285,286,287,288,289,290,291] This work has increased scenario plausibility and relevance and improved facilitation and efficiency of climate adaptation decision-making.[283] It has also clarified the importance of distinguishing climate futures (i.e., climate scenarios) from climate-resource scenarios (i.e., scenarios of both changes in climate and associated changes in resource condition).[289,292] Importantly, this work has created a model to support climate adaptation for natural resource decision-making in the face of climate uncertainty.

Adaptation Planning



Scenario-based planning accounts for uncertainty by considering a range of ways in which change might occur.

Figure 25.12. Forecast-based planning uses predictions of a single future (**b**), whereas scenario-based planning works with a set of plausible futures that capture a broad range of potential future conditions, providing a framework to support decisions under conditions that are uncertain and uncontrollable. Scenario-based planning at Wind Cave National Park identified four potential outcomes (**a**, **c**) for grassland and pine forest vegetation, surface water availability, and American bison (*Bison bison*) and prairie dog colonies under different climate futures—very dry and droughty (brown), frequent droughts (red), generally drier (green), and a bit wetter (blue)—all of which have different management implications for the natural and cultural resources in the park. Each dot in the graph represents a climate projection, and the set of four circled projections collectively encompasses most of the range of ways in which drought and springtime moisture levels could change by midcentury. SPEI—the Standardized Precipitation–Evaporation Index—is a multi-scalar drought index, based on precipitation and potential evapotranspiration, that is used to identify wet and dry periods in a given location.[293] A zero value indicates average moisture balance, positive values signify above-average wetness, and negative values represent drier-than-average conditions. SPEI-3 is a three-monthly SPEI calculation, and this figure shows values for April–June. Adapted from Schuurman et al. 2022[294] and Runyon et al. 2021.[289]

Rural Community Adaptation

Rural communities have two key needs to foster climate adaptation (KM 11.3). The first is economic diversification to create more resilient economies (e.g., broadband connectivity, restoration activities that create jobs and restore ecological function, and conservation that improves access and opportunity in recreation-based economies). The second is the need for a new social contract around resource extraction, especially for communities that will remain rural, isolated, and resource-dependent.[295] Major investments in community services, infrastructure, and economic development led by rural communities require long-term and sustainable funding to build capacity and resilience (Box 25.1).[194,200] Barriers to building adaptive capacity include a lack of coordinated federal assistance programs.[296] The region also has the potential for population growth in communities currently facing out-migration driven by favorable changes in climate coupled with a robust recreation economy, particularly in the intermountain West.[297,298]

Traceable Accounts

Process Description

The chapter lead authors were identified in the summer of 2021. This team compiled a list of nominated and Fourth National Climate Assessment (NCA4) authors as a pool of possible contributors. Additions to this list came from professional networks, research into priority departments at key regional institutions, and searches on several databases of experts from historically marginalized populations. The lead authors defined potential themes for the region based on team expertise and a review of literature published since the release of NCA4 and then narrowed the list of potential authors based on their ability to address these themes and a desire for diversity.

Candidates were selected based on a mix of expertise, regional distribution, career stage, age, gender, sector, discipline, and race and ethnicity. After preliminary research on potential contributors, introductory conversations were pursued to gauge interest and answer questions. The majority of the chapter team was recruited in September and October 2021, although as gaps were identified, other authors were added. Weekly all-author meetings started in September 2021 to craft the Zero Order Draft, with subgroup meetings held when needed to work out details. Once key topics were identified in December 2021, authors were divided into Key Message teams, based on interest and relevant knowledge. Virtual all-author meetings continued weekly, with Key Message teams meeting approximately every other week and more frequently before submitting the Zero Order Draft.

Key topics were identified through discussion, relevant literature, and knowledge of the region. Authors held two virtual engagement meetings, one during the day and one in the evening, to provide options for participants. Engagement events were promoted by the US Global Change Research Program through author networks, on social media, and with personal invitations to individuals whose voices the author team wanted to be represented. Feedback from engagement aligned well with the draft structure, but some of the emphases were adjusted based on stakeholder feedback. The author team incorporated inputs received in a public call for the technical material and relevant scientific publications and added several key technical contributors to bring other types of knowledge (e.g., Indigenous and experiential) that would provide a more complete assessment. Key Message teams discussed and came to consensus about Key Messages proposed in the First Order Draft and revised and came to consensus on Key Messages for the Second and Third Order Drafts. Key Messages were further iterated in the Fourth and Fifth Order Drafts to respond to comments from the public, National Academies, and agency technical review.

Key Message 25.1

Climate Change Is Compounding the Impacts of Extreme Events

Description of Evidence Base

The role of climate variability in the region has been well established.[39,42,299] The added effect of climate change is still emerging. NOAA State Climate Summaries document long-term increases in temperature in the region and varying changes in precipitation across the region.[14,15,16,17,18] Recent USGS trend and attribution efforts reflect the trends in flooding presented here, and the majority of attributions for those changes are related to changes in precipitation, with some also related to changes in temperature.[43]

The upper Missouri River basin combines the varying effects of east–west and north–south gradients in precipitation and temperature, respectively, for the Northern Great Plains. However, the Key Message team

wants to acknowledge that the Northern Great Plains region also includes parts of the Columbia, Colorado, Souris, Red, and Minnesota River basins.

Multiple independent scientific assessments and analyses of climate change effects on drought occurrence in the region are reaching similar conclusions across multiple climate change scenarios.[22,26,45,48,51] The study showing increased wildfire activity in the Northern Great Plains is based on satellite data, which adds credibility, because the use of the same methodology to assess wildfire across the region eliminates discrepancies caused by differences in how local governments record wildfire occurrence.[57]

Major Uncertainties and Research Gaps

Given the high degree of natural climate variability in the region, predicting future hydroclimatic and ecological conditions at specific locations is a major challenge. Climate change predictions of increased drought occurrence vary spatially and temporally. Complex interactions among temperature, precipitation, evapotranspiration, and moisture storage also create uncertainty for future conditions and agricultural production in this region (KM 3.4). As many of the projections of soil moisture predict close to no net change and the region already has a low effective precipitation that has high interannual variability, projected changes in soil moisture vacillate between overall net positive and negative changes.[47,48,49] Better understanding of how climate change affects soil moisture will require a greater assessment of the variability in soil moisture among global climate models and the incorporation of other factors such as soil type and plant species–specific responses at the local scale.[117,118]

Lack of long-term observations for small-scale and rare hail events and shortcomings in high-resolution models create uncertainty for predicting future events in specific areas,[28,29] so the models rely on trends in favorable hail environments.[30,31,32,33,34,35,300] Projections of severe convection in current research have largely focused on a very high scenario (RCP8.5).

Although drought frequency and severity are expected to increase, changes in multiyear drought occurrence due to climate change are relatively unknown.[45,52,53] Research on wildfires in the region has not addressed how human presence has influenced wildfire activity in the grasslands but has covered it in the forests.[58]

Description of Confidence and Likelihood

The coauthors of this section discussed the initial levels of confidence and likelihood, weighing the literature, observational data, and collective subject-matter expertise. The authors assigned a *likely* estimate with *high confidence* for an increase in severe droughts because of the pervasive evidence that increasing summer temperatures will increase evaporative demand, while changes in precipitation patterns lean toward increasingly dry summers. The authors assigned a *medium* confidence and no likelihood estimate for increasing hail frequency and size because the literature is still emergent and precludes a likelihood estimate but does present evidence that suggest increasing hail frequency and size in the High Plains area under at least some climate change scenarios. The authors assigned a *very likely* estimate with *high confidence* for changes in flood potential because research and observations strongly support both an increase of snowmelt runoff and flood potential in the eastern half of this region and respective decreases in the west. NOAA State Climate Summaries cited predict increases in extreme precipitation, which are expected to increase flood risk, even in areas with declines in overall precipitation. The authors assigned a *likely* estimate with *high confidence* for increased wildfire risk because the increase in evaporative demand and precipitation variability that favors drought also favors increased numbers of wildfires. Research indicating shorter duration of snowpack coverage also favors longer wildfire seasons. The authors assigned a *very likely* estimate with *very high confidence* for increases in evapotranspiration because multiple sources and subject-matter experts agree that the increasing warm-season temperatures will increase evaporative demand. The authors assigned a *very likely* estimate with *high confidence* for greater precipitation variability

because of the depth of both observational and model-based studies and consensus among subject-matter experts for current and future trends toward increased variability.

Key Message 25.2

Human and Ecological Health Face Rising Threats from Climate-Related Hazards

Description of Evidence Base

Climate trends from NOAA State Climate Summaries,[14,15,16,17,18] individual state-level climate assessments, USGS studies,[43] and demographic data from the 2020 US Census Bureau provided information to help characterize the region in terms of ecological conditions[99,100,101] and human populations.[61] CDC databases were also used extensively for health-related statistics. Multiple recent peer-reviewed studies of the impacts of specific aspects of climate change on human health were reviewed and included in the assessment. With relatively few region-specific studies of the health impacts of climate change, analyses based on areas with more concentrated populations provided valuable insights that are applicable to the Northern Great Plains. Several studies related to mental health have addressed the impacts on ranchers and farmers, rural residents, and Indigenous populations and are included in this assessment.[73,75,76] Many studies predict water quality changes in response to climate change; fewer studies have identified such changes.[90] Land-use change was predicted to be a larger driver of changes in water quality than climate change, and, along with management practices, land-use change appears to be the major driver in many cases;[90,91] however, the interaction of land use, management practices, and climate extremes is an important area for future research and potential harm reduction.[93,94,95]

Major Uncertainties and Research Gaps

The complex interactions among climate-related indicators themselves, with even more variability contributed by the considerable east–west geographical expanse of the region, lead to notable uncertainties for future climate conditions and the interactions between those climate conditions and local populations. The overall low population and population density across the region make data collection relative to health-related impacts difficult, adding to even more uncertainty in projections for impacts on individuals or locales. Research gaps include limited studies relating to health impacts specific to the region. In addition to the demographic barriers noted above, many areas within the region have limited sensors for measuring local conditions related to air quality, temperature, water quality, and air and soil moisture. The paucity of sensors, most notable in nonurban areas of the region, for these conditions introduces uncertainty when focusing on specific locations. The need for location-specific data is particularly important when addressing adaptive measures, since some conditions, such as air quality and temperature, can vary dramatically within small geographical areas.

Climate impacts on the ecology of the Northern Great Plains are difficult to generalize because individual species are expected to respond very differently to changes in climate. While declines have been observed and are projected for some taxa,[104,106] there are knowledge gaps around what those impacts might be for many taxa, species, and culturally significant plants and animals. Climate impacts will interact with and are expected to compound many other anthropogenic stressors, such as invasive species and conversion of natural ecosystems to row crop agriculture, and it is unknown which taxa are most vulnerable to climate change and what the magnitude of these impacts could be.

While the authors understand water-quality and physical processes related to climate, many management activities designed to reduce nutrients are taking place on the landscape, along with changing agricul-

tural nutrient requirements. Therefore, it can be difficult to find the climate signal in trends related to surface water quality, apart from the signal related to other important factors, such as land use, agricultural practices, and wastewater treatment.[90,94] The problem of attribution is further confounded by the complex effects of reaction-transport lags between any climate or landscape-scale driver and detectable changes in nutrients in surface or groundwater.[90,91] Recent findings based on observational data[90,91] support past predictions that land-use changes would have comparable or greater effects on water quality than climate changes.

Climate change has long been hypothesized as a driver of harmful algal blooms. Warming water temperature, higher carbon dioxide levels, and increases in heavy precipitation can create preferential conditions for algae. Blue-green algae can thrive in warming, slow-moving water; high carbon dioxide levels can result in rapid algae growth; and heavy precipitation can result in more nutrient runoff.[96] Unfortunately, supporting these hypotheses with observations has been challenging because of gaps in monitoring, lack of long-term algae data, and changes in laboratory and remote-sensing methods.[97,98]

Description of Confidence and Likelihood

Likelihood and confidence statements for climate change impacts on the health of residents of the region (*virtually certain*, *high confidence*) and on the region's ecology (*very likely*, *medium confidence*) are based on literature, some of which is cited in Key Message 25.2, observational data, and collective subject-matter expertise. The *very likely* rating for the region's ecology in both likelihood statements was based on the information that impacts are already being observed, and the *medium confidence* rating for both confidence statements was assigned because data or projections of impacts exist for some taxa but not all. Impacts to some aspects of the region's ecology are unclear or unknown. The research gaps and uncertainties listed in the preceding section limit the ability to project impacts for specific locations but do not lessen the confidence regarding current impacts on the various aspects of human health in the region as a whole, assertions strongly supported by an increasing number of studies (Ch. 15).[301] Levels of confidence and likelihood have been discussed in an ongoing fashion among the coauthors of the section, who weighed the overall literature and personal expertise to reach consensus for the stated levels.

Key Message 25.3

Resource- and Land-Based Livelihoods Are at Risk

Description of Evidence Base

Multiple national government economic reports provide the background for population growth and the importance of the agricultural and energy sectors to livelihoods in the Northern Great Plains. The most recent comprehensive syntheses of crop and climate impacts,[3,114,119] the most recent publications focused on Indigenous communities,[126] and the most recent foundational publications on crop physiology impacts of climate change at a broader scale than the region[120] support the projected negative impacts that rising temperatures would have on crop and culturally significant plant yields and timing. The net effect of climate change on agricultural livelihoods is uncertain due to the unresolved interacting effects of temperature, soil moisture, and carbon dioxide levels, as well as the degree of climate adaptations that may occur.[120,122] Projected aboveground net primary productivity increases and effects of drought are well documented across multiple scientific papers,[129,130,131] with recent papers supporting older papers from the literature and reinforcing the expected outcomes. The current resilience of rangeland-based livelihoods[135,136] and their future challenges[137,138] are well documented and in agreement. Although extensive peer-reviewed literature does not exist for climate effects on tourism and recreation, a few peer-reviewed literature examples documented climate change impacts on water-based, hunting, winter, and sightseeing recre-

ational activities.[150,151,153] The scientific literature on projected changes in electricity use within the region in response to climate change is readily available and in agreement (Ch. 5),[157,158] but literature on energy resource and electricity demands on the region from outside the region is limited and lacks specificity.[155,159] Examples of increasing and shifting types of energy demands on the region are well documented in both peer-reviewed scientific literature as well as government reports,[163,165,169,170] but comprehensive literature reviews providing overviews of how all energy shifts are occurring in relation to one another and in response to climate change and climate change policy are lacking. Literature on the effects of current and projected energy demand and shifts among types of energy sources on the livelihoods within the region is less available, and information is gleaned from government reports.[8] The impact of climate extremes on energy infrastructure is general in nature (Ch. 5)[161] and does not cover climatic variability and extremes unique to the region for all the energy infrastructure types found in the region.[162] Peer-reviewed literature on climate change impacts to livelihoods in the region does not fully address recent extreme events, so agency reports (e.g., FEMA 2019[177]) and Tribal documents (e.g., Blackfeet Nation 2022[139]) are used to document examples of impacts. This is also the case with Tribal infrastructure, where critical information on infrastructure was pulled from Indian Health Service and Bureau of Indian Affairs reports. Impacts are also identified by a technical contributor (Cullen) who works directly with communities affected by disasters in the region.

Major Uncertainties and Research Gaps

As stated in the text of the Key Message, the net effect of climate change on specific crop yields is uncertain, and multiple interacting effects would benefit from further study to fully grasp how climate change will comprehensively impact the agricultural industry, especially as it develops cultivars and management practices that adapt to the changing environment.

The net impact on forage quantity and quality in the region remains to be further explored. Productivity responses of Northern Great Plains rangelands to climate change have a degree of uncertainty, as the response of the vegetation to climate change may vary between the two dominant plant functional groups (C_3 and C_4). Scaling up the climate change responses of individual species and functional groups and how they contribute to larger ecosystem processes and properties, such as evapotranspiration or productivity, is important for improving the forecasting of climate change impacts to grasslands and shrublands in the region; this is a research gap. There is also uncertainty about how the negative impact of drought, which is expected to increase under climate change, will impact the expected positive gains on forage quantity and quality due to rising temperatures and elevated carbon dioxide.

Comprehensive studies of how climate change will affect tourism and recreation in the region are missing from the literature. Climate change impacts on tourism livelihoods are often limited to case studies and would benefit from more directed scientific study. Although some climate change models predict changes in insect outbreaks, which can lead to large impacts on recreational areas, correlations between outbreaks and climate change (e.g., mountain pine beetle) were not widespread, indicating a research gap in understanding all the interactions contributing to the relationship of observed outbreaks and climate change (e.g., Weed et al. 2015[152]).

Further studies detailing how increased national energy demand impacts regional energy harvest would provide a deeper understanding of the economic connections that in turn greatly affect regional communities. Strategic planning for the development of new oil and gas resources while transitioning to other energy resources in the region could benefit the grassland resource as a whole. Carbon capture, utilization, and storage (CCUS) in the region may play a role in mitigating US emissions. However, little carbon is currently being sequestered, and documentation of the costs and benefits for the region, as well as its many barriers and uncertainty, is a major research gap. It would be helpful to gather more information

on these topics before CCUS technology is deployed at scale in the region. Specific research examining how energy infrastructure in our region would respond to climate extremes is another research gap.

The effects of extreme events on agricultural, energy, and recreation-based livelihoods are often investigated more by the general media than by scientific studies and are therefore insufficiently covered in the research literature. This is also apparent when trying to evaluate the impact of climate change and climate extreme events on socially vulnerable communities. Peer-reviewed literature focused on climate change effects on rural and Indigenous communities in the region is a research gap.

Description of Confidence and Likelihood

The coauthors of this section discussed the initial levels of confidence and likelihood, weighing the literature, observational data, and collective subject-matter expertise. The authors assigned a *likely* estimate with *medium confidence* for agriculture and recreation seeing some positive but primarily negative effects of changing temperature and precipitation regimes on livelihoods. The *medium confidence* level was assigned because regional-specific agricultural literature is limited and requires multiple sources to be pieced together to evaluate the likelihood and confidence of changes in agriculture, and because recreation and tourism literature was limited to case studies often focused on extreme climate events that could increase with climate change. The authors assigned a *likely* estimate with *high confidence* to the statement that energy-sector livelihoods would be affected by shifts away from fossil fuel sources driven by emissions-reductions policies; this is because the coal industry has declined undeniably due to market competition, air-quality regulations, non-regulatory decisions made by public and private power utilities, and state and federal climate rules and renewable energy investments. Demand for oil and gas remains stable. The authors assigned a *likely* estimate and *medium confidence* to the statement that climate change will test the adaptive resilience of the region's socially vulnerable residents. This statement is assigned that particular likelihood and confidence because of instances in which recent extreme events have set back rural, Indigenous, and low-income communities, although there is a lack of extensive documentation or literature addressing this risk.

Key Message 25.4

Climate Response Involves Navigating Complex Trade-Offs and Tensions

Description of Evidence Base

The evidence that climate change is creating new and exacerbating existing tensions and trade-offs relies heavily on peer-reviewed literature cited throughout the chapter. There is increasing evidence and examples of how climate change is impacting, and will continue to impact, human communities and natural resources in the Northern Great Plains in complex and interacting ways.[167,219] The region is expected to see higher temperatures, a longer growing season, and shifts in water availability (KM 25.1) that will have impacts on livelihoods, land use, and water quantity and quality (KM 25.3). Climate change may also impact regional demographics over time, driving population growth of urban and amenity communities[9] and the continuing depopulation of rural communities.[5]

The evidence in the peer-reviewed literature indicates that when these impacts are combined, adaptation and mitigation decisions will result in benefits to some individuals and communities and have negative impacts for others. For example, as climate change alters the productivity of existing farmland, some producers are choosing to adapt by planting biofuel energy crops, such as switchgrass (Figure 25.10).[214] The peer-reviewed evidence identifies many benefits for such an action, including sequestration of carbon from the atmosphere,[215,216] sales that exceed current income,[217] and enhanced soil health and resilience

to drought.[218] However, peer-reviewed evidence also indicates that some communities may experience negative impacts, such as the disruption of food production processes, reduced biodiversity, and water competition.[219] Evidence for how decision-makers are navigating these trade-offs is emergent and highly dependent on local context.

Evidence has been well established in the peer-reviewed literature that individual and community knowledge and culture determines how climate change is experienced and managed (KM 20.2). Within this region, the acceptance of human-caused climate change is lower than the national average.[188,189] In a recent nationwide assessment,[187] several states in the region (Wyoming, Colorado, and North Dakota) had curricula that supported the notion that climate change is real and human-caused and can be mitigated, despite reliance on fossil fuel. Lower-scoring states (Montana and Nebraska) failed to link human activities to climate change or stated that climate change is controversial and that educating students about climate change should be the responsibility of parents (South Dakota). As a result of low acceptance and varied educational efforts, discourse in the region focuses on the adaptation and resilience effects of climate action rather than the mitigation effects (KM 25.5). These factors provide evidence of the complicated and shifting landscape for decision-making.

Peer-reviewed demographic and economic literature describes how the regional economy is reliant on agriculture and resource-based sectors (KM 25.3), so adaptation conversations have focused on land-use shifts to alternative crops (Figure 25.10),[214] conversion to grasslands (Figure 25.9),[203,204] and changes in energy infrastructure.[165,205] Many factors complicate the ability of communities in the region to adapt to climate change, but recent peer-reviewed data and literature highlight the high degree of rurality (Figure 25.1) and low capacity to compete for and utilize federal funds (Box 25.1) as particularly inhibiting.

Major Uncertainties and Research Gaps

Major uncertainties surround the choices that decision-makers and communities will make regarding the management and allocation of resources within the region and the impacts of those choices. There are additional gaps in understanding. For example, increased renewable energy in the region will impact labor opportunities in the region, but little is known on the labor effects of increased renewable energy. Estimates on land area that is required by different energy resources (e.g., wind versus oil) to produce similar amounts of energy are variable. Planning for minimizing grassland fragmentation while developing renewable resources with larger footprints could benefit from more accurate estimates.

Description of Confidence and Likelihood

Likelihood and confidence statements are based on literature cited in the narrative text, observational data, and collective subject-matter expertise. Confidence for the statement that climate change is leading to decisions that are expected to benefit some and set back others (*very high confidence*) was assigned based on the strong evidence of positive and negative effects of land-use change between agriculture, grassland, and energy in response to changes in climate (e.g., possible negative effects of large-scale conversion to biofuels).[219] Confidence for the statement that decision-makers are navigating a complicated landscape of shifting demographics, policy and regulatory tensions, and barriers to action (*high confidence*) was assigned based on the evidence of policy and decision-making around trade-offs in energy investment and infrastructure development (e.g., state legislation compelling, easing, or resisting energy transition),[167] although it's unclear how widespread such action is. Likelihood was not assigned to these two statements, as the uncertainty associated with human decision- and policymaking is difficult to quantify and is context dependent. For the statement that changes in temperature and precipitation averages, extremes, and seasonality will alter the productivity of working lands, resulting in land-use shifts to alternative crops or conversion to grasslands (*likely*, *medium confidence*), confidence and likelihood were assigned based on evidence of benefits from pilot actions in the region (Figure 25.10), although the scalability of these actions

to large geographies is still an area of study. For the statement that shifts in energy demand, production, and policy will change land-use needs for energy infrastructure (*likely*, *medium confidence*), confidence and likelihood were assigned based on evidence from the literature regarding the transition away from fossil fuel energy systems and its impact on abandonment of infrastructure[165,205] and possible fragmentation of existing grasslands due to new infrastructure.[159]

Key Message 25.5

Communities Are Building the Capacity to Adapt and Transform

Description of Evidence Base

Recent peer-reviewed literature provided the evidence base for adaptation actions being taken around soil health practices in the Northern Great Plains.[245,247] This literature has expanded significantly in recent years; the cited literature describes not only scientific understanding of soil changes and its related adaptive benefits but also research on farmer knowledge networks specific to this region. The evidence base for drought planning also draws from recent peer-reviewed literature and is growing.[261,262] The evidence base for diversification of grass-based livelihoods draws on a more limited peer-reviewed literature base and is more case specific.[217,246] Recent reports and planning efforts provide the evidence base for the newly implemented flood monitoring system in the upper Missouri River basin.[268,269] Reports, planning documents, limited peer-reviewed literature, and conversations with Tribal members provided the evidence for adaptation actions and challenges in rural and Indigenous communities.[271,272,273] A rapidly growing body of peer-reviewed literature provided the evidence for recent advances in ecosystem-based adaptation and scenario planning in the region (Ch. 8).[283,284]

Major Uncertainties and Research Gaps

Given the already high degree of climatic variability in the region and uncertainty in predicting future conditions, climate adaptation planning is a challenge. Despite these challenges, the evidence base shows that many climate adaptation actions are being tried across the region. In the process of implementing these adaptation actions, one of the major uncertainties is whether planned or implemented actions will ultimately be successful at helping communities or ecosystems adapt to climate change. There is a lack of research evaluating the success of climate adaptation actions, possibly due to insufficient time to judge success or a lack of robust monitoring and evaluation of outcomes. Furthermore, many climate adaptation actions are implemented in very context-dependent situations; therefore, it is uncertain how generalizable some adaptation actions or strategies may be.

Description of Confidence and Likelihood

It is difficult to quantify adaptation responses and to estimate their numerical variability. Therefore, the authors have not assigned any likelihood estimates to this Key Message. The authors assigned a *medium confidence* rating to the statement about adaptation actions in agricultural communities because there is evidence that a shift toward soil health and other adaptation practices is starting (e.g., Brown 2018;[245] Zilverberg et al. 2018[247]), but widespread adoption of these practices is not yet a reality. The authors assigned a *high confidence* rating to the third statement because there is good evidence that several Tribal Nations are leading efforts to incorporate Traditional Knowledge and governance into their adaptation plans (e.g., Blackfeet Nation 2018;[271] CSKT 2016;[272] Sicangu Climate Crisis Working Group 2022[273]). The statement about adaptation planning for natural resource managers is assigned a *medium confidence* rating because scenario planning is a well-developed tool and gaining traction in the National Park Service (e.g., Ch. 8),[283,284] but it is not yet being used widely outside of the National Park Service.

References

1. Briske, D.D., J.P. Ritten, A.R. Campbell, T. Klemm, and A.E.H. King, 2021: Future climate variability will challenge rangeland beef cattle production in the Great Plains. *Rangelands*, **43** (1), 29–36. https://doi.org/10.1016/j.rala.2020.11.001

2. Miller, A.B., P.L. Winter, J.J. Sánchez, D.L. Peterson, and J.W. Smith, 2022: Climate change and recreation in the western United States: Effects and opportunities for adaptation. *Journal of Forestry*, **120** (4), 453–472. https://doi.org/10.1093/jofore/fvab072

3. Wienhold, B.J., M.F. Vigil, J.R. Hendrickson, and J.D. Derner, 2018: Vulnerability of crops and croplands in the US Northern Plains to predicted climate change. *Climatic Change*, **146** (1), 219–230. https://doi.org/10.1007/s10584-017-1989-x

4. Husa, A. and C.E. Morse, 2020: Rurality as a key factor for place attachment in the Great Plains. *Geographical Review*, **112** (1), 27–45. https://doi.org/10.1080/00167428.2020.1786384

5. BEA, 2021: Regional Economic Accounts. U.S. Department of Commerce, Bureau of Economic Analysis. https://www.bea.gov/data/economic-accounts/regional

6. Wilson, R., 2020: Moving to economic opportunity: The migration response to the fracking boom. *Journal of Human Resources*, **57** (3), 918–955. https://doi.org/10.3368/jhr.57.3.0817-8989r2

7. ERS. 2015: County Typology Codes. U.S. Department of Agriculture, Economic Research Service. https://www.ers.usda.gov/data-products/county-typology-codes/

8. U.S. Census Bureau, 2020: American Community Survey (ACS). U.S. Department of Commerce, U.S. Census Bureau. https://www.census.gov/programs-surveys/acs

9. Dimke, C., M.C. Lee, and J. Bayham, 2021: COVID-19 and the renewed migration to the rural West. *Western Economics Forum*, **19** (1), 89–102. https://doi.org/10.22004/ag.econ.311309

10. Gilio-Whitaker, D., 2019: *As Long as Grass Grows: The Indigenous Fight for Environmental Justice, from Colonization to Standing Rock*. Beacon Press. http://www.beacon.org/as-long-as-grass-grows-p1445.aspx

11. Shamon, H., O.G. Cosby, C.L. Andersen, H. Augare, J. BearCub Stiffarm, C.E. Bresnan, B.L. Brock, E. Carlson, J.L. Deichmann, A. Epps, N. Guernsey, C. Hartway, D. Jørgensen, W. Kipp, D. Kinsey, K.J. Komatsu, K. Kunkel, R. Magnan, J.M. Martin, and T.S. Akre, 2022: The potential of bison restoration as an ecological approach to future tribal food sovereignty on the northern Great Plains. *Frontiers in Ecology and Evolution*, **10**, 1–15. https://doi.org/10.3389/fevo.2022.826282

12. Cain, C., 2021: Ch. 33. Developing climatic capacity in rural places. In: *Investing In Rural Prosperity*. Dumont, A. and D.P. Davis, Eds. Federal Reserve Bank of St. Louis, 475–486. https://www.stlouisfed.org/-/media/project/frbstl/stlouisfed/files/pdfs/community-development/investing-rural/chapters/chapter33.pdf

13. ERS, 2019: Frontier and Remote Area Codes. U.S. Department of Agriculture, Economic Research Service, accessed May 24, 2023. https://www.ers.usda.gov/data-products/frontier-and-remote-area-codes/

14. Frankson, R., K.E. Kunkel, S.M. Champion, D.R. Easterling, and K. Jencso, 2022: Montana State Climate Summary 2022. NOAA Technical Report NESDIS 150-MT. National Oceanic and Atmospheric Administration, National Environmental Satellite, Data, and Information Service, Silver Spring, MD. 5 pp. https://statesummaries.ncics.org/chapter/mt/

15. Frankson, R., K.E. Kunkel, S.M. Champion, D.R. Easterling, N.A. Umphlett, and C.J. Stiles, 2022: South Dakota State Climate Summary 2022. NOAA Technical Report NESDIS 150-SD. National Oceanic and Atmospheric Administration, National Environmental Satellite, Data, and Information Service, Silver Spring, MD. 5 pp. https://statesummaries.ncics.org/chapter/sd/

16. Frankson, R., K.E. Kunkel, L.E. Stevenes, D.R. Easterling, M. Shulski, A. Akyüz, N.A. Umphlett, and C.J. Stiles, 2022: North Dakota State Climate Summary 2022. NOAA Technical Report NESDIS 150-ND. National Oceanic and Atmospheric Administration, National Environmental Satellite, Data, and Information Service, Silver Spring, MD. 5 pp. https://statesummaries.ncics.org/chapter/nd/

17. Frankson, R., K.E. Kunkel, L.E. Stevens, D.R. Easterling, B.C. Stewart, N.A. Umphlett, and C.J. Stiles, 2022: Wyoming State Climate Summary 2022. NOAA Technical Report NESDIS 150-WY. National Oceanic and Atmospheric Administration, National Environmental Satellite, Data, and Information Service, Silver Spring, MD. 5 pp. https://statesummaries.ncics.org/chapter/wy/

18. Frankson, R., K.E. Kunkel, L.E. Stevens, M. Shulski, N.A. Umphlett, and C.J. Stiles, 2022: Nebraska State Climate Summary 2022. NOAA Technical Report NESDIS 150-NE. National Oceanic and Atmospheric Administration, National Environmental Satellite, Data, and Information Service, Silver Spring, MD. 5 pp. https://statesummaries.ncics.org/chapter/ne/

19. Siirila-Woodburn, E.R., A.M. Rhoades, B.J. Hatchett, L.S. Huning, J. Szinai, C. Tague, P.S. Nico, D.R. Feldman, A.D. Jones, W.D. Collins, and L. Kaatz, 2021: A low-to-no snow future and its impacts on water resources in the western United States. *Nature Reviews Earth & Environment*, **2** (11), 800–819. https://doi.org/10.1038/s43017-021-00219-y

20. Krajick, K., 2018: The 100th meridian, where the Great Plains begin, may be shifting: Warming climate may be moving western aridity eastward. Columbia University, Columbia Climate School: Climate, Earth, and Society, New York, NY, April 11, 2018. https://news.climate.columbia.edu/2018/04/11/the-100th-meridian-where-the-great-plains-used-to-begin-now-moving-east/

21. Seager, R., J. Feldman, N. Lis, M. Ting, A.P. Williams, J. Nakamura, H. Liu, and N. Henderson, 2018: Whither the 100th meridian? The once and future physical and human geography of America's arid–humid divide. Part II: The meridian moves east. *Earth Interactions*, **22** (5), 1–24. https://doi.org/10.1175/ei-d-17-0012.1

22. Swain, S. and K. Hayhoe, 2015: CMIP5 projected changes in spring and summer drought and wet conditions over North America. *Climate Dynamics*, **44** (9), 2737–2750. https://doi.org/10.1007/s00382-014-2255-9

23. Landers, J., 2021: P3 improves US Army Corps' Midwest flood-diversion project. *Civil Engineering Magazine*. https://www.asce.org/publications-and-news/civil-engineering-source/civil-engineering-magazine/article/2021/08/p3-improves-us-army-corps-midwest-flood-diversion-project

24. Jacobs, J., 2011: The sustainability of water resources in the Colorado River Basin. *Bridge*, **41** (4), 6–12. https://www.nae.edu/19582/bridge/55183/55194.aspx

25. UCRC, 2021: The Seventy-Second Annual Report of the Upper Colorado River Commission. Upper Colorado River Commission, Salt Lake City, UT, 161 pp. http://www.ucrcommission.com/wp-content/uploads/2021/06/UCRC-WY2020-Annual-Report-Final-June-10-2021.pdf

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

27. McCabe, G.J., D.M. Wolock, G.T. Pederson, C.A. Woodhouse, and S. McAfee, 2017: Evidence that recent warming is reducing upper Colorado River flows. *Earth Interactions*, **21** (10), 1–14. https://doi.org/10.1175/ei-d-17-0007.1

28. Raupach, T.H., O. Martius, J.T. Allen, M. Kunz, S. Lasher-Trapp, S. Mohr, K.L. Rasmussen, R.J. Trapp, and Q. Zhang, 2021: The effects of climate change on hailstorms. *Nature Reviews Earth & Environment*, **2** (3), 213–226. https://doi.org/10.1038/s43017-020-00133-9

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

30. Childs, S.J., R.S. Schumacher, and S.M. Strader, 2020: Projecting end-of-century human exposure from tornadoes and severe hailstorms in eastern Colorado: Meteorological and population perspectives. *Weather, Climate, and Society*, **12** (3), 575–595. https://doi.org/10.1175/wcas-d-19-0153.1

31. Lepore, C., R. Abernathey, N. Henderson, J.T. Allen, and M.K. Tippett, 2021: Future global convective environments in CMIP6 models. *Earth's Future*, **9** (12), e2021EF002277. https://doi.org/10.1029/2021ef002277

32. Rasmussen, K.L., A.F. Prein, R.M. Rasmussen, K. Ikeda, and C. Liu, 2020: Changes in the convective population and thermodynamic environments in convection-permitting regional climate simulations over the United States. *Climate Dynamics*, **55** (1), 383–408. https://doi.org/10.1007/s00382-017-4000-7

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

34. Brimelow, J.C., W.R. Burrows, and J.M. Hanesiak, 2017: The changing hail threat over North America in response to anthropogenic climate change. *Nature Climate Change*, **7**, 516–522. https://doi.org/10.1038/nclimate3321

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

36. Barth, N.A., K.R. Ryberg, A. Gregory, and A.G. Blum, 2022: Ch. A. Introduction to attribution of monotonic trends and change points in peak streamflow across the conterminous United States using a multiple working hypotheses framework, 1941–2015 and 1966–2015. In: *Attribution of Monotonic Trends and Change Points in Peak Streamflow Across the Conterminous United States Using a Multiple Working Hypotheses Framework, 1941–2015 and 1966–2015*. Ryberg, K.R., Ed. U.S. Geological Survey, Reston, VA, A1–A29. https://doi.org/10.3133/pp1869

37. Berghuijs, W.R., R.A. Woods, C.J. Hutton, and M. Sivapalan, 2016: Dominant flood generating mechanisms across the United States. *Geophysical Research Letters*, **43** (9), 4382–4390. https://doi.org/10.1002/2016gl068070

38. Livneh, B., M. Hoerling, A. Badger, and J. Eischeid, 2016: Climate Assessment Report: Causes for Hydrologic Extremes in the Upper Missouri River Basin. National Oceanic and Atmospheric Administration, Office of Oceanic and Atmospheric Research, Earth System Research Laboratory, Boulder, CO. https://www.esrl.noaa.gov/psd/csi/factsheets/pdf/mrb-climate-assessment-report-hydroextremes_2016.pdf

39. Ryberg, K.R., A.V. Vecchia, F.A. Akyüz, and W. Lin, 2016: Tree-ring-based estimates of long-term seasonal precipitation in the Souris River Region of Saskatchewan, North Dakota and Manitoba. *Canadian Water Resources Journal / Revue canadienne des ressources hydriques*, **41** (3), 412–428. https://doi.org/10.1080/07011784.2016.1164627

40. Spotted Eagle, F. and J. Veilleux, 2021: Land and water policy in the Missouri River Basin from Indigenous perspectives. *Water Resources Impact*, **23** (2), 7–12. https://online.flippingbook.com/view/446296713/8

41. NCEI, 2022: U.S. Billion-Dollar Weather and Climate Disasters: Disaster and Risk Mapping. National Oceanic and Atmospheric Administration, National Environmental Satellite, Data, and Information Service, National Centers for Environmental Information. https://www.ncdc.noaa.gov/billions/mapping

42. Hoell, A., M. Hoerling, X.-W. Quan, and R. Robinson, 2023: Recent high Missouri River Basin runoff was unlikely due to climate change. *Journal of Applied Meteorology and Climatology*, **62** (6), 657–675. https://doi.org/10.1175/jamc-d-22-0158.1

43. Sando, T.R., S.K. Sando, K.R. Ryberg, and K.J. Chase, 2022: Ch. C. Attribution of monotonic trends and change points in peak streamflow in the Upper Plains Region of the United States, 1941–2015 and 1966–2015. In: *Attribution of Monotonic Trends and Change Points in Peak Streamflow Across the Conterminous United States Using a Multiple Working Hypotheses Framework, 1941–2015 and 1966–2015*. Ryberg, K.R., Ed. U.S. Geological Survey, Reston, VA. https://doi.org/10.3133/pp1869

44. EPA, 2021: Climate Change and Social Vulnerability in the United States: A Focus on Six Impacts. EPA 430-R-21-003. U.S. Environmental Protection Agency. https://www.epa.gov/cira/social-vulnerability-report

45. Peters, M.P. and L.R. Iverson, 2019: Ch. 2. Projected drought for the conterminous United States in the 21st century. In: *Effects of Drought on Forests and Rangelands in the United States: Translating Science Into Management Responses*. Vose, J.M., D.L. Peterson, C.H. Luce, and T. Patel-Weynand, Eds. U.S. Department of Agriculture, Forest Service, Washington Office, Washington, DC, 19–39. https://www.fs.usda.gov/treesearch/pubs/59161

46. Robertson, D.M., H.A. Perlman, and T.N. Narisimhan, 2022: Ch. 4. Hydrological cycle and water budgets. In: *Encyclopedia of Inland Waters*, 2nd ed. Mehner, T. and K. Tockner, Eds. Elsevier, Oxford, UK, 19–27. https://doi.org/10.1016/b978-0-12-819166-8.00008-6

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

48. Hanberry, B., M.C. Reeves, A. Brischke, M. Hannemann, T. Hudson, R. Mayberry, D. Ojima, H.R. Prendeville, and I. Rangwala, 2019: Ch. 7. Managing effects of drought in the Great Plains. In: *Effects of Drought on Forests and Rangelands in the United States: Translating Science Into Management Responses*. Vose, J.M., D.L. Peterson, C.H. Luce, T. Patel-Weynand, E.J.M. Vose, D.L. Peterson, C.H. Luce, and T. Patel-Weynand, Eds. U.S. Department of Agriculture, Forest Service, Washington Office, Washington, DC, 141–164. https://www.fs.usda.gov/research/treesearch/59166

49. Wehner, M.F., J.R. Arnold, T. Knutson, K.E. Kunkel, and A.N. LeGrande, 2017: Ch. 8. Droughts, floods, and wildfires. In: *Climate Science Special Report: Fourth National Climate Assessment, Volume I*. Wuebbles, D.J., D.W. Fahey, K.A. Hibbard, D.J. Dokken, B.C. Stewart, and T.K. Maycock, Eds. U.S. Global Change Research Program, Washington, DC, USA, 231–256. https://doi.org/10.7930/j0cj8bnn

50. Hoell, A., J. Perlwitz, C. Dewes, K. Wolter, I. Rangwala, X.W. Quan, and J. Eisceid, 2019: Anthropogenic contributions to the intensity of the 2017 United States Northern Great Plains drought. *Bulletin of the American Meteorological Society*, **100** (1), 19–24. https://doi.org/10.1175/bams-d-18-0127.1

51. Martin, J.T., G.T. Pederson, C.A. Woodhouse, E.R. Cook, G.J. McCabe, K.J. Anchukaitis, E.K. Wise, P.J. Erger, L. Dolan, M. McGuire, S. Gangopadhyay, K.J. Chase, J.S. Littell, S.T. Gray, S. St. George, J.M. Friedman, D.J. Sauchyn, J.-M. St-Jacques, and J. King, 2020: Increased drought severity tracks warming in the United States' largest river basin. *Proceedings of the National Academy of Sciences of the United States of America*, **117** (21), 11328–11336. https://doi.org/10.1073/pnas.1916208117

52. Christian, J.I., J.B. Basara, J.A. Otkin, and E.D. Hunt, 2019: Regional characteristics of flash droughts across the United States. *Environmental Research Communications*, **1** (12), 125004. https://doi.org/10.1088/2515-7620/ab50ca

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

54. Liu, Y., S.L. Goodrick, and J.A. Stanturf, 2013: Future U.S. wildfire potential trends projected using a dynamically downscaled climate change scenario. *Forest Ecology and Management*, **294**, 120–135. https://doi.org/10.1016/j.foreco.2012.06.049

55. Clarke, H., T. Penman, M. Boer, G.J. Cary, J.B. Fontaine, O. Price, and R. Bradstock, 2020: The proximal drivers of large fires: A pyrogeographic study. *Frontiers in Earth Science*, **8**, 90. https://doi.org/10.3389/feart.2020.00090

56. Littell, J.S., D.L. Peterson, K.L. Riley, Y. Liu, and C.H. Luce, 2016: A review of the relationships between drought and forest fire in the United States. *Global Change Biology*, **22** (7), 2353–2369. https://doi.org/10.1111/gcb.13275

57. Donovan, V.M., C.L. Wonkka, and D. Twidwell, 2017: Surging wildfire activity in a grassland biome. *Geophysical Research Letters*, **44** (12), 5986–5993. https://doi.org/10.1002/2017gl072901

58. Westerling, A.L., 2016: Increasing western US forest wildfire activity: Sensitivity to changes in the timing of spring. *Philosophical Transactions of the Royal Society B: Biological Sciences*, **371** (1696), 20150178. https://doi.org/10.1098/rstb.2015.0178

59. Knapp, E.E., B.L. Estes, and C.N. Skinner, 2009: Ecological Effects of Prescribed Fire Season: A Literature Review and Synthesis for Managers. Gen. Tech. Rep. PSW-GTR-224. U.S. Department of Agriculture, Forest Service, Pacific Southwest Research Station, Albany, CA, 80 pp. https://doi.org/10.2737/psw-gtr-224

60. Knowles, N., 2015: Trends in snow cover and related quantities at weather stations in the conterminous United States. *Journal of Climate*, **28** (19), 7518–7528. https://doi.org/10.1175/jcli-d-15-0051.1

61. Adams, A., R. Byron, B. Maxwell, S. Higgins, M. Eggers, L. Byron, and C. Whitlock, 2021: Climate Change and Human Health in Montana: A Special Report of the Montana Climate Assessment. Montana State University, Institute on Ecosystems, Center for American Indian and Rural Health Equity, Bozeman, MT, 216 pp. https://doi.org/10.15788/c2h22021

62. Palinkas, L.A. and M. Wong, 2020: Global climate change and mental health. *Current Opinion in Psychology*, **32**, 12–16. https://doi.org/10.1016/j.copsyc.2019.06.023

63. Hedegaard, H., S.C. Curtin, and M. Warner, 2021: Suicide Mortality in the United States, 1999–2019. NCHS Data Brief, No 398. Centers for Disease Control and Prevention, National Center for Health Statistics, Hyattsville, MD. https://doi.org/10.15620/cdc:101761

64. Ivey-Stephenson, A.Z., A.E. Crosby, S.P. Jack, T. Haileyesus, and M. Kresnow-Sedacca, 2017: Suicide trends among and within urbanization levels by sex, race/ethnicity, age group, and mechanism of death — United States, 2001–2015. *MMWR Surveillance Summaries*, **66** (18), 1–16. https://doi.org/10.15585/mmwr.ss6618a1

65. Bjornestad, A., C. Cuthbertson, and J. Hendricks, 2021: An analysis of suicide risk factors among farmers in the Midwestern United States. *International Journal of Environmental Research and Public Health*, **18** (7), 3563. https://doi.org/10.3390/ijerph18073563

66. Nestadt, P.S., P. Triplett, D.R. Fowler, and R. Mojtabai, 2017: Urban–rural differences in suicide in the state of Maryland: The role of firearms. *American Journal of Public Health*, **107** (10), 1548–1553. https://doi.org/10.2105/ajph.2017.303865

67. Burke, M., F. González, P. Baylis, S. Heft-Neal, C. Baysan, S. Basu, and S. Hsiang, 2018: Higher temperatures increase suicide rates in the United States and Mexico. *Nature Climate Change*, **8** (8), 723–729. https://doi.org/10.1038/s41558-018-0222-x

68. Yazd, S.D., S.A. Wheeler, and A. Zuo, 2019: Key risk factors affecting farmers' mental health: A systematic review. *International Journal of Environmental Research and Public Health*, **16** (23), 4849. https://doi.org/10.3390/ijerph16234849

69. Howard, M., S. Ahmed, P. Lachapelle, and M.B. Schure, 2020: Farmer and rancher perceptions of climate change and their relationships with mental health. *Journal of Rural Mental Health*, **44** (2), 87–95. https://doi.org/10.1037/rmh0000131

70. Albrecht, G., G.-M. Sartore, L. Connor, N. Higginbotham, S. Freeman, B. Kelly, H. Stain, A. Tonna, and G. Pollard, 2007: Solastalgia: The distress caused by environmental change. *Australasian Psychiatry*, **15** (Sup1), S95–S98. https://doi.org/10.1080/10398560701701288

71. Galway, L.P., T. Beery, K. Jones-Casey, and K. Tasala, 2019: Mapping the solastalgia literature: A scoping review study. *International Journal of Environmental Research and Public Health*, **16** (15), 2662. https://doi.org/10.3390/ijerph16152662

72. The World Bank, 2023: Understanding Poverty: Indigenous Peoples. World Bank Group, accessed April 4, 2023. https://www.worldbank.org/en/topic/indigenouspeoples

73. Ellis, N.R. and G.A. Albrecht, 2017: Climate change threats to family farmers' sense of place and mental wellbeing: A case study from the Western Australian Wheatbelt. *Social Science & Medicine*, **175**, 161–168. https://doi.org/10.1016/j.socscimed.2017.01.009

74. Cajete, G.A., 2020: Indigenous science, climate change, and Indigenous community building: A framework of foundational perspectives for Indigenous community resilience and revitalization. *Sustainability*, **12** (22), 9569. https://doi.org/10.3390/su12229569

75. Doyle, J.T., M.H. Redsteer, and M.J. Eggers, 2013: Exploring effects of climate change on Northern Plains American Indian health. *Climatic Change*, **120** (3), 643–655. https://doi.org/10.1007/s10584-013-0799-z

76. Martin, C., J. Doyle, J. LaFrance, M.J. Lefthand, S.L. Young, E. Three Irons, and M.J. Eggers, 2020: Change rippling through our waters and culture. *Journal of Contemporary Water Research & Education*, **169** (1), 61–78. https://doi.org/10.1111/j.1936-704x.2020.03332.x

77. O'Dell, K., B. Ford, E.V. Fischer, and J.R. Pierce, 2019: Contribution of wildland-fire smoke to us $PM_{2.5}$ and its influence on recent trends. *Environmental Science Technology*, **53** (4), 1797–1804. https://doi.org/10.1021/acs.est.8b05430

78. NWS, 2021: Weather Related Fatality and Injury Statistics. National Oceanic and Atmospheric Administration, National Weather Service. https://www.weather.gov/hazstat/

79. Dahl, K. and R. Licker, 2021: Too Hot to Work: Assessing the Threats Climate Change Poses to Outdoor Workers. Union of Concerned Scientists, Cambridge, MA. https://doi.org/10.47923/2021.14236

80. Harrigan, R.J., H.A. Thomassen, W. Buermann, and T.B. Smith, 2014: A continental risk assessment of West Nile virus under climate change. *Global Change Biology*, **20** (8), 2417–2425. https://doi.org/10.1111/gcb.12534

81. Paull, S.H., D.E. Horton, M. Ashfaq, D. Rastogi, L.D. Kramer, N.S. Diffenbaugh, and A.M. Kilpatrick, 2017: Drought and immunity determine the intensity of West Nile virus epidemics and climate change impacts. *Proceedings of the Royal Society B: Biological Sciences*, **284** (1848). https://doi.org/10.1098/rspb.2016.2078

82. Smith, K.H., A.J. Tyre, J. Hamik, M.J. Hayes, Y. Zhou, and L. Dai, 2020: Using climate to explain and predict West Nile virus risk in Nebraska. *GeoHealth*, **4** (9), e2020GH000244. https://doi.org/10.1029/2020gh000244

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

84. Kuhn, K.G., K.M. Nygård, B. Guzman-Herrador, L.S. Sunde, R. Rimhanen-Finne, L. Trönnberg, M.R. Jepsen, R. Ruuhela, W.K. Wong, and S. Ethelberg, 2020: Campylobacter infections expected to increase due to climate change in Northern Europe. *Scientific Reports*, **10** (1), 13874. https://doi.org/10.1038/s41598-020-70593-y

85. Koks, E., 2018: Moving flood risk modelling forwards. *Nature Climate Change*, **8**, 561–562. https://doi.org/10.1038/s41558-018-0185-y

86. Räsänen, A., S. Juhola, A. Nygren, M. Käkönen, M. Kallio, A.M. Monge, and M. Kanninen, 2016: Climate change, multiple stressors and human vulnerability: A systematic review. *Regional Environmental Change*, **16**, 2291–2302. https://doi.org/10.1007/s10113-016-0974-7

87. Williams, A.P., B. Livneh, K.A. McKinnon, W.D. Hansen, J.S. Mankin, B.I. Cook, J.E. Smerdon, A.M. Varuolo-Clarke, N.R. Bjarke, C.S. Juang, and D.P. Lettenmaier, 2022: Growing impact of wildfire on western US water supply. *Proceedings of the National Academy of Sciences of the United States of America*, **119** (10), 2114069119. https://doi.org/10.1073/pnas.2114069119

88. Coughlan, M.R., A. Ellison, and A.H. Cavanaugh, 2019: Social Vulnerability and Wildfire in the Wildland Urban Interface: Literature Synthesis. University of Oregon, Northwest Fire Science Consortium, 24 pp. https://scholarsbank.uoregon.edu/xmlui/handle/1794/25359

89. Pohl, K., 2021: The Unequal Impacts of Wildfire. Headwaters Economics, Bozeman, MT. https://headwaterseconomics.org/natural-hazards/unequal-impacts-of-wildfire/

90. Ryberg, K.R. and J.G. Chanat, 2022: Climate extremes as drivers of surface-water-quality trends in the United States. *Science of The Total Environment*, **809**, 152165. https://doi.org/10.1016/j.scitotenv.2021.152165

91. Stets, E.G., L.A. Sprague, G.P. Oelsner, H.M. Johnson, J.C. Murphy, K. Ryberg, A.V. Vecchia, R.E. Zuellig, J.A. Falcone, and M.L. Riskin, 2020: Landscape drivers of dynamic change in water quality of U.S. rivers. *Environmental Science & Technology*, **54** (7), 4336–4343. https://doi.org/10.1021/acs.est.9b05344

92. Murphy, J.C., R.M. Hirsch, and L.A. Sprague, 2014: Antecedent flow conditions and nitrate concentrations in the Mississippi River Basin. *Hydrology and Earth System Sciences*, **10** (3), 967–979. https://doi.org/10.5194/hessd-10-11451-2013

93. Lu, C., J. Zhang, H. Tian, W.G. Crumpton, M.J. Helmers, W.-J. Cai, C.S. Hopkinson, and S.E. Lohrenz, 2020: Increased extreme precipitation challenges nitrogen load management to the Gulf of Mexico. *Communications Earth & Environment*, **1** (1), 21. https://doi.org/10.1038/s43247-020-00020-7

94. Michalak, A.M., 2016: Study role of climate change in extreme threats to water quality. *Nature*, **535** (7612), 349–350. https://doi.org/10.1038/535349a

95. Otten, T.G. and H.W. Paerl, 2015: Health effects of toxic cyanobacteria in U.S. drinking and recreational waters: Our current understanding and proposed direction. *Current Environmental Health Reports*, **2** (1), 75–84. https://doi.org/10.1007/s40572-014-0041-9

96. EPA, 2022: Nutrient Pollution: Climate Change and Harmful Algal Blooms. U.S. Environmental Protection Agency, accessed February 14, 2022. https://www.epa.gov/nutrientpollution/climate-change-and-harmful-algal-blooms

97. Laughrey, Z.R., V.G. Christensen, R.J. Dusek, S. Senegal, J.S. Lankton, T.A. Ziegler, L.C. Jones, D.K. Jones, B.M. Williams, S. Gordon, G.A. Clyde, E.B. Emery, and K.A. Loftin, 2022: A review of algal toxin exposures on reserved federal lands and among trust species in the United States. *Critical Reviews in Environmental Science and Technology*, **52** (23), 4284–4307. https://doi.org/10.1080/10643389.2021.2010511

98. Wheeling, K., 2019: Toxic algal blooms are worsening with climate change. *Eos*, **100**. https://doi.org/10.1029/2019eo136398

99. Lark, T.J., S.A. Spawn, M. Bougie, and H.K. Gibbs, 2020: Cropland expansion in the United States produces marginal yields at high costs to wildlife. *Nature Communications*, **11** (1), 4295. https://doi.org/10.1038/s41467-020-18045-z

100. Hendrickson, J.R., K.K. Sedivec, D. Toledo, and J. Printz, 2019: Challenges facing grasslands in the northern Great Plains and north central region. *Rangelands*, **41** (1), 23–29. https://doi.org/10.1016/j.rala.2018.11.002

101. Palit, R., G. Gramig, and E.S. DeKeyser, 2021: Kentucky bluegrass invasion in the northern Great Plains and prospective management approaches to mitigate its spread. *Plants*, **10** (4), 817. https://doi.org/10.3390/plants10040817

102. Niemuth, N.D., M.E. Estey, S.P. Fields, B. Wangler, A.A. Bishop, P.J. Moore, R.C. Grosse, and A.J. Ryba, 2017: Developing spatial models to guide conservation of grassland birds in the U.S. Northern Great Plains. *The Condor*, **119** (3), 506–525. https://doi.org/10.1650/condor-17-14.1

103. Pulliam, J.P., S. Somershoe, M. Sather, and L.B. McNew, 2020: Habitat targets for imperiled grassland birds in northern mixed-grass prairie. *Rangeland Ecology & Management*, **73** (4), 511–519. https://doi.org/10.1016/j.rama.2020.02.006

104. Bateman, B.L., C. Wilsey, L. Taylor, J. Wu, G.S. LeBaron, and G. Langham, 2020: North American birds require mitigation and adaptation to reduce vulnerability to climate change. *Conservation Science and Practice*, **2** (8), 242. https://doi.org/10.1111/csp2.242

105. Otto, C.R.V., H. Zheng, A.L. Gallant, R. Iovanna, B.L. Carlson, M.D. Smart, and S. Hyberg, 2018: Past role and future outlook of the Conservation Reserve Program for supporting honey bees in the Great Plains. *Proceedings of the National Academy of Sciences of the United States of America*, **115** (29), 7629–7634. https://doi.org/10.1073/pnas.1800057115

106. Durant, J.L. and C.R.V. Otto, 2019: Feeling the sting? Addressing land-use changes can mitigate bee declines. *Land Use Policy*, **87**, 104005. https://doi.org/10.1016/j.landusepol.2019.05.024

107. Otto, C.R.V., C.L. Roth, B.L. Carlson, and M.D. Smart, 2016: Land-use change reduces habitat suitability for supporting managed honey bee colonies in the Northern Great Plains. *Proceedings of the National Academy of Sciences of the United States of America*, **113** (37), 10430–10435. https://doi.org/10.1073/pnas.1603481113

108. Niemuth, N.D., B. Wangler, J.J. LeBrun, D. Dewald, S. Larson, T. Schwagler, C. Bradbury, R.D. Pritchert, and R. Iovanna, 2021: Conservation planning for pollinators in the U.S. Great Plains: Considerations of context, treatments, and scale. *Ecosphere*, **12** (7), 03556. https://doi.org/10.1002/ecs2.3556

109. Miller Hesed, C. and H. Yocum, 2023: Grassland Management Priorities for the North Central Region. USGS Open-File Report 2023–1037. U.S. Geological Survey, 53 pp. https://doi.org/10.3133/ofr20231037

110. Miller Hesed, C.D., H.M. Yocum, I. Rangwala, A.J. Symstad, J.M. Martin, K. Ellison, D.J.A. Wood, M. Ahlering, K.J. Chase, S. Crausbay, A.D. Davidson, J. Elliott, J. Giocomo, D.L. Hoover, T. Klemm, D. Lightfoot, O.P. McKenna, B.W. Miller, D. Mosher, R.C. Nagy, J.B. Nippert, J. Pittman, L. Porensky, J. Stephens, and A.V. Zale, 2023: Synthesis of Climate and Ecological Science to Support Grassland Management Priorities in the North Central Region. USGS Open-File Report 2023–1036. U.S. Geological Survey, 21 pp. https://doi.org/10.3133/ofr20231036

111. NRCS, 2018: National Resources Inventory Rangeland Resource Assessment. U.S. Department of Agriculture, Natural Resources Conservation Service, 624 pp. https://www.nrcs.usda.gov/sites/default/files/2022-10/RangelandReport2018_0.pdf

112. U.S. Census Bureau. 2021: County Business Patterns 2019. U.S. Department of Commerce, U.S. Census Bureau. https://www.census.gov/data/datasets/2019/econ/cbp/2019-cbp.html

113. Arora, G., H. Feng, C.J. Anderson, and D.A. Hennessy, 2020: Evidence of climate change impacts on crop comparative advantage and land use. *Agricultural Economics*, **51** (2), 221–236. https://doi.org/10.1111/agec.12551

114. Kukal, M.S. and S. Irmak, 2018: U.S. agro-climate in 20th century: Growing degree days, first and last frost, growing season length, and impacts on crop yields. *Scientific Reports*, **8** (1), 6977. https://doi.org/10.1038/s41598-018-25212-2

115. Rosenzweig, S.T. and M.E. Schipanski, 2019: Landscape-scale cropping changes in the High Plains: Economic and environmental implications. *Environmental Research Letters*, **14** (12), 124088. https://doi.org/10.1088/1748-9326/ab5e8b

116. Vick, E.S.K., P.C. Stoy, A.C.I. Tang, and T. Gerken, 2016: The surface-atmosphere exchange of carbon dioxide, water, and sensible heat across a dryland wheat-fallow rotation. *Agriculture, Ecosystems & Environment*, **232**, 129–140. https://doi.org/10.1016/j.agee.2016.07.018

117. Berg, A., J. Sheffield, and P.C.D. Milly, 2017: Divergent surface and total soil moisture projections under global warming. *Geophysical Research Letters*, **44** (1), 236–244. https://doi.org/10.1002/2016gl071921

118. Rigden, A.J., N.D. Mueller, N.M. Holbrook, N. Pillai, and P. Huybers, 2020: Combined influence of soil moisture and atmospheric evaporative demand is important for accurately predicting US maize yields. *Nature Food*, **1**, 127–133. https://doi.org/10.1038/s43016-020-0028-7

119. Zhu, P., T. Kim, Z. Jin, C. Lin, X. Wang, P. Ciais, N.D. Mueller, A. Aghakouchak, J. Huang, D. Mulla, and D. Makowski, 2022: The critical benefits of snowpack insulation and snowmelt for winter wheat productivity. *Nature Climate Change*, **12** (5), 485–490. https://doi.org/10.1038/s41558-022-01327-3

120. Ainsworth, E.A. and S.P. Long, 2021: 30 years of free-air carbon dioxide enrichment (FACE): What have we learned about future crop productivity and its potential for adaptation? *Global Change Biology*, **27** (1), 27–49. https://doi.org/10.1111/gcb.15375

121. Lombardozzi, D.L., G.B. Bonan, S. Levis, and D.M. Lawrence, 2018: Changes in wood biomass and crop yields in response to projected CO_2, O_3, nitrogen deposition, and climate. *Journal of Geophysical Research: Biogeosciences*, **123** (10), 3262–3282. https://doi.org/10.1029/2018jg004680

122. Sloat, L.L., S.J. Davis, J.S. Gerber, F.C. Moore, D.K. Ray, P.C. West, and N.D. Mueller, 2020: Climate adaptation by crop migration. *Nature Communications*, **11** (1), 1243. https://doi.org/10.1038/s41467-020-15076-4

123. Mertens, A., J. Van Meensel, L. Willem, L. Lauwers, and J. Buysse, 2018: Ensuring continuous feedstock supply in agricultural residue value chains: A complex interplay of five influencing factors. *Biomass and Bioenergy*, **109**, 209–220. https://doi.org/10.1016/j.biombioe.2017.12.024

124. Kant, J.M., G.E. Larson, S.R. Burckhard, B.W. Berdanier, and R.T. Meyers, 2015: Contemporary use of wild fruits by the Lakota in South Dakota and implications for cultural identity. *Great Plains Research*, **25** (1), 13–24. https://doi.org/10.1353/gpr.2015.0011

125. Yuzicapi, L., F. Gendron, and R. Bouch-van Dusen, 2013: Dakota and Lakota traditional food and tea: Teachings from elder Lorraine Yuzicapi. *Pimatisiwin: A Journal of Aboriginal and Indigenous Community Health*, **11** (1), 65–97. https://iportal.usask.ca/record/35678

126. Hoell, A., B.A. Parker, M. Downey, N. Umphlett, K. Jencso, F.A. Akyuz, D. Peck, T. Hadwen, B. Fuchs, D. Kluck, L. Edwards, J. Perlwitz, J. Eischeid, V. Deheza, R. Pulwarty, and K. Bevington, 2020: Lessons learned from the 2017 flash drought across the U.S. Northern Great Plains and Canadian Prairies. *Bulletin of the American Meteorological Society*, **101** (12), 2171–2185. https://doi.org/10.1175/bams-d-19-0272.1

127. McKenna, O.P., D.M. Mushet, D.O. Rosenberry, and J.W. LaBaugh, 2017: Evidence for a climate-induced ecohydrological state shift in wetland ecosystems of the southern Prairie Pothole Region. *Climatic Change*, **145**, 273–287. https://doi.org/10.1007/s10584-017-2097-7

128. Sohl, T., J. Dornbierer, and S. Wika, 2019: Linking landscapes and people—Projecting the future of the Great Plains. *Rangelands*, **41** (2), 79–87. https://doi.org/10.1016/j.rala.2018.12.001

129. Hufkens, K., T.F. Keenan, L.B. Flanagan, R.L. Scott, C.J. Bernacchi, E. Joo, N.A. Brunsell, J. Verfaillie, and A.D. Richardson, 2016: Productivity of North American grasslands is increased under future climate scenarios despite rising aridity. *Nature Climate Change*, **6**, 710–714. https://doi.org/10.1038/nclimate2942

130. Klemm, T., D.D. Briske, and M.C. Reeves, 2020: Potential natural vegetation and NPP responses to future climates in the U.S. Great Plains. *Ecosphere*, **11** (10), 03264. https://doi.org/10.1002/ecs2.3264

131. Reeves, M.C., A.L. Moreno, K.E. Bagne, and S.W. Running, 2014: Estimating climate change effects on net primary production of rangelands in the United States. *Climatic Change*, **126** (3), 429–442. https://doi.org/10.1007/s10584-014-1235-8

132. Augustine, D.J., D.M. Blumenthal, T.L. Springer, D.R. LeCain, S.A. Gunter, and J.D. Derner, 2018: Elevated CO_2 induces substantial and persistent declines in forage quality irrespective of warming in mixedgrass prairie. *Ecological Applications*, **28** (3), 721–735. https://doi.org/10.1002/eap.1680

133. Milchunas, D.G., A.R. Mosier, J.A. Morgan, D.R. LeCain, J.Y. King, and J.A. Nelson, 2005: Elevated CO_2 and defoliation effects on a shortgrass steppe: Forage quality versus quantity for ruminants. *Agriculture, Ecosystems and Environment*, **111** (1), 166–184. https://doi.org/10.1016/j.agee.2005.06.014

134. Moore, K.J., A.W. Lenssen, and S.L. Fales, 2020: Ch. 39. Factors affecting forage quality. In: *Forages: The Science of Grassland Agriculture*, 7th ed. Moore, K.J., M. Collins, C.J. Nelson, and D.D. Redfearn, Eds. Wiley, 701–717. https://doi.org/10.1002/9781119436669.ch39

135. Klemm, T. and D.D. Briske, 2021: Retrospective assessment of beef cow numbers to climate variability throughout the U.S. Great Plains. *Rangeland Ecology & Management*, **78**, 273–280. https://doi.org/10.1016/j.rama.2019.07.004

136. Haigh, T.R., J.A. Otkin, A. Mucia, M. Hayes, and M.E. Burbach, 2019: Drought early warning and the timing of range managers' drought response. *Advances in Meteorology*, **2019**, 1–14. https://doi.org/10.1155/2019/9461513

137. Derner, J., D. Briske, M. Reeves, T. Brown-Brandl, M. Meehan, D. Blumenthal, W. Travis, D. Augustine, H. Wilmer, D. Scasta, J. Hendrickson, J. Volesky, L. Edwards, and D. Peck, 2018: Vulnerability of grazing and confined livestock in the Northern Great Plains to projected mid- and late-twenty-first century climate. *Climatic Change*, **146** (1–2), 19–42. https://doi.org/10.1007/s10584-017-2029-6

138. Reeves, M.C., M.E. Manning, J.P. DiBenedetto, K.A. Palmquist, W.K. Lauenroth, J.B. Bradford, and D.R. Schlaepfer, 2018: Ch. 6. Effects of climate change on rangeland vegetation in the Northern Rockies. In: *Climate Change and Rocky Mountain Ecosystems*. Halofsky, J.E. and D.L. Peterson, Eds. Springer, Cham, Switzerland, 97–114. https://doi.org/10.1007/978-3-319-56928-4_6

139. Blackfeet Nation, 2022: Blackfeet Nation Agricultural Resource Management Plan. Blackfeet Nation, Browning, MT. https://bnsga.com/governing-documents

140. Olimb, S.K. and B. Robinson, 2019: Grass to grain: Probabilistic modeling of agricultural conversion in the North American Great Plains. *Ecological Indicators*, **102**, 237–245. https://doi.org/10.1016/j.ecolind.2019.02.042

141. Epstein, K., J.H. Haggerty, and H. Gosnell, 2021: With, not for, money: Ranch management trajectories of the super-rich in Greater Yellowstone. *Annals of the American Association of Geographers*, **112** (2), 432–448. https://doi.org/10.1080/24694452.2021.1930512

142. Fairbairn, M., 2020: *Fields of Gold: Financing the Global Land Rush*. Cornell University Press. http://www.jstor.org/stable/10.7591/j.ctvrnfpvf

143. Haggerty, J.H., M. Auger, and K. Epstein, 2018: Ranching sustainability in the Northern Great Plains: An appraisal of local perspectives. *Rangelands*, **40** (3), 83–91. https://doi.org/10.1016/j.rala.2018.03.005

144. Cutter, S.L., B.J. Boruff, and W.L. Shirley, 2003: Social vulnerability to environmental hazards. *Social Science Quarterly*, **84** (2), 242–261. https://doi.org/10.1111/1540-6237.8402002

145. Hjerpe, E., A. Hussain, and T. Holmes, 2020: Amenity migration and public lands: Rise of the protected areas. *Environmental Management*, **66** (1), 56–71. https://doi.org/10.1007/s00267-020-01293-6

146. Powell, L.A., R. Edwards, K.D.J. Powell, and K. Nieland, 2018: Geography of ecotourism potential in the Great Plains: Incentives for conservation. *Great Plains Research*, **28** (1), 15–24. https://doi.org/10.1353/gpr.2018.0001

147. Jedd, T.M., M.J. Hayes, C.M. Carrillo, T. Haigh, C.J. Chizinski, and J. Swigart, 2018: Measuring park visitation vulnerability to climate extremes in U.S. Rockies National Parks tourism. *Tourism Geographies*, **20** (2), 224–249. https://doi.org/10.1080/14616688.2017.1377283

148. Warziniack, T., M. Lawson, and S.K. Dante-Wood, 2018: Ch. 11. Effects of climate change on ecosystem services in the Northern Rockies Region. In: *Climate Change Vulnerability and Adaptation in the Northern Rocky Mountains Part 2*. Halofsky, J.E., D.L. Peterson, S.K.H. Dante-Wood, L. , J.J. Ho, and L.A. Joyce, Eds. U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station, Fort Collins, CO, 434–461. https://www.fs.usda.gov/treesearch/pubs/55996

149. Sage, J.L., 2016: Economic Contributions of the Yellowstone River to Park County, Montana. Institute for Tourism and Recreation Research Publications, 346. University of Montana. https://scholarworks.umt.edu/itrr_pubs/346/

150. Hand, M.S. and M. Lawson, 2018: Ch. 9. Effects of climate change on recreation in the Northern Rockies. In: *Climate Change and Rocky Mountain Ecosystems*. Halofsky, J.E. and D.L. Peterson, Eds. Springer, Cham, Switzerland, 169–188. https://doi.org/10.1007/978-3-319-56928-4_9

151. Sage, J.L. and N.P. Nickerson, 2017: The Montana Expression 2017: 2017's Costly Fire Season. Institute for Tourism and Recreation Research, 363. University of Montana. https://scholarworks.umt.edu/itrr_pubs/363

152. Weed, A.S., B.J. Bentz, M.P. Ayres, and T.P. Holmes, 2015: Geographically variable response of *Dendroctonus ponderosae* to winter warming in the western United States. *Landscape Ecology*, **30** (6), 1075–1093. https://doi.org/10.1007/s10980-015-0170-z

153. Wobus, C., E.E. Small, H. Hosterman, D. Mills, J. Stein, M. Rissing, R. Jones, M. Duckworth, R. Hall, M. Kolian, J. Creason, and J. Martinich, 2017: Projected climate change impacts on skiing and snowmobiling: A case study of the United States. *Global Environmental Change*, **45**, 1–14. https://doi.org/10.1016/j.gloenvcha.2017.04.006

154. Parthum, B. and P. Christensen, 2022: A market for snow: Modeling winter recreation patterns under current and future climate. *Journal of Environmental Economics and Management*, **113**, 102637. https://doi.org/10.1016/j.jeem.2022.102637

155. Roemer, K.F. and J.H. Haggerty, 2022: The energy transition as fiscal rupture: Public services and resilience pathways in a coal company town. *Energy Research & Social Science*, **91**, 102752. https://doi.org/10.1016/j.erss.2022.102752

156. Haggerty, J.H., M.N. Haggerty, K. Roemer, and J. Rose, 2018: Planning for the local impacts of coal facility closure: Emerging strategies in the U.S. West. *Resources Policy*, **57**, 69–80. https://doi.org/10.1016/j.resourpol.2018.01.010

157. Huang, J. and K.R. Gurney, 2017: Impact of climate change on U.S. building energy demand: Financial implications for consumers and energy suppliers. *Energy and Buildings*, **139**, 747–754. https://doi.org/10.1016/j.enbuild.2017.01.077

158. van Ruijven, B.J., E. De Cian, and I. Sue Wing, 2019: Amplification of future energy demand growth due to climate change. *Nature Communications*, **10** (1), 2762. https://doi.org/10.1038/s41467-019-10399-3

159. Ott, J.P., B.B. Hanberry, M. Khalil, M.W. Paschke, M. Post van der Burg, and A.J. Prenni, 2021: Energy development and production in the Great Plains: Implications and mitigation opportunities. *Rangeland Ecology & Management*, **78**, 257–272. https://doi.org/10.1016/j.rama.2020.05.003

160. Davis, L.W. and C. Hausman, 2022: Who Will Pay for Legacy Utility Costs? NBER Working Paper 28955. National Bureau of Economic Research. https://doi.org/10.3386/w28955

161. Bie, Z., Y. Lin, G. Li, and F. Li, 2017: Battling the extreme: A study on the power system resilience. *Proceedings of the IEEE*, **105** (7), 1253–1266. https://doi.org/10.1109/jproc.2017.2679040

162. Chinowsky, P., J. Helman, S. Gulati, J. Neumann, and J. Martinich, 2019: Impacts of climate change on operation of the US rail network. *Transport Policy*, **75**, 183–191. https://doi.org/10.1016/j.tranpol.2017.05.007

163. EIA, 2022: Annual Energy Outlook 2022. U.S. Energy Information Administration, Washington, DC. https://www.eia.gov/outlooks/archive/aeo22/

164. Grubert, E., 2020: Fossil electricity retirement deadlines for a just transition. *Science*, **370** (6521), 1171–1173. https://doi.org/10.1126/science.abe0375

165. Johnson, S. and K. Chau, 2019: Today in Energy: More U.S. coal-fired power plants are decommissioning as retirements continue. U.S. Energy Information Administration. https://www.eia.gov/todayinenergy/detail.php?id=40212

166. Schlinger, C., O. Conroy-Ben, C. Cooley, N. Cooley, M. Cruz, D. Dotson, J. Doyle, M.J. Eggers, P. Hardison, M. Hatch, C. Hogue, K. Jacobson Hedin, C. Jones, K. Lanphier, D. Marks-Marino, D. Mosley, F. Olsen Jr., and M. Peacock, 2021: Ch. 4.2. Water. In: *Status of Tribes and Climate Change Report*. Marks-Marino, D., Ed. Institute for Tribal Environmental Professionals, Flagstaff, AZ, 98–141. http://nau.edu/stacc2021

167. Righetti, T.K., T. Stoellinger, and R. Godby, 2021: Adapting to coal plant closures: A framework to understand state energy transition resistance. *Environmental Law*, **51** (4), 957–990. https://doi.org/10.13140/rg.2.2.32801.74083

168. Roemer, K.F. and J.H. Haggerty, 2021: Coal communities and the U.S. energy transition: A policy corridors assessment. *Energy Policy*, **151**, 112112. https://doi.org/10.1016/j.enpol.2020.112112

169. Jenkins, J.D., E.N. Mayfield, J. Farbes, R. Jones, N. Patankar, Q. Xu, and G. Schivley, 2022: Preliminary Report: The Climate and Energy Impacts of the Inflation Reduction Act of 2022. REPEAT Project. Princeton University, Princeton, NJ. https://repeatproject.org/docs/repeat_ira_prelminary_report_2022-08-04.pdf

170. EIA, 2022: Electricity Data. U.S. Energy Information Administration. https://www.eia.gov/electricity/data.php

171. Carwile, C., 2021: Race, power, and place: Lakota lessons from Pine Ridge Reservation. *Michigan Journal of Community Service Learning*, **27** (1), 129–153. https://eric.ed.gov/?id=ej1315005

172. Oceti Sakowin Power Authority, 2019: Testimony of Lyle Jack Chairman of the Board of Directors Oceti Sakowin Power Authority. Oceti Sakowin Power Authority, 21 pp. https://democrats-naturalresources.house.gov/download/2-testimony-attachment-ospa-lyle-jack-043019

173. Singletary, L., S. Clow, M. Connolly, D. Marks-Marino, A. Samoy, and S. Stout, 2021: Ch. 6. Economic development. In: *Status of Tribes and Climate Change Report*. Marks-Marino, D., Ed. Institute for Tribal Environmental Professionals, Flagstaff, AZ, 174–189. http://nau.edu/stacc2021

174. Wyoming Energy Authority, 2023: WIH2 submits application for DOE funding grant: Western Interstate Hydrogen Hub submits application for U.S. Department of Energy funding grant. Wyoming Energy Authority, Cheyenne, WY, April 10, 2023. https://wyoenergy.org/wih2-application-submitt

175. Vogt, R., C. Burkhart-Kriesel, B. Lubben, L.J. McElravy, T. Meyer, S. Schulz, and J. Weigle, 2020: Severe Weather in Nebraska: Impacts on Nonmetropolitan Nebraskans. Nebraska Rural Poll Research Report 20-1. University of Nebraska, Rural Futures Institute. https://digitalcommons.unl.edu/rfipubs/29/

176. Zambrano, L., C. Cooley, D. Crow Ghost, M. Cruz, P. Hardison, P. Hingst, C. Jones, J. Maldonado, D. Marks-Marino, and S. Tangen, 2021: Ch. 9. Emergency management. In: *Status of Tribes and Climate Change Report*. Marks-Marino, D., Ed. Institute for Tribal Environmental Professionals, Flagstaff, AZ, 222–240. http://nau.edu/stacc2021

177. FEMA, 2019: South Dakota Severe Storms, Tornadoes, and Flooding. DR-4469-SD. U.S. Department of Homeland Security, Federal Emergency Management Agency. https://www.fema.gov/disaster/4469

178. Martin, C., V.W. Simonds, S.L. Young, J. Doyle, M. Lefthand, and M.J. Eggers, 2021: Our relationship to water and experience of water insecurity among Apsáalooke (Crow Indian) people, Montana. *International Journal of Environmental Research and Public Health*, **18** (2), 582. https://doi.org/10.3390/ijerph18020582

179. IHS, 2020: Annual Report to the Congress of the United States on Sanitation Deficiency Levels for Indian Homes and Communities: Fiscal Year 2019. Indian Health Service, Office of Environmental Health and Engineering, Division of Sanitation Facilities Construction, Rockville, MD. https://www.ncbi.nlm.nih.gov/books/nbk571290/

180. Rumbach, A., E. Sullivan, and C. Makarewicz, 2020: Mobile home parks and disasters: Understanding risk to the third housing type in the United States. *Natural Hazards Review*, **21** (2), 05020001. https://doi.org/10.1061/(asce)nh.1527-6996.0000357

181. Paine, M., 2016: Floodplain Management Today: Who Lives in Nebraska Floodplains? Nebraska Department of Natural Resources, 8 pp. https://dnr.nebraska.gov/sites/dnr.nebraska.gov/files/doc/floodplain/newsletters/Floodplain_Management_Today_December_2016.pdf

182. Morris, A.C., 2016: The Challenge of State Reliance on Revenue from Fossil Fuel Production. Climate and Energy Economics Discussion Paper. The Brookings Institution, Washington, DC. https://www.brookings.edu/wp-content/uploads/2016/08/state-fiscal-implications-of-fossil-fuel-production-0809216-morris.pdf

183. NSF, 2022: EPSCoR Criteria for Eligibility. National Science Foundation. https://new.nsf.gov/funding/initiatives/epscor/epscor-criteria-eligibility

184. Van Boven, L. and D.K. Sherman, 2021: Elite influence on public attitudes about climate policy. *Current Opinion in Behavioral Sciences*, **42**, 83–88. https://doi.org/10.1016/j.cobeha.2021.03.023

185. Charnley, S., H. Gosnell, R. Davee, and J. Abrams, 2020: Ranchers and beavers: Understanding the human dimensions of beaver-related stream restoration on western rangelands. *Rangeland Ecology & Management*, **73** (5), 712–723. https://doi.org/10.1016/j.rama.2020.04.008

186. Pfaeffle, T., M.A. Moore, A.E. Cravens, J. McEvoy, and A. Bamzai-Dodson, 2022: Murky waters: Divergent ways scientists, practitioners, and landowners evaluate beaver mimicry. *Ecology and Society*, **27** (1). https://doi.org/10.5751/es-13006-270141

187. NCSE and TFN, 2020: Making the Grade? How State Public School Science Standards Address Climate Change. National Center for Science Education and Texas Freedom Network Education Fund. https://ncse.ngo/files/MakingTheGrade_Final_10.8.2020.pdf

188. Howe, P.D., M. Mildenberger, J.R. Marlon, and A. Leiserowitz, 2015: Geographic variation in opinions on climate change at state and local scales in the USA. *Nature Climate Change*, **5** (6), 596–603. https://doi.org/10.1038/nclimate2583

189. Prokopy, L.S., L.W. Morton, J.G. Arbuckle, A.S. Mase, and A.K. Wilke, 2015: Agricultural stakeholder views on climate change: Implications for conducting research and outreach. *Bulletin of the American Meteorological Society*, **96** (2), 181–190. https://doi.org/10.1175/bams-d-13-00172.1

190. Carley, S., T.P. Evans, M. Graff, and D.M. Konisky, 2018: A framework for evaluating geographic disparities in energy transition vulnerability. *Nature Energy*, **3** (8), 621–627. https://doi.org/10.1038/s41560-018-0142-z

191. Snyder, B.F., 2018: Vulnerability to decarbonization in hydrocarbon-intensive counties in the United States: A just transition to avoid post-industrial decay. *Energy Research & Social Science*, **42**, 34–43. https://doi.org/10.1016/j.erss.2018.03.004

192. Morris, A.C., N. Kaufman, and S. Doshi, 2021: Revenue at risk in coal-reliant counties. *Environmental and Energy Policy and the Economy*, **2**, 83–116. https://doi.org/10.1086/711307

193. Haggerty, J.H., M. Haggerty, and R. Rasker, 2014: Uneven local benefits of renewable energy in the U.S. West: Property tax policy effects. *Western Economics Forum*, **13** (1), 8–22. https://doi.org/10.22004/ag.econ.189734

194. Haggerty, M.N. and J.H. Haggerty, 2021: Ch. 31. Rethinking fiscal policy for inclusive rural development. In: *Investing in Rural Prosperity*. Dumont, A. and D.P. Davis, Eds. Federal Reserve Bank of St. Louis, 447–460. https://www.stlouisfed.org/-/media/project/frbstl/stlouisfed/files/pdfs/community-development/investing-rural/investinginruralprosperity-book.pdf

195. Wen, C., Y. Xu, Y. Kim, and M.E. Warner, 2020: Starving counties, squeezing cities: Tax and expenditure limits in the US. *Journal of Economic Policy Reform*, **23** (2), 101–119. https://doi.org/10.1080/17487870.2018.1509711

196. Haggerty, M., 2021: Innovating fiscal policy to power enduring rural prosperity. In: *Principal Ideas: How Can We Secure Enduring Capital for Equitable Rural Prosperity?* Aspen Institute Community Strategies Group, 4–7. https://www.aspeninstitute.org/publications/principal-ideas/

197. STACCWG, 2021: The Status of Tribes and Climate Change Report. Marks-Marino, D., Ed. Northern Arizona University, Institute for Tribal Environmental Professionals, Flagstaff, AZ. http://nau.edu/stacc2021

198. Zimmerman, M.G. and T.G. Reames, 2021: Where the wind blows: Exploring barriers and opportunities to renewable energy development on United States tribal lands. *Energy Research & Social Science*, **72**, 101874. https://doi.org/10.1016/j.erss.2020.101874

199. The White House, 2021: Fact sheet: The bipartisan infrastructure deal boosts clean energy jobs, strengthens resilience, and advances environmental justice. The White House, Washington, DC, November 8, 2021. https://www.whitehouse.gov/briefing-room/statements-releases/2021/11/08/fact-sheet-the-bipartisan-infrastructure-deal-boosts-clean-energy-jobs-strengthens-resilience-and-advances-environmental-justice/

200. Look, W., M. Haggerty, and D. Mazzone, 2022: Community Hubs to Support Energy Transition. Issue Brief 22-02. Resources for the Future and Environmental Defense Fund, Washington, DC, 11 pp. https://www.rff.org/publications/issue-briefs/community-hubs-to-support-energy-transition/

201. Smith, K. and P. Hernandez, 2022: Capacity-Limited States Still Struggle to Access FEMA BRIC Grants. Headwaters Economics, Bozeman, MT. https://headwaterseconomics.org/equity/capacity-limited-fema-bric-grants/

202. Hernandez, P., B. Daigle, T. Preston, K. Pohl, K. Smith, B. Powell, and S. Story, 2022: A Rural Capacity Map. Headwaters Economics, Bozeman, MT. https://headwaterseconomics.org/equity/rural-capacity-map/

203. Anderson, S., 2019: *One Size Fits None: A Farm Girl's Search for the Promise of Regenerative Agriculture*. University of Nebraska Press, Lincoln, NE, 312 pp. https://www.nebraskapress.unl.edu/nebraska/9781496205056/

204. Montgomery, D.R., 2017: *Growing a Revolution: Bringing Our Soil Back to Life*. WW Norton & Company, 320 pp. https://wwnorton.com/books/9780393356090

205. Jenkins, J.D., E.N. Mayfield, E.D. Larson, S.W. Pacala, and C. Greig, 2021: Mission net-zero America: The nation-building path to a prosperous, net-zero emissions economy. *Joule*, **5** (11), 2755–2761. https://doi.org/10.1016/j.joule.2021.10.016

206. Trainor, A.M., R.I. McDonald, and J. Fargione, 2016: Energy sprawl is the largest driver of land use change in United States. *PLoS ONE*, **11** (9), e0162269. https://doi.org/10.1371/journal.pone.0162269

207. van Zalk, J. and P. Behrens, 2018: The spatial extent of renewable and non-renewable power generation: A review and meta-analysis of power densities and their application in the U.S. *Energy Policy*, **123**, 83–91. https://doi.org/10.1016/j.enpol.2018.08.023

208. Lark, T.J., 2020: Protecting our prairies: Research and policy actions for conserving America's grasslands. *Land Use Policy*, **97**, 104727. https://doi.org/10.1016/j.landusepol.2020.104727

209. Scholtz, R. and D. Twidwell, 2022: The last continuous grasslands on Earth: Identification and conservation importance. *Conservation Science and Practice*, **4** (3), e626. https://doi.org/10.1111/csp2.626

210. Hise, C., B. Obermeyer, M. Ahlering, J. Wilkinson, and J. Fargione, 2022: Site wind right: Identifying low-impact wind development areas in the central United States. *Land*, **11** (4). https://doi.org/10.3390/land11040462

211. Ginger Paige (Author), November 10, 2020: Oral communication with Anne MacKinnon, University of Wyoming.

212. Lamborn, C.C. and J.W. Smith, 2019: Human perceptions of, and adaptations to, shifting runoff cycles: A case-study of the Yellowstone River (Montana, USA). *Fisheries Research*, **216**, 96–108. https://doi.org/10.1016/j.fishres.2019.04.005.

213. Penmetsa, V. and K.E. Holbert, 2019: Climate change effects on solar, wind and hydro power generation. In: *North American Power Symposium* (NAPS). Wichita, KS, 13–15 October 2019. IEEE. https://doi.org/10.1109/naps46351.2019.9000213

214. Dolan, K.A., P.C. Stoy, and B. Poulter, 2020: Land management and climate change determine second-generation bioenergy potential of the US Northern Great Plains. *GCB Bioenergy*, **12** (7), 491–509. https://doi.org/10.1111/gcbb.12686

215. Hamada, Y., C.R. Zumpf, J.F. Cacho, D. Lee, C.H. Lin, A. Boe, E. Heaton, R. Mitchell, and M.C. Negri, 2021: Remote sensing-based estimation of advanced perennial grass biomass yields for bioenergy. *Land*, **10** (11), 1221. https://doi.org/10.3390/land10111221

216. Peni, D., M.J. Stolarski, A. Bordiean, M. Krzyżaniak, and M. Dębowski, 2020: *Silphium perfoliatum*—A herbaceous crop with increased interest in recent years for multi-purpose use. *Agriculture*, **10** (12), 640. https://doi.org/10.3390/agriculture10120640

217. Zilverberg, C.J., W.C. Johnson, D. Archer, S. Kronberg, T. Schumacher, A. Boe, and C. Novotny, 2014: Profitable prairie restoration: The EcoSun Prairie Farm experiment. *Journal of Soil and Water Conservation*, **69** (1), 22–25. https://doi.org/10.2489/jswc.69.1.22a

218. Stewart, C.E., R.F. Follett, E.G. Pruessner, G.E. Varvel, K.P. Vogel, and R.B. Mitchell, 2015: Nitrogen and harvest effects on soil properties under rainfed switchgrass and no-till corn over 9 years: Implications for soil quality. *GCB Bioenergy*, **7** (2), 288–301. https://doi.org/10.1111/gcbb.12142

219. Stoy, P.C., S. Ahmed, M. Jarchow, B. Rashford, D. Swanson, S. Albeke, G. Bromley, E.N.J. Brookshire, M.D. Dixon, J. Haggerty, P. Miller, B. Peyton, A. Royem, L. Spangler, C. Straub, and B. Poulter, 2018: Opportunities and trade-offs among BECCS and the food, water, energy, biodiversity, and social systems nexus at regional scales. *BioScience*, **68** (2), 100–111. https://doi.org/10.1093/biosci/bix145

220. Oakes, L.E., M.S. Cross, and E.S. Zavaleta, 2021: Rapid assessment to facilitate climate-informed conservation and nature-based solutions. *Conservation Science and Practice*, **3** (8), 472. https://doi.org/10.1111/csp2.472

221. Schipper, E.L.F., 2020: Maladaptation: When adaptation to climate change goes very wrong. *One Earth*, **3** (4), 409–414. https://doi.org/10.1016/j.oneear.2020.09.014

222. Findlater, K., S. Hagerman, R. Kozak, and V. Gukova, 2022: Redefining climate change maladaptation using a values-based approach in forests. *People and Nature*, **4** (1), 231–242. https://doi.org/10.1002/pan3.10278

223. Ojima, D.S., R.T. Conant, W.J. Parton, J.M. Lackett, and T.L. Even, 2021: Recent climate changes across the Great Plains and implications for natural resource management practices. *Rangeland Ecology and Management*, **78**, 180–190. https://doi.org/10.1016/j.rama.2021.03.008

224. Blann, K.L., J.L. Anderson, G.R. Sands, and B. Vondracek, 2009: Effects of agricultural drainage on aquatic ecosystems: A review. *Critical Reviews in Environmental Science and Technology*, **39** (11), 909–1001. https://doi.org/10.1080/10643380801977966

225. Yang, Y., M. Anderson, F. Gao, C. Hain, W. Kustas, T. Meyers, W. Crow, R. Finocchiaro, J. Otkin, L. Sun, and Y. Yang, 2017: Impact of tile drainage on evapotranspiration in South Dakota, USA, based on high spatiotemporal resolution evapotranspiration time series from a multisatellite data fusion system. *IEEE Journal of Selected Topics in Applied Earth Observations and Remote Sensing*, **10** (6), 2550–2564. https://doi.org/10.1109/jstars.2017.2680411

226. Werner, B., J. Tracy, W.C. Johnson, R.A. Voldseth, G.R. Guntenspergen, and B. Millett, 2016: Modeling the effects of tile drain placement on the hydrologic function of farmed prairie wetlands. *JAWRA Journal of the American Water Resources Association*, **52** (6), 1482–1492. https://doi.org/10.1111/1752-1688.12471

227. Finocchiaro, R.G. 2014: Agricultural Subsurface Drainage Tile Locations by Permits in South Dakota. U.S. Geological Survey Data Release. https://doi.org/10.5066/f7ks6pnw

228. Finocchiaro, R.G. 2016: Agricultural Subsurface Drainage Tile Locations by Permits in North Dakota. U.S. Geological Survey Data Release. https://doi.org/10.5066/f7qf8qzw

229. Sando, T., 2015: Trends in North Dakota field water management. *The Oxbow - North Dakota State Water Commission*, April 2015. https://www.swc.nd.gov/info_edu/reports_and_publications/oxbow_articles/2015_april.pdf

230. Tangen, B. and M.T. Wiltermuth, 2018: Prairie Pothole Region wetlands and subsurface drainage systems: Key factors for determining drainage setback distances. *Journal of Fish and Wildlife Management*, **9** (1), 274–284. https://doi.org/10.3996/092017-jfwm-076

231. Dahl, T.E., 2014: Status and Trends of Prairie Wetlands in the United States 1997 to 2009. U.S. Department of the Interior, Fish and Wildlife Service, Ecological Services, Washington, DC, 67 pp. https://www.fws.gov/wetlands/documents/Status-and-Trends-of-Prairie-Wetlands-in-the-United-States-1997-to-2009.pdf

232. Mushet, D.M., M.B. Goldhaber, C.T. Mills, K.I. McLean, V.M. Aparicio, R.B. McCleskey, J.M. Holloway, and C.A. Stockwell, 2015: Chemical and Biotic Characteristics of Prairie Lakes and Large Wetlands in South-Central North Dakota—Effects of a Changing Climate. Scientific Investigations Report 2015–5126. U.S. Geological Survey, Reston, VA, 55 pp. https://doi.org/10.3133/sir20155126

233. McCauley, L.A., M.J. Anteau, M.P. van der Burg, and M.T. Wiltermuth, 2015: Land use and wetland drainage affect water levels and dynamics of remaining wetlands. *Ecosphere*, **6** (6), 92. https://doi.org/10.1890/es14-00494.1

234. McKenna, O.P., S.R. Kucia, D.M. Mushet, M.J. Anteau, and M.T. Wiltermuth, 2019: Synergistic interaction of climate and land-use drivers alter the function of North American, prairie-pothole wetlands. *Sustainability*, **11** (23), 6581. https://doi.org/10.3390/su11236581

235. Schottler, S.P., J. Ulrich, P. Belmont, R. Moore, J.W. Lauer, D.R. Engstrom, and J.E. Almendinger, 2014: Twentieth century agricultural drainage creates more erosive rivers. *Hydrological Processes*, **28** (4), 1951–1961. https://doi.org/10.1002/hyp.9738

236. King, K.W., M.R. Williams, M.L. Macrae, N.R. Fausey, J. Frankenberger, D.R. Smith, P.J.A. Kleinman, and L.C. Brown, 2015: Phosphorus transport in agricultural subsurface drainage: A review. *Journal of Environmental Quality*, **44** (2), 467–485. https://doi.org/10.2134/jeq2014.04.0163

237. Speir, S.L., J.L. Tank, M. Bieroza, U.H. Mahl, and T.V. Royer, 2021: Storm size and hydrologic modification influence nitrate mobilization and transport in agricultural watersheds. *Biogeochemistry*, **156** (3), 319–334. https://doi.org/10.1007/s10533-021-00847-y

238. Cheng, F.Y., K.J. Van Meter, D.K. Byrnes, and N.B. Basu, 2020: Maximizing US nitrate removal through wetland protection and restoration. *Nature*, **588** (7839), 625–630. https://doi.org/10.1038/s41586-020-03042-5

239. Doherty, K.E., D.W. Howerter, J.H. Devries, and J. Walker, 2018: Prairie Pothole Region of North America. In: *The Wetland Book: II: Distribution, Description, and Conservation*. Finlayson, C.M., G.R. Milton, R.C. Prentice, and N.C. Davidson, Eds. Springer, Dordrecht, Netherlands, 679–688. https://doi.org/10.1007/978-94-007-4001-3_15

240. Johnson, W.C. and G.R. Guntenspergen, 2022: Ch. 10. Maintaining wetland ecosystem services in a changing climate. In: *Soil Hydrology in a Changing Climate*. Blanco, H., S. Kumar, and S. Anderson, Eds. CSIRO Publishing, 32. https://www.publish.csiro.au/book/7978/

241. Mitchell, M.E., S.D. Shifflett, T. Newcomer-Johnson, A. Hodaj, W. Crumpton, J. Christensen, B. Dyson, T.J. Canfield, S. Richmond, M. Helmers, D. Lemke, M. Lechtenberg, C. Taylor, and K.J. Forshay, 2022: Ecosystem services in Iowa agricultural catchments: Hypotheses for scenarios with water quality wetlands and improved tile drainage. *Journal of Soil and Water Conservation*, **77** (4), 426–440. https://doi.org/10.2489/jswc.2022.00127

242. Keeler, J., 2019: Yankton Sioux: 'Our community is literally drowning'. *Indian Country Today*, October 1, 2019. https://www.indianz.com/news/2019/10/01/yankton-sioux-our-community-is-literally.asp

243. Johnson, W.C. and D.H. Knight, 2022: *Ecology of the Dakotas: Past, Present, and Future*. Yale University Press, New Haven, CT, 336 pp. https://yalebooks.yale.edu/book/9780300253818/ecology-of-dakota-landscapes/

244. Basche, A., K. Tully, N.L. Álvarez-Berríos, J. Reyes, L. Lengnick, T. Brown, J.M. Moore, R.E. Schattman, L.K. Johnson, and G. Roesch-McNally, 2020: Evaluating the untapped potential of US conservation investments to improve soil and environmental health. *Frontiers in Sustainable Food Systems*, **4**, 547876. https://doi.org/10.3389/fsufs.2020.547876

245. Brown, G., 2018: *Dirt to Soil: One Family's Journey into Regenerative Agriculture*. Chelsea Green Publishing, 240 pp. https://www.chelseagreen.com/product/dirt-to-soil/

246. Smart, A.J., D. Redfearn, R. Mitchell, T. Wang, C. Zilverberg, P.J. Bauman, J.D. Derner, J. Walker, and C. Wright, 2021: Forum: Integration of crop-livestock systems: An opportunity to protect grasslands from conversion to cropland in the US Great Plains. *Rangeland Ecology and Management*, **78**, 250–256. https://doi.org/10.1016/j.rama.2019.12.007

247. Zilverberg, C.J., K. Heimerl, T.E. Schumacher, D.D. Malo, J.A. Schumacher, and W.C. Johnson, 2018: Landscape dependent changes in soil properties due to long-term cultivation and subsequent conversion to native grass agriculture. *CATENA*, **160**, 282–297. https://doi.org/10.1016/j.catena.2017.09.020

248. Fenster, T.L.D., C.E. LaCanne, J.R. Pecenka, R.B. Schmid, M.M. Bredeson, K.M. Busenitz, A.M. Michels, K.D. Welch, and J.G. Lundgren, 2021: Defining and validating regenerative farm systems using a composite of ranked agricultural practices. *F1000Research*, **10**, 115. https://doi.org/10.12688/f1000research.28450.1

249. Krupek, F.S., D. Redfearn, K.M. Eskridge, and A. Basche, 2022: Ecological intensification with soil health practices demonstrates positive impacts on multiple soil properties: A large-scale farmer-led experiment. *Geoderma*, **409**, 115594. https://doi.org/10.1016/j.geoderma.2021.115594

250. LaCanne, C.E. and J.G. Lundgren, 2018: Regenerative agriculture: Merging farming and natural resource conservation profitably. *PeerJ*, **6**, 4428. https://doi.org/10.7717/peerj.4428

251. Rosenzweig, S.T., S.J. Fonte, and M.E. Schipanski, 2018: Intensifying rotations increases soil carbon, fungi, and aggregation in semi-arid agroecosystems. *Agriculture, Ecosystems & Environment*, **258**, 14–22. https://doi.org/10.1016/j.agee.2018.01.016

252. Rosenzweig, S.T., M.E. Stromberger, and M.E. Schipanski, 2018: Intensified dryland crop rotations support greater grain production with fewer inputs. *Agriculture, Ecosystems & Environment*, **264**, 63–72. https://doi.org/10.1016/j.agee.2018.05.017

253. Rosenzweig, S.T., M.S. Carolan, and M.E. Schipanski, 2020: A dryland cropping revolution? Linking an emerging soil health paradigm with shifting social fields among wheat growers of the High Plains. *Rural Sociology*, **85** (2), 545–574. https://doi.org/10.1111/ruso.12304

254. Wick, A.F., J. Haley, C. Gasch, T. Wehlander, L. Briese, and S. Samson-Liebig, 2019: Network-based approaches for soil health research and extension programming in North Dakota, USA. *Soil Use and Management*, **35** (1), 177–184. https://doi.org/10.1111/sum.12444

255. Wang, T., H. Jin, U. Kreuter, and R. Teague, 2021: Expanding grass-based agriculture on marginal land in the U.S. Great Plains: The role of management intensive grazing. *Land Use Policy*, **104**, 105155. https://doi.org/10.1016/j.landusepol.2020.105155

256. Craig, R.K., 2020: Water law and climate change in the United States: A review of the legal scholarship. *WIREs Water*, **7** (3), e1423. https://doi.org/10.1002/wat2.1423

257. Ginger Paige (Author), August 25, 2022: Oral communication with Joseph Cook, Irrigation Science and Management Center, University of Wyoming.

258. Ginger Paige (Author), April 4, 2023: Email communication with Kelsey Peck, Popo Agie Conservation District, Lander, WY.

259. Cosens, B. and B. Chaffin, 2016: Adaptive governance of water resources shared with Indigenous Peoples: The role of law. *Water*, **8** (3), 97. https://doi.org/10.3390/w8030097

260. Rinella, M.J., S.E. Bellows, T.W. Geary, R.C. Waterman, L.T. Vermeire, K.O. Reinhart, M.L. Van Emon, and L.A. Cook, 2022: Early calving benefits livestock production under winter and spring warming. *Rangeland Ecology & Management*, **81**, 63–68. https://doi.org/10.1016/j.rama.2022.01.003

261. Haigh, T.R., M. Hayes, J. Smyth, L. Prokopy, C. Francis, and M. Burbach, 2021: Ranchers' use of drought contingency plans in protective action decision making. *Rangeland Ecology and Management*, **74**, 50–62. https://doi.org/10.1016/j.rama.2020.09.007

262. Lassa, M.J., H. Wilmer, M. Boone, Z. Brown, J.D. Derner, D.E. Peck, C. Thissen, and C. Marlow, 2020: How to talk with ranchers about drought and climate resilience: Lessons from knowledge exchange workshops in Montana. *Journal of Extension*, **58** (5), 18. https://www.fs.usda.gov/treesearch/pubs/61765

263. Smart, A.J., K. Harmoney, J.D. Scasta, M.B. Stephenson, J.D. Volesky, L.T. Vermeire, J.C. Mosley, K. Sedivec, M. Meehan, T. Haigh, J.D. Derner, and M.P. McClaran, 2021: Forum: Critical decision dates for drought management in central and northern Great Plains rangelands. *Rangeland Ecology & Management*, **78**, 191–200. https://doi.org/10.1016/j.rama.2019.09.005

264. Wilmer, H., D.J. Augustine, J.D. Derner, M.E. Fernández-Giménez, D.D. Briske, L.M. Roche, K.W. Tate, and K.E. Miller, 2018: Diverse management strategies produce similar ecological outcomes on ranches in western Great Plains: Social-ecological assessment. *Rangeland Ecology & Management*, **71** (5), 626–636. https://doi.org/10.1016/j.rama.2017.08.001

265. Hillenbrand, M.R., F. Thompson, S. Wang, S. Apfelbaum, and R. Teague, 2019: Impacts of holistic planned grazing with bison compared to continuous grazing with cattle in South Dakota shortgrass prairie. *Agriculture, Ecosystems & Environment*, **279**, 156–168. https://doi.org/10.1016/j.agee.2019.02.005

266. Smith, A.P., L. Yung, A.J. Snitker, R.K. Bocinsky, E.C. Metcalf, and K. Jencso, 2021: Scalar mismatches and underlying factors for underutilization of climate information: Perspectives from farmers and ranchers. *Frontiers in Climate*, **3**, 663071. https://doi.org/10.3389/fclim.2021.663071

267. Peck, D., J. Derner, W. Parton, M. Hartman, and B. Fuchs, 2019: Flexible stocking with Grass-Cast: A new grassland productivity forecast to translate climate outlooks for ranchers. *Western Economics Forum*, **17** (1), 24–39. https://doi.org/10.22004/ag.econ.287342

268. *Water Resources Development Act* 2020, 2020: 116th Congress. H.R. 7575. https://www.congress.gov/bill/116th-congress/house-bill/7575/text

269. Spinrad, R., 2021: Statement from NOAA Administrator Rick Spinrad on the signing of the bipartisan Infrastructure Investment and Jobs Act. National Oceanic and Atmospheric Administration, November 15, 2021. https://www.noaa.gov/news-release/statement-from-noaa-administrator-rick-spinrad-on-signing-of-bipartisan-infrastructure-investment

270. Smith, K. and A. Savitt, 2020: Implementing watershed-scale flood mitigation projects Grand Island, Nebraska. In: *Building for the Future: Five Midwestern Communities Reduce Flood Risk*. Headwaters Economics, 15–18. https://headwaterseconomics.org/wp-content/uploads/FloodCaseStudies_LowRes.pdf

271. Blackfeet Nation, 2018: Blackfeet Climate Change Adaptation Plan. Blackfeet Nation. https://bcapwebsite.files.wordpress.com/2018/04/bcap_final_4-11.pdf

272. CSKT, 2016: Climate Change Strategic Plan. Confederated Salish and Kootenai Tribes of the Flathead Reservation. http://csktclimate.org/index.php/resources/resources

273. Sicangu Climate Crisis Working Group, 2022: A Climate Adaptation Plan for the Sicangu Lakota Oyate. Rosebud Sioux Tribe. https://www.rosebudsiouxtribe-nsn.gov/_files/ugd/ed1fef_53c3d954c1ef4c9d8d8ce441f58cb55c.pdf

274. Flandreau Santee Sioux Tribe and Great Plains Tribal Water Alliance, 2020: Flandreau Santee Sioux Tribe Drought Adaptation Plan. Flandreau Santee Sioux Tribe. https://www.tribalwateralliance.org/drought-adaptation-plans

275. Oglala Sioux Tribe and Great Plains Tribal Water Alliance, 2020: Oglala Sioux Tribe Drought Adaptation Plan. Oglala Sioux Tribe. https://www.tribalwateralliance.org/drought-adaptation-plans

276. Rosebud Sioux Tribe and Great Plains Tribal Water Alliance, 2020: Rosebud Sioux Tribe Drought Adaptation Plan. Rosebud Sioux Tribe. https://www.tribalwateralliance.org/drought-adaptation-plans

277. Standing Rock Sioux Tribe and Great Plains Tribal Water Alliance, 2020: Standing Rock Sioux Tribe Drought Adaptation Plan. Standing Rock Sioux Tribe. https://www.tribalwateralliance.org/drought-adaptation-plans

278. Pomerville, A., A. Kawennison Fetter, and J.P. Gone, 2022: American Indian behavioral health treatment preferences as perceived by Urban Indian Health Program providers. *Qualitative Health Research*, **32** (3), 465–478. https://doi.org/10.1177/10497323211057857

279. Stefan Tangen (Author), May 12, 2022: Oral communication with P. Antoine, Sicangu Lakota Treaty Council.

280. Stefan Tangen (Author), April 27, 2022: Oral communication with P. Two Eagle, Sicangu Lakota Treaty Council.

281. DOI, 2022: Secretary Haaland takes action to restore tribal authority to adopt water laws. U.S. Department of the Interior, Washington, DC, April 7, 2022. https://www.doi.gov/pressreleases/secretary-haaland-takes-action-restore-tribal-authority-adopt-water-laws

282. Levitus, J., 2019: The Ksik Stakii Project Beaver Mimicry Guidebook: A Guide to Natural Water Storage in Blackfeet Nation. Blackfeet Nation. https://bcapwebsite.files.wordpress.com/2019/12/beaver-mimicry-guidebook.pdf

283. Miller, B.W., G.W. Schuurman, A.J. Symstad, A.N. Runyon, and B.C. Robb, 2022: Conservation under uncertainty: Innovations in participatory climate change scenario planning from U.S. national parks. *Conservation Science and Practice*, **4** (3), 12633. https://doi.org/10.1111/csp2.12633

284. Runyon, A.N., A.R. Carlson, J. Gross, D.J. Lawrence, and G.W. Schuurman, 2020: Repeatable approaches to work with scientific uncertainty and advance climate change adaptation in US national parks. *Parks Stewardship Forum*, **36** (1), 98–104. https://doi.org/10.5070/p536146402

285. Fisichelli, N.A., G. Schuurman, A.J. Symstad, A. Ray, J.M. Friedman, B. Miller, and E. Rowland, 2016: Resource Management and Operations in Central North Dakota: Climate Change Scenario Planning Workshop Summary November 12–13, 2015, Bismarck, ND. Natural Resource Report NPS/NRSS/NRR--2016/1262. U.S. Department of the Interior, National Park Service, Fort Collins, CO. https://pubs.er.usgs.gov/publication/70176346

286. Fisichelli, N.A., G.W. Schuurman, A.J. Symstad, A. Ray, B. Miller, M. Cross, and E. Rowland, 2016: Resource Management and Operations in Southwest South Dakota: Climate Change Scenario Planning Workshop Summary January 20–21, 2016, Rapid City, SD. Natural Resource Report NPS/NRSS/NRR—2016/1289. U.S. Department of the Interior, National Park Service, Fort Collins, CO. http://pubs.er.usgs.gov/publication/70176347

287. Miller, B., A. Symstad, and G.W. Schuurman, 2019: Implications of Climate Scenarios for Badlands National Park Resource Management. U.S. Geological Survey and the National Park Service, 5 pp. https://www.nps.gov/subjects/climatechange/upload/2019-03-26badlclimatescenariosbrief_508compliant.pdf

288. Miller, B., A.J. Symstad, L. Frid, N.A. Fisichelli, and G.W. Schuurman, 2017: Co-producing simulation models to inform resource management: A case study from southwest South Dakota. *Ecosphere*, **8** (12), 02020. https://doi.org/10.1002/ecs2.2020

289. Runyon, A.N., G.W. Schuurman, B.W. Miller, A.J. Symstad, and A.R. Hardy, 2021: Climate Change Scenario Planning for Resource Stewardship at Wind Cave National Park: Climate Change Scenario Planning Summary. Natural Resource Report, NPS/NRSS/NRR—2021/2274. U.S. Department of the Interior, National Park Service, Fort Collins, CO. https://doi.org/10.36967/nrr-2286672

290. Schuurman, G.W., A. Symstad, B.W. Miller, A. Runyon, and R. Ohms, 2019: Climate Change Scenario Planning for Resource Stewardship: Applying a Novel Approach in Devils Tower National Monument. Natural Resource Report NPS/NRSS/CCRP/NRR—2019/2052. U.S. Department of the Interior, National Park Service, Fort Collins, CO. https://irma.nps.gov/datastore/downloadfile/632857

291. Symstad, A.J., N.A. Fisichelli, B.W. Miller, E. Rowland, and G.W. Schuurman, 2017: Multiple methods for multiple futures: Integrating qualitative scenario planning and quantitative simulation modeling for natural resource decision making. *Climate Risk Management*, **17**, 78–91. https://doi.org/10.1016/j.crm.2017.07.002

292. Lawrence, D.J., A.N. Runyon, J.E. Gross, G.W. Schuurman, and B.W. Miller, 2021: Divergent, plausible, and relevant climate futures for near- and long-term resource planning. *Climatic Change*, **167** (3), 1–20. https://doi.org/10.1007/s10584-021-03169-y

293. Vicente-Serrano, S.M., S. Beguería, and J.I. López-Moreno, 2010: A multiscalar drought index sensitive to global warming: The standardized precipitation evapotranspiration Index. *Journal of Climate*, **23** (7), 1696–1718. https://doi.org/10.1175/2009jcli2909.1

294. Schuurman, G.W., B.W. Miller, A.J. Symstad, A.N. Runyon, and B.C. Robb, 2022: Overcoming "Analysis Paralysis" through Better Climate Change Scenario Planning. *Park Science*, **36** (1). https://www.nps.gov/articles/000/overcoming-analysis-paralysis-through-better-climate-change-scenario-planning.htm

295. National Academies of Sciences, Engineering, and Medicine, 2021: *Accelerating Decarbonization of the U.S. Energy System*. The National Academies Press, Washington, DC, 268 pp. https://doi.org/10.17226/25932

296. Pipa, A.F. and N. Geismar, 2020: Reimagining Rural Policy: Organizing Federal Assistance to Maximize Rural Prosperity. The Brookings Institution, 37 pp. https://www.brookings.edu/wp-content/uploads/2020/11/rural-dev-assistance-brief.pdf

297. Fan, Q., K. Fisher-Vanden, and H.A. Klaiber, 2018: Climate change, migration, and regional economic impacts in the United States. *Journal of the Association of Environmental and Resource Economists*, **5** (3), 643–671. https://doi.org/10.1086/697168

298. Xu, C., T.A. Kohler, T.M. Lenton, J.C. Svenning, and M. Scheffer, 2020: Future of the human climate niche. *Proceedings of the National Academy of Sciences of the United States of America*, **117** (21), 11350–11355. https://doi.org/10.1073/pnas.1910114117

299. Hoerling, M., J. Eischeid, and R. Webb, 2013: Climate Assessment Report: Understanding and Explaining Climate Extremes in the Missouri River Basin Associated with the 2011 Flooding. National Oceanic and Atmospheric Administration, Office of Oceanic and Atmospheric Research, Earth System Research Laboratory, Boulder, CO. https://www.esrl.noaa.gov/psd/csi/factsheets/pdf/noaa-mrb-climate-assessment-report.pdf

300. Allen, J.T., 2017: Hail potential heating up. *Nature Climate Change*, **7** (7), 474–475. https://doi.org/10.1038/nclimate3327

301. Lancet Countdown, 2021: 2021 Lancet Countdown on Health and Climate Change: Policy Brief for the United States of America. Salas, R.N., P.K. Lester, and J.J. Hess, Eds. Lancet Countdown, London, UK. https://www.lancetcountdownus.org/2021-lancet-countdown-us-brief/

Fifth National Climate Assessment: Chapter 26

Southern Great Plains

Chapter 26. Southern Great Plains

Authors and Contributors

Federal Coordinating Lead Author

Philip A. Fay, USDA Agricultural Research Service

Chapter Lead Author

Renee A. McPherson, University of Oklahoma, South Central Climate Adaptation Science Center

Chapter Authors

Susan G. Alvarez, City of Dallas, Texas

Darrian Bertrand, University of Oklahoma, Southern Climate Impacts Planning Program

Taylor L. Broadbent, South Central Climate Adaptation Science Center

Tianna Bruno, University of California, Berkeley

Ali Fares, Prairie View A&M University

Brian McCullough, Texas A&M University

Georgianne W. Moore, Georgia Southern University

Bee Moorhead, Texas Impact Foundation

Laura Patiño, City of Austin, Texas

Alexander "Sascha" Petersen, Adaptation International

Nicholas G. Smith, Texas Tech University

Jean L. Steiner, Kansas State University

April Taylor, Chickasaw Nation

Travis Warziniack, USDA Forest Service

Technical Contributors

Juan Pablo Carvallo, Lawrence Berkeley National Laboratory
Mark Junker, Sac and Fox Nation of Missouri in Kansas and Nebraska
Gary McManus, Oklahoma Climatological Survey
Lauren E. Mullenbach, University of Oklahoma
John W. Nielsen-Gammon, Texas A&M University
John A. Quinlan, NOAA Fisheries, Southeast Fisheries Science Center
Adrienne M. Wootten, University of Oklahoma

Review Editor

Mark Shafer, University of Oklahoma

Cover Art

Cody Norton

Recommended Citation

McPherson, R.A., P.A. Fay, S.G. Alvarez, D. Bertrand, T.L. Broadbent, T. Bruno, A. Fares, B. McCullough, G.W. Moore, B. Moorhead, L. Patiño, A. Petersen, N.G. Smith, J.L. Steiner, A. Taylor, and T. Warziniack, 2023: Ch. 26. Southern Great Plains. In: *Fifth National Climate Assessment*. Crimmins, A.R., C.W. Avery, D.R. Easterling, K.E. Kunkel, B.C. Stewart, and T.K. Maycock, Eds. U.S. Global Change Research Program, Washington, DC, USA. https://doi.org/10.7930/NCA5.2023.CH26

Table of Contents

Introduction **5**

Key Message 26.1
How We Live: Climate Change Is Degrading Lands, Waters, Culture, and Health **7**

Box 26.1. Place Matters: A Case Study of Houston, Texas 8

Key Message 26.2
How We Work: Climate Changes Are Creating Economic Challenges and Opportunities **11**

Box 26.2. February 2021 Severe Cold Outbreak 14

Key Message 26.3
How We Play: Climate Extremes Are Endangering Sports, Recreation, and Leisure **19**

Key Message 26.4
How We Heal: Climate Change Is Exacerbating Existing Social and Environmental Disparities **26**

Box 26.3. Adaptation Planning Led by the Tribes of Kansas, Nebraska, and Iowa 28

Key Message 26.5
How We Serve: Climate Change Is Straining Public Infrastructure and Services **31**

Box 26.4. Building a Sustainable City: Greensburg, Kansas 36

Traceable Accounts **38**

Process Description 38
Key Message 26.1 39
Key Message 26.2 40
Key Message 26.3 41
Key Message 26.4 43
Key Message 26.5 44

References **47**

Introduction

Residents and visitors in the Southern Great Plains—Kansas, Oklahoma, and Texas—benefit from the region's working coasts, sandy beaches, southern forests, grasslands, urban areas, rural towns, scrublands, rangelands, and croplands. The region spans 20 ecoregions,[1] each with distinct and diverse species of plants and animals. Those ecosystems provide clean air and water, healthy soils, landscapes for recreation and tourism, habitats for wild plants and animals, and other benefits.[2] The region's 47 Federally Recognized Tribes were forcibly relocated to the region from elsewhere or constricted to fragments of their traditional homelands (circa 1830–1890).[3] Contemporary immigrants from many countries have joined generations of Indigenous Peoples and those who trace their roots to Mexico, Europe, and Africa.[4] The region's distinct peoples and ecosystems experience the impacts of climate change differently, requiring unique responses to climate risk and resources for resilience.

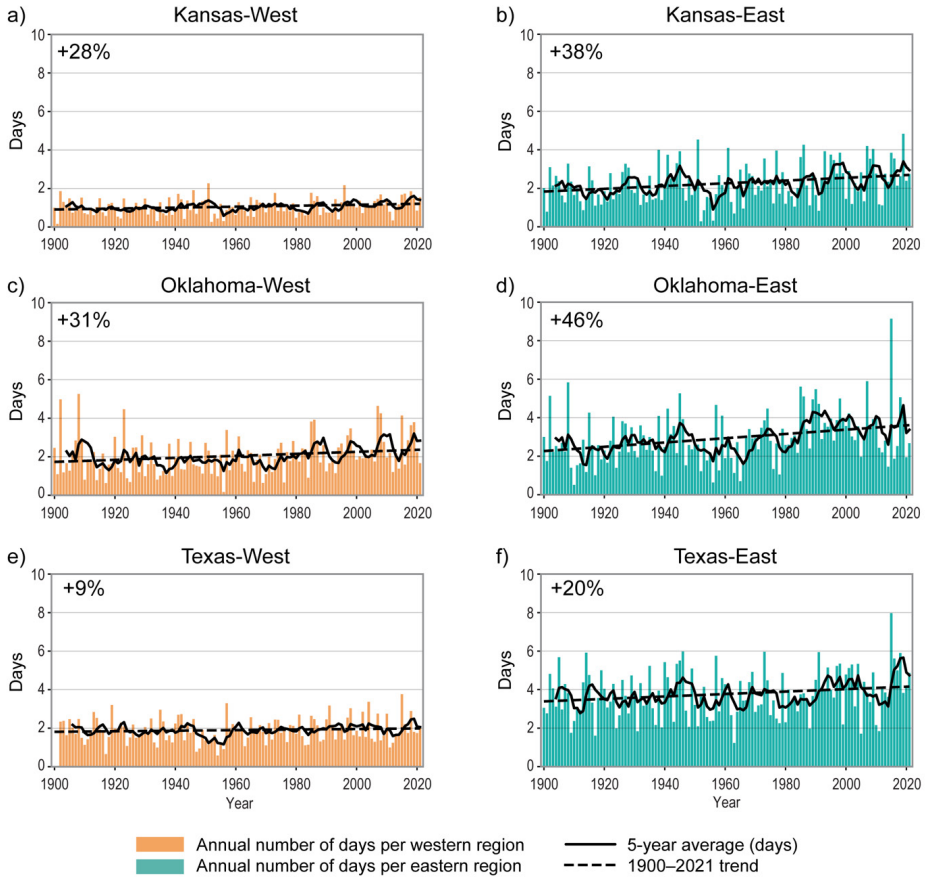
Water is unevenly available across the Southern Great Plains, contributing to distinct lifestyles, workforces, and social burdens. Annual precipitation amounts are lowest in the western portion of the region (10–15 inches) and increase substantially near the eastern boundary (over 50 inches), with high annual and seasonal precipitation variability everywhere.[4] Rivers generally flow from northwest to southeast, and shallow transient wetlands dot western landscapes. These surface waters are critical to sustain irrigation, livestock, and ecological diversity.[5,6] Groundwater is essential near and west of Interstate 35, with aquifers primarily supporting agricultural production and public water supply.[7] Although governments have created reservoirs for flood control, drinking water, irrigation, and recreation,[8] the region experiences some of the country's worst water shortages, and these are projected to increase in both intensity and duration.[9]

Energy is a dominant driver of the region's economy. The vast reserves of fossil fuels in the region have supported economic development nationwide and worldwide.[10] In the past two decades, wind and solar energy generation has proliferated across western lands. In 2021 Texas, Oklahoma, and Kansas ranked first (34,400 megawatts [MW] of installed capacity), third (10,400 MW), and fourth (8,300 MW), respectively, in the Nation in wind energy generation.[11] The reliability of renewable and nonrenewable energy generation and distribution is challenged by tropical storms, wildfire, heat, winter storms, flooding, and drought (KM 5.1).

The region encompasses some of the Nation's fastest-growing cities as well as many small rural communities with declining populations. Rural communities support much of the region's food, fiber, and energy production, in addition to recreational activities. The region's metropolitan areas are leaders in finance, research and development, service and energy industries, medical care, and tourism. Climate extremes and their impacts have harmed all communities, damaging infrastructure and agricultural production, disrupting commerce and price stability, and amplifying social inequities (KMs 11.1, 11.3, 12.2).

Although climate change is global (KM 3.1), its specific impacts are regional (KM 3.3). Thus far, the Southern Great Plains has seen fewer direct, large-scale impacts of climate change than other regions because of its relatively low latitude, flat terrain, and high natural climate variability. Even so, annual average temperatures have increased from 1900 to 2020: 1.5°F for Texas and Kansas[12,13] and 0.6°F for Oklahoma.[14] Annual precipitation has increased across most of the region except far west Texas (Figure 2.4). In addition, days with 2 or more inches of precipitation have become more frequent across the Southern Great Plains, with larger increases in the eastern half of the region than the western half (Figure 26.1).[15] Between 2000 and 2021, Texas endured its five wettest months on record, as well as 19 named tropical storms;[13] 8 of these storms were hurricanes, including Harvey (2017), Ike (2008), and Rita (2005). In contrast, over one-quarter of Kansas experienced severe to exceptional drought during 56 of the 156 months from 2010 to 2022. During this period, Oklahoma and Texas experienced 69 and 82 months, respectively, of these severe to exceptional drought conditions.[16] Between 2018 and 2022 NOAA reported 52 individual billion-dollar climate-related disasters affecting all or part of the region.[17]

Annual Number of Days with Precipitation of 2 Inches or More (1900–2021)



The frequency of days with precipitation of 2 inches or more has increased across the Southern Great Plains.

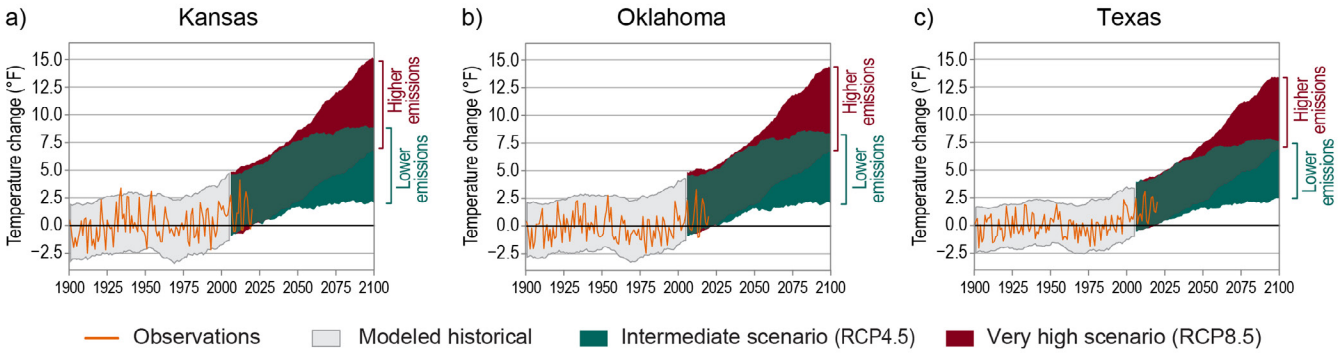
Figure 26.1. These graphs show the annual number of days (colored bars) with daily precipitation of 2 inches or more from 1900 to 2021 in (**a**) western Kansas (28% increase for the long-term, linear trend), (**b**) eastern Kansas (38% increase), (**c**) western Oklahoma (31% increase), (**d**) eastern Oklahoma (46% increase), (**e**) western Texas (9% increase), and (**f**) eastern Texas (20% increase). (Station data were unavailable for 1900 and 1901 in western Texas.) Solid black lines show five-year averages; dashed black lines denote the 1900–2021 trend. The number of days has been highly variable from year to year, with fewer 2-inch events in the west (gold bars) on average than in the east (green bars; divided at 97.5° west, near Wichita, Oklahoma City, Fort Worth, and Corpus Christi). Days with precipitation of 2 inches or more have increased in all six regions. Figure credit: NOAA NCEI and CISESS NC.

Since the Fourth National Climate Assessment in 2018, there has been substantial growth in utility-scale electricity generation from wind energy across the region and from solar energy in Texas. At the same time, there has been a significant decrease in the use of coal for electricity in Oklahoma and Texas,[18] although Texas's greenhouse gas emissions still far exceed those of any other US state.[19] The February 2021 cold outbreak and the COVID-19 pandemic highlighted the fragility of the energy and healthcare systems to large-scale stressors. Many of the largest cities in the Southern Great Plains have released climate resilience or sustainability plans since 2018. As research has grown on the disproportionate impacts of climate change on overburdened populations, these cities also have started incorporating social justice concepts into their planning processes.

Future temperatures are expected to be historically unprecedented in the instrumental record in all three states (Figure 26.2). By midcentury, annual average temperatures are projected to exceed historical record levels regardless of emissions pathway. In addition, the number of extremely hot days and the intensity of drought conditions are projected to increase, and the number of extremely cold days is expected to

decrease (KM 2.2). In general, southwestern and southern areas of the Southern Great Plains are projected to become drier, and northeastern areas are expected to become wetter (Figure 2.10). The changes in timing, intensity, and frequency of certain climate conditions and extreme events are expected to influence how we—the residents of the Southern Great Plains—live with family and friends (KM 26.1), work in business and industry (KM 26.2), play sports and enjoy leisure activities (KM 26.3), heal existing environmental inequities and injustices (KM 26.4), and serve residents through public infrastructure and services (KM 26.5).

Historical and Projected Changes in Air Temperature (1900–2100)



Air temperatures for Kansas, Oklahoma, and Texas are projected to be historically unprecedented by the end of the century.

Figure 26.2. These graphs show observed and projected changes (compared to the 1901–1960 average; thick black line) in near-surface air temperature for (**a**) Kansas, (**b**) Oklahoma, and (**c**) Texas. Annual average temperature observations (orange line) are plotted with the range of temperatures from climate model output (light gray shading) for the historical period. The overlap of observed and modeled temperatures indicates that the models represent the region's climate reasonably well. Climate projections out to 2100 use an intermediate scenario (RCP4.5; green shading) and a very high scenario (RCP8.5; red shading), showing a range of possible future temperatures. Results from both scenarios indicate substantial warming in Kansas, Oklahoma, and Texas by midcentury and historically unprecedented warming by the end of the century. (a, b) Adapted from Frankson et al. 2022[12] and Frankson et al. 2022;[14] (c) adapted from Runkle et al. 2022.[13]

Key Message 26.1

How We Live: Climate Change Is Degrading Lands, Waters, Culture, and Health

Climate change is beginning to alter how we live in the Southern Great Plains, putting us at risk from climate hazards that degrade our lands and waters, quality of life, health and well-being, and cultural interconnectedness (*high confidence*). Many climate hazards are expected to become more frequent, intense, or prolonged; to broaden in spatial extent; and to result in more people experiencing costly, deadly, or stressful climate-related conditions (*very likely*, *high confidence*). To address the growing risk, effective climate-resilient actions include implementing nature-based solutions; valuing Indigenous, traditional, and local knowledges; and infusing climate change solutions into community planning (*medium confidence*).

Lands and waters of the Southern Great Plains are important to people's ways of life, shaping the stories of family and community successes and struggles. Climate change has added stress to lands and waters that already contend with invasive species, land-use change, and land fragmentation (KM 8.2).[20] Rangeland and grassland health is being degraded by woody plant encroachment from precipitation changes[21] or fire suppression.[22] Wetlands are suffering from high evaporation rates or excess nutrient inputs from flood runoff.[23] Ice storms, drought, and high temperatures have stressed forests, making them susceptible to post-event trauma (e.g., disease, pests, fire) and mortality.[24,25,26]

Urban landscapes are being harmed by air and water pollution, extreme heat, drought, and flooding (KM 12.2). As climate change brings heavier rainfall, cities and towns are increasingly at risk of high-impact floods. The extensive impervious surfaces (e.g., parking lots, roofs) of metropolitan areas such as Houston (Box 26.1) increase the likelihood of widespread flooding because of increased runoff.[27] Coastal cities have added risk from sea level rise. By 2100, under a projected 3.3 feet of sea level rise along the Texas Gulf Coast, a Category 2 hurricane is estimated to cause 3–10 times more damage to buildings and be $10.4 billion (in 2022 dollars) more costly (from averages of $3.7 to $14.1 billion) than a similar storm today.[28]

Traditions, heritage, and culture related to land and water are also at risk because of changes forced by novel climatic conditions.[29,30] Warming temperatures are shifting ranges of culturally significant species, making them absent or rare on lands where Indigenous People have access.[31] Heavy rainfall and resulting flooding have inundated archaeological sites.[32] Large-scale or repetitive damages from sea level rise, tropical cyclones, drought, and flooding have increased displacement of people and migration at the Texas–Mexico border and from coastal communities (KM 9.3).[33,34,35,36]

Tribes are revitalizing their cultural practices and relationships with nature to find solutions that resonate with their traditions (KMs 16.2, 16.3). For example, the Tribal Alliance for Pollinators is building on Indigenous cultural and medicinal traditions to preserve and restore grassland ecosystems for monarch butterflies and other threatened pollinators.[31] To reduce harmful algal blooms that proliferate with hot temperatures,[37] the Chickasaw Nation has teamed with local landowners and agriculture producers in southern Oklahoma to remove invasive junipers, improve fertilizer application methods, and restore native habitats for ground-nesting birds.[38]

Box 26.1. Place Matters: A Case Study of Houston, Texas

Adaptation and mitigation actions occur at the local level, where people's values and the neighboring landscape matter. Houston, Texas, illustrates how urban communities are starting to incorporate climate-smart actions into their planning efforts.

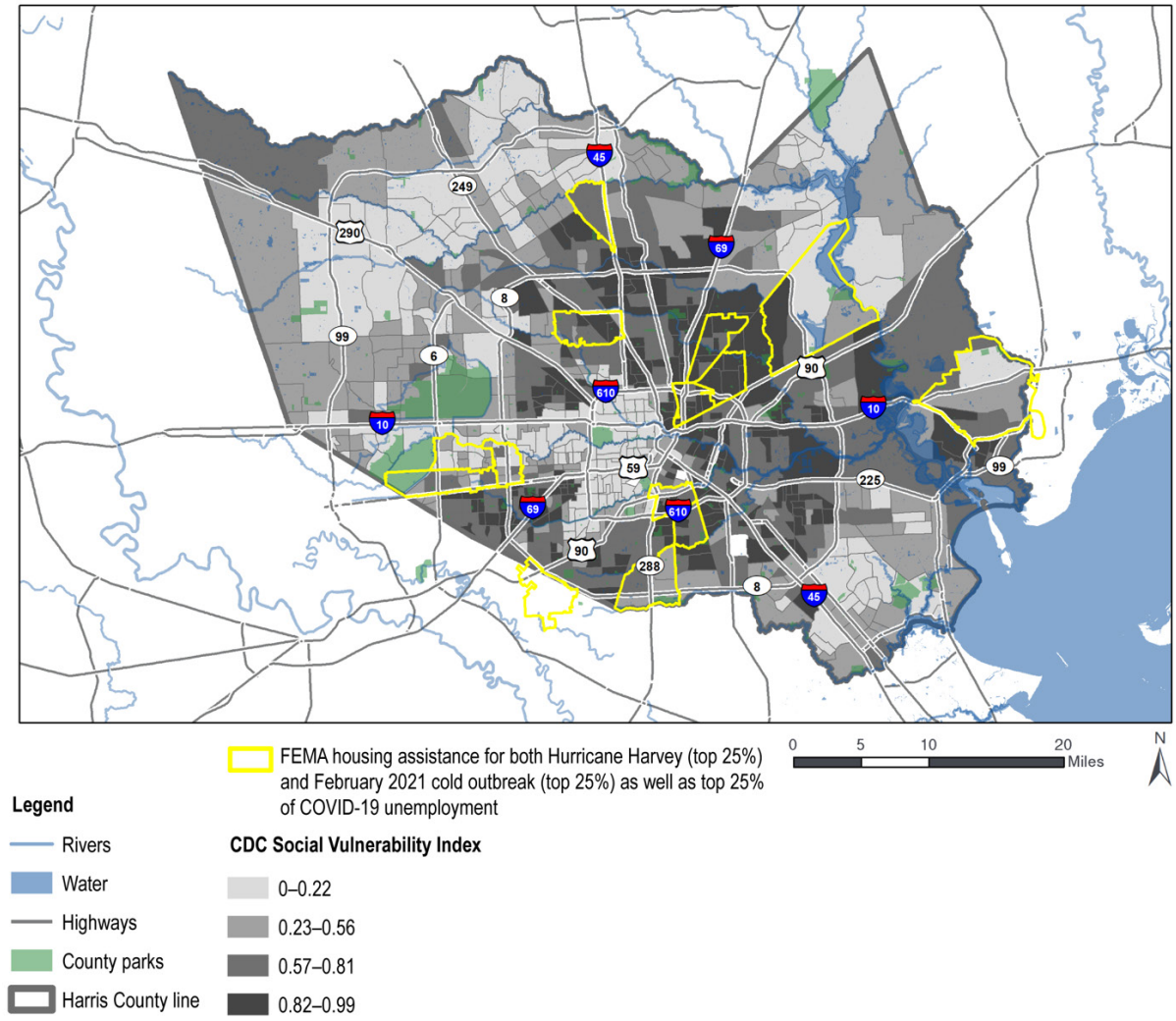
Houston is a city of 2.3 million people within a broader metropolitan area of 7.2 million.[39,40] It became a major port city because the navigable depth and orientation of the Buffalo Bayou supported the export of products from fertile inland croplands.[41] By the early 1900s, oil and gas production emerged, and companies moved into Houston to shelter from coastal storms after the catastrophic 1900 Galveston hurricane.[42] Now, Houston is one of the Nation's fastest-growing cities, and its port is the Nation's largest by tonnage. It is home to NASA's Johnson Space Center and the world's largest medical complex, the Texas Medical Center.

Demographically diverse, Houston residents are predominantly Hispanic (38%), White (35%), Black (17%), and Asian (8%).[43] One-quarter of Houstonians are foreign born, speaking almost 150 different languages. Social inequities and historic racism exacerbate many Houstonians' ability to prepare for, respond to, and recover from climate impacts. For example, 45% of Black and Hispanic residents do not have cash available to cover an unexpected $400 expense during an emergency, as compared to 13% for Whites and 7% for Asians.[44]

Houston experienced 35 federally declared disasters during 1982–2022; one-third of these were since 2015. Devastating floods occurred in April 2016 (the "Tax Day Flood"), August 2017 (Hurricane Harvey), September 2019 (Tropical Storm

Imelda), and September 2020 (Tropical Storm Beta). In August 2011, residents experienced 24 days of air temperatures above 98°F.[45] The February 2021 cold outbreak (Box 26.2) crippled much of Houston's energy and water systems. The effects of these disasters compound (Figure 26.3; Focus on Compound Events), amplifying harm to populations especially at risk.

Compounding Damages in Houston, Texas, from a Hurricane, Cold Outbreak, and Pandemic



Damages from compounding events—a hurricane, cold outbreak, and pandemic—disproportionately impacted socially vulnerable populations in Houston, Texas.

Figure 26.3. Several areas in Houston (yellow outlines) that were most affected by Hurricane Harvey, the February 2021 cold outbreak (unofficially named "Uri"), and COVID-19 unemployment coincided with census blocks with high scores on the Social Vulnerability Index (SVI) from the CDC (darker gray shading). (The SVI measures 16 social factors that describe socioeconomic status, household characteristics, racial and ethnic status, housing type, and transportation access.) For the weather events, zip codes were ranked by number of valid registrants to FEMA's Individual and Households Program for financial assistance; for COVID-19, zip codes were ranked by percentage of population claiming unemployment insurance due to COVID-19, according to Texas Workforce Commission data from May 2020 to June 2021. The zip codes in the top 25% by those metrics are outlined in yellow. Adapted from Map 5 of Rice University's Kinder Institute for Urban Research 2022.[46]

Houston acted in response to these experiences and the scientific consensus on climate change. The city established a chief resilience officer in 2019. It published its Resilient Houston strategy and climate action plan in 2020[47] to prepare for, withstand, and recover from sudden catastrophic events and slow-moving disasters, including those worsened by climate change. In August 2020, Houston hosted the Nation's largest single-day, community-led effort to measure and map where urban heat was most severe. One month later, the city released its climate impact assessment,[48] illustrating how climate change is expected to affect Houston's future. Other initiatives included an urban prairie resilience project and a green stormwater tax-abatement program.

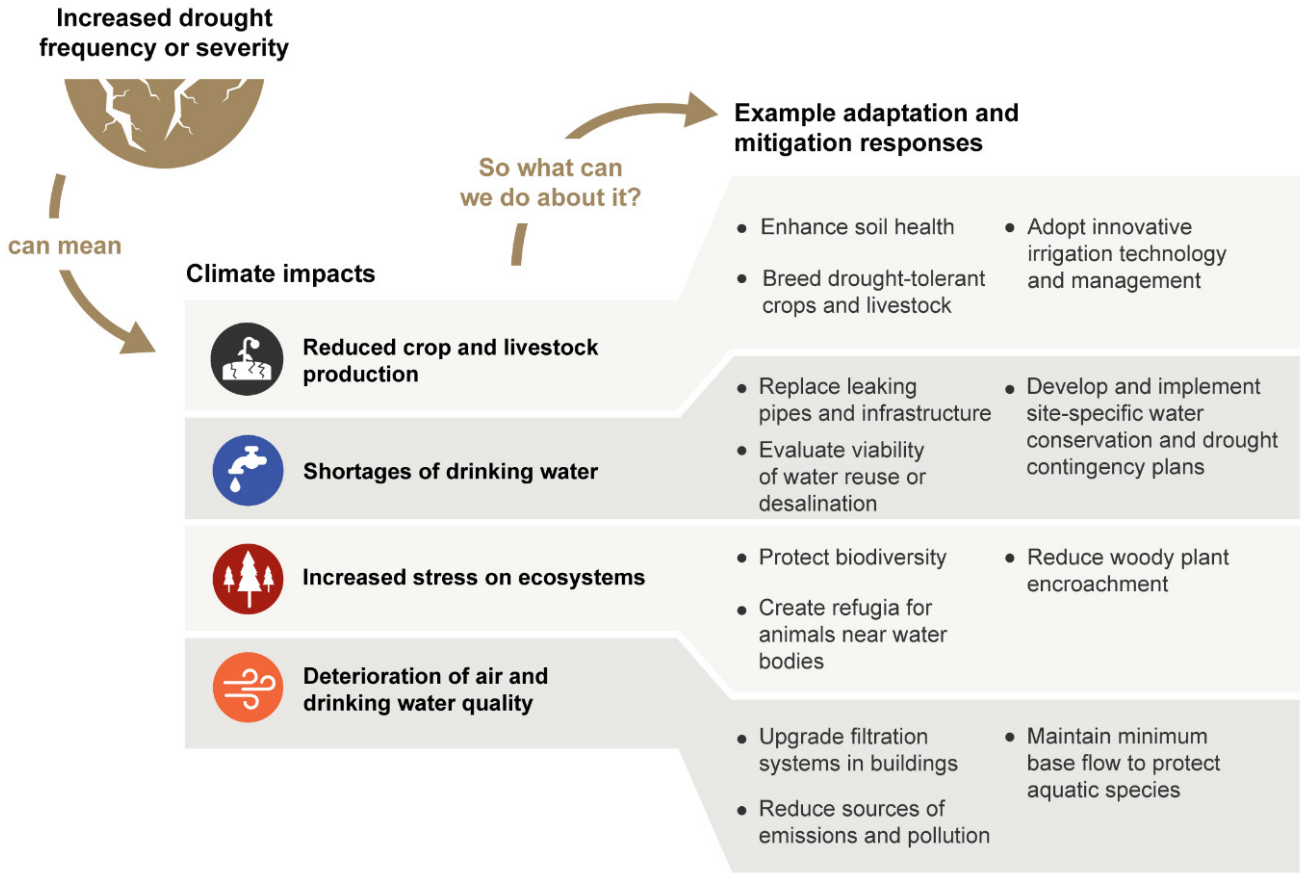
Climate change is also affecting public health through cardiovascular stress from temperature extremes, respiratory diseases enhanced by allergens and pollutants, increases in transmission of vector-borne diseases (e.g., via mosquitoes), and illnesses caused by poor water quality (KM 15.1). Many of these risks are compounded by ecosystem and land-use change. For example, global warming has induced earlier and longer pollen seasons, with consistent changes during the past three decades in Texas.[49] From 1987 to 2020, expansion of eastern red cedars was associated with a 205% increase in allergenic pollen intensity in Tulsa, Oklahoma.[50] During grass-pollen season, the region's emergency medical facilities are expected to see an average of 720 (under an intermediate scenario [RCP4.5]) to 980 (very high scenario [RCP8.5]) more asthma patients annually by 2050.[51]

High temperatures, particularly when combined with high humidity, have impaired human health. In Oklahoma, most heat-related deaths have occurred from July to September during heatwaves.[52] People who are male, Black, 65 years or older, diabetic, unmarried, without air-conditioning, or living below the poverty line have been at higher risk of heat-related death (KM 15.2).[52,53] Warmer temperatures also have worsened air pollution by increasing near-surface ozone.[54] In 2023, 18 Texas counties in the Dallas–Fort Worth and Houston–Galveston metropolitan areas exceeded national ozone standards (i.e., 8-hour ozone concentrations of 0.100 – 0.113 parts per million), affecting more than 12 million people.[55]

Rising temperatures are extending the ranges and lengthening the active seasons of ticks, mosquitoes, and other disease vectors (KM 15.1).[56] For instance, host-seeking activities of ticks, which usually suspend in cold temperatures, were reported during January and February 2017 in eastern Kansas and Oklahoma.[57] Warmer temperatures in the future are expected to support the range expansion of tropical diseases, including dengue, West Nile virus, Chagas disease, and chikungunya.[58] Across western parts of the region, future warmer and drier conditions are projected to support an increased incidence of Valley fever,[59] which is endemic in parts of Texas.[60]

Climate-smart planning (Figure 26.4) is alleviating some harmful consequences of climate variability and change that threaten residents' health. Urban tree canopy assessment,[61] planning,[62] and planting[63] efforts are aiming to reduce the negative impacts of increased temperatures, air pollution, and variable precipitation on urban landscapes.[64] Community food forests, such as the Osage Orchard in Pawhuska, Oklahoma, provide food sovereignty and security, climate resilience, and public health benefits.[65] Still, a lack of resources among many Tribes,[66] outdoor and migrant workers,[67] and overburdened populations[68] has limited the ability of these groups to respond to climate-related health risks.

Resilience Actions to Address the Impacts of More Frequent or Severe Droughts on Communities



Resilience actions can help alleviate harmful consequences to communities of more frequent or severe drought.

Figure 26.4. The increasing frequency or severity of drought has negative impacts on lands and waters across the Southern Great Plains, including reduced crop and livestock production, shortages of drinking water, increased stress on ecosystems, and deterioration of air and drinking water quality. The example adaptation and mitigation actions can increase resilience and reduce negative impacts. Figure credit: See figure metadata for contributors.

Key Message 26.2

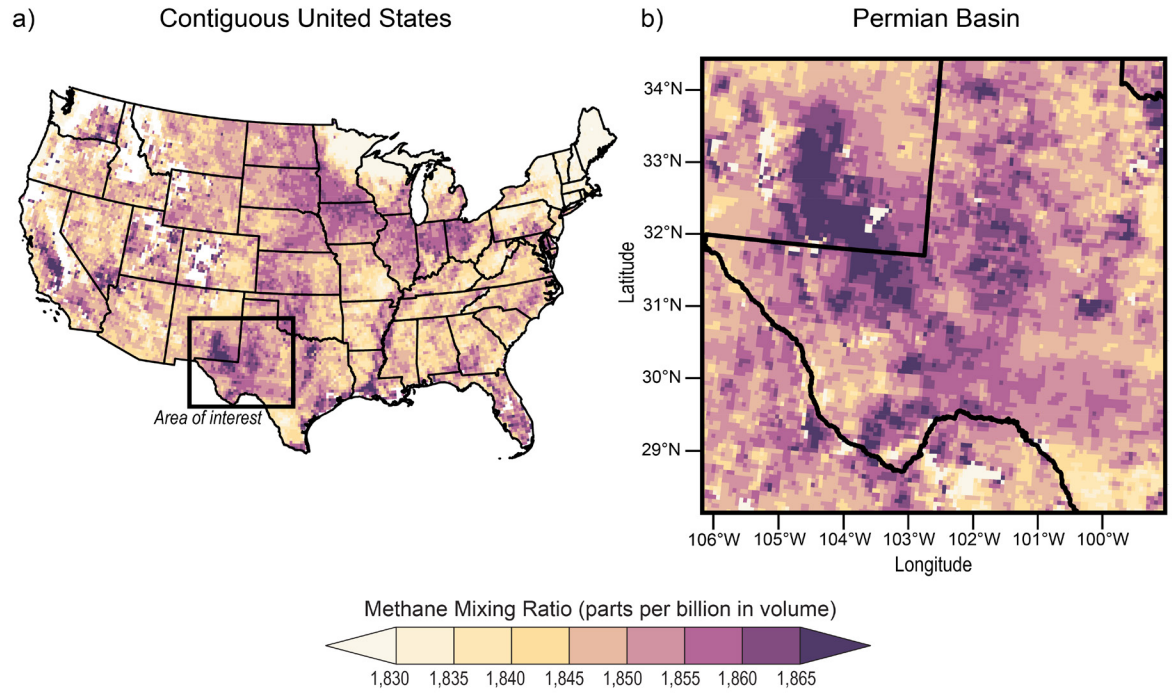
How We Work: Climate Changes Are Creating Economic Challenges and Opportunities

As climate conditions change, businesses and industries across the Southern Great Plains are experiencing disruptions and losses in productivity and profits—but also new economic opportunities (*high confidence*). In coming decades, warmer temperatures, more erratic precipitation, and sea level rise are expected to force widespread and costly changes in how we work (*very likely*, *high confidence*). Businesses and industries have opportunities to harness their diverse knowledge, resources, and workers to develop products and services in climate mitigation technologies, adaptation strategies, and resilient design that will enhance the region's economy (*medium confidence*).

The region's economy provides for daily needs of residents, supports their long-term aspirations, and addresses societal needs inside and beyond the region. Hotter temperatures, heavier precipitation, stronger tropical cyclones, and other climate changes (App. 4) have harmed workers' health and productivity, inflated product or building costs, and disrupted supply chains (Focus on Risks to Supply Chains). Extreme weather events, such as the February 2021 winter storm (Box 26.2), have exposed gaps in the resilience of businesses to climate extremes while also highlighting opportunities to develop products and services in response to worldwide demand for resilient solutions.

The energy industry in the Southern Great Plains is a global leader in fossil fuel exploration and production, serving a large fraction of global energy demand and supporting rural towns through local employment and tax revenues.[69] Fossil fuels release greenhouse gases when burned, contributing substantially to atmospheric warming (KM 2.1). In 2020 Texas led the Nation in emissions of carbon dioxide (CO_2; 667 million metric tons)—double that of the next-highest emitting state.[19] Texas also had the highest methane emissions (94 million metric tons of CO_2 equivalent in 2020).[19] Natural gas operations in the Permian Basin leak the largest amount of methane per year from any US gas-producing region, an amount sufficient to supply natural gas to 7 million Texas households annually.[70] Atmospheric methane concentrations are high across the Permian Basin as compared to the rest of the US (Figure 26.5) and are attributed primarily to natural gas production.[70]

Methane Across the Permian Basin (May 2018–March 2019)



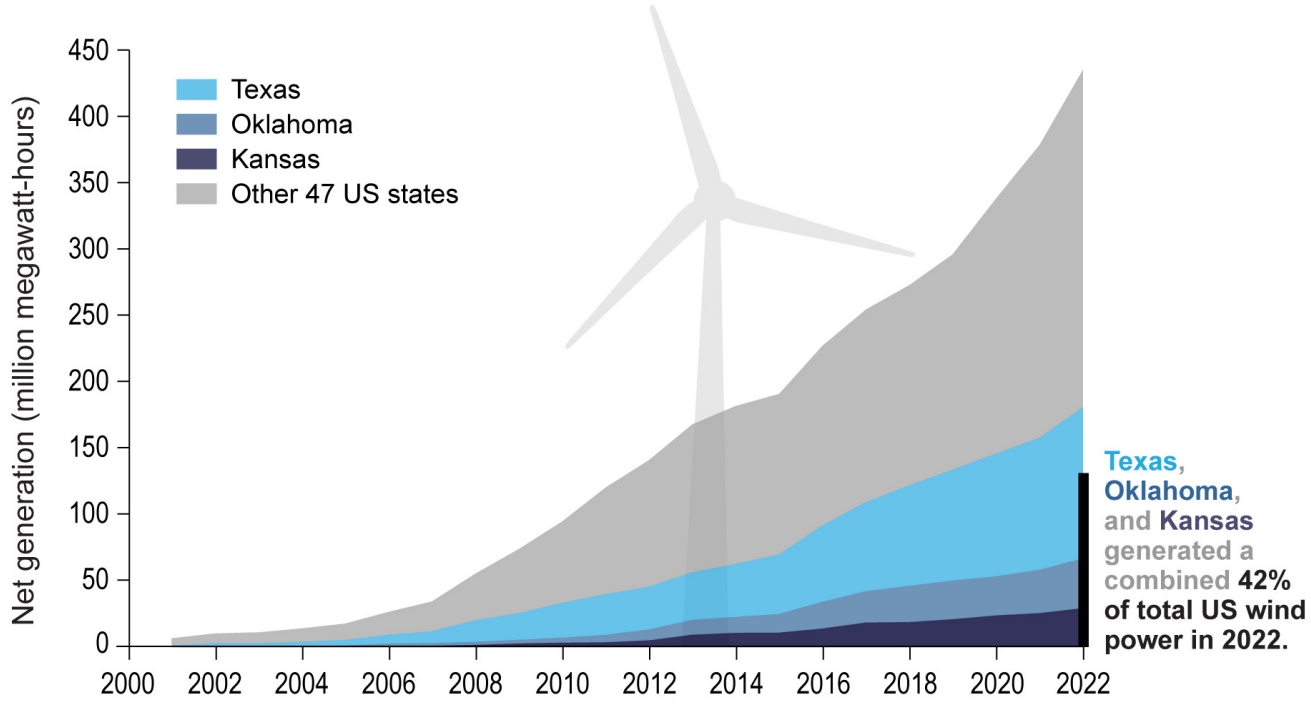
Natural gas operations in the Permian Basin leak large amounts of methane.

Figure 26.5. The maps show satellite-estimated methane mixing ratio (in parts per billion by volume [ppbv]) across (**a**) the contiguous United States and (**b**) the Permian Basin (black box and inset map), averaged from May 2018 to March 2019. Mixing ratio is a measure of the concentration of a gas such as methane in the air. Darker shading represents higher methane mixing ratios; missing data are shaded white. Accounting for atmospheric transport, the spatial pattern of methane mixing ratio across the basin is closely associated with gross (before processing) natural gas production and, to a lesser extent, with oil production. (The original published source did not include data for Alaska, Hawai'i and the US-Affiliated Pacific Islands, and the US Caribbean.) Natural gas operations in the Permian Basin leak a large volume of methane, contributing to atmospheric warming. Adapted from Zhang et al. 2020[70] [CC BY-NC 4.0].

Throughout the region, a major shift in energy generation from fossil fuels toward renewables (KM 5.3) is underway, creating new jobs, cleaner air, and climate change mitigation benefits. For example, the Electric Reliability Council of Texas (ERCOT; Texas's main power supplier) estimates that installed capacity for electricity generated by wind from their suppliers alone will increase from 31,100 MW in 2020 to 41,700 MW in 2025.[71] During the same time, ERCOT expects growth in solar generation capacity from 6,000 MW to 46,400 MW, and in battery storage from 275 MW to 14,500 MW. Electricity generated from gas and coal, however, is not planned to increase substantially.[71,72] In the third quarter of 2022, about 285,000 workers were employed in fossil fuel extraction, distribution, and support activities across the three states.[73] A transition of this workforce from a carbon-intensive to a low-carbon economy is expected to affect some Southern Great Plains communities disproportionately.[74] Within Tribes, a just transition also means a strengthening of Tribal sovereignty, economic independence, and nonextractive, Indigenous-based restoration of ecosystems.[3] For Tribes and communities facing this transition, there generally is a lack of planning, infrastructure, financing, and workforce training in new careers (including in renewable energy) across the region (e.g., Williams et al. 2021[75]).

The Southern Great Plains accounts for 42% of the Nation's wind-generated electricity (Figure 26.6).[18] Major wind installations in rural communities support the local tax base, stabilizing funding for public services such as education, road maintenance, and emergency services, as well as for infrastructure such as hospitals, jails, and parks.[76] Wind-turbine productivity across western Kansas, western Oklahoma, and the Texas Panhandle is projected to increase with climate change because of a more stable low-level jet stream—a regional atmospheric feature that generates strong winds at turbine height, particularly at night during spring and summer.[77]

Net Generation of Electricity from Wind (2001–2022)



The Southern Great Plains contributes a large share to total US wind-generated electricity.

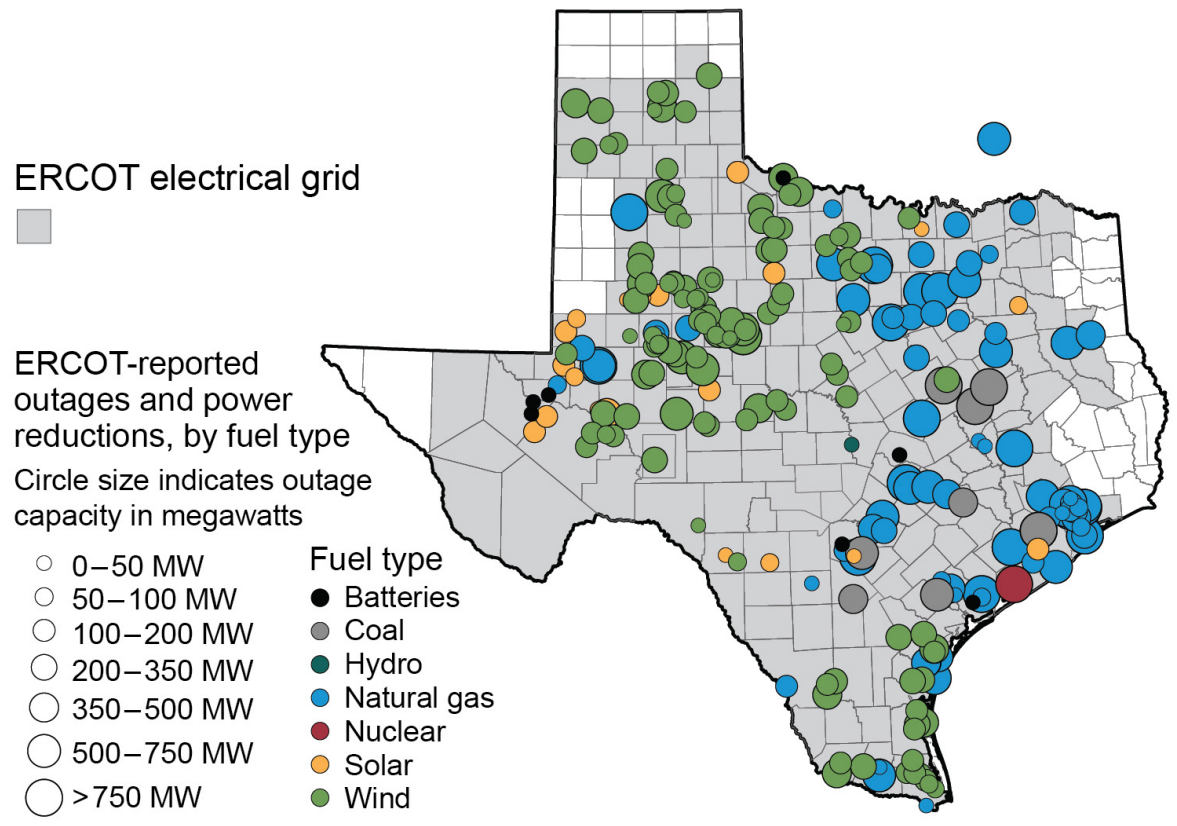
Figure 26.6. US producers in the 50 states generated 435 million megawatt-hours of electricity from wind power in 2022. Together, Texas, Oklahoma, and Kansas contributed 159 million megawatt-hours, or 42% of total US production. Data were not available for the US-Affiliated Pacific Islands or the US Caribbean. Figure credit: See figure metadata for contributors.

Box 26.2. February 2021 Severe Cold Outbreak

Cold outbreaks occur when the jet stream weakens, causing Arctic air to advance southward. From February 8–20, 2021, Arctic air moved far into the Southern Great Plains.[78,79] Wind chills were below 0°F from central Texas northward on Valentine's Day, snow fell along the Texas Gulf Coast, and almost 3,000 daily minimum-temperature records were tied or broken across the region.[80] The prolonged cold caused large-scale power disruption, left 14.4 million households without tap water, and led to more than 200 deaths.[81,82]

Electricity-generation units failed in large numbers during the frigid conditions (Figure 26.7), requiring grid operators to implement rolling blackouts to try to avoid widespread, uncontrolled outages.[81,83] Most of the unplanned outages and reductions in available capacity were associated with problems with natural-gas (58%) and wind (27%) generation units.[83] The Electric Reliability Council of Texas (ERCOT) was particularly devastated, losing up to 34,000 megawatts of capacity—almost half of its all-time peak load for the winter—from February 15–17.[83] As a result, more than 4.5 million people lost power, some for up to four days. Millions had to boil water for drinking and cooking, and many cities issued water conservation orders because of low water pressure.[81] In Houston, data indicate that non-White populations disproportionately experienced outages, regardless of their income level (Figure 26.8). Economic losses in Texas were estimated at $85.6–$139.1 billion (in 2022 dollars).[84]

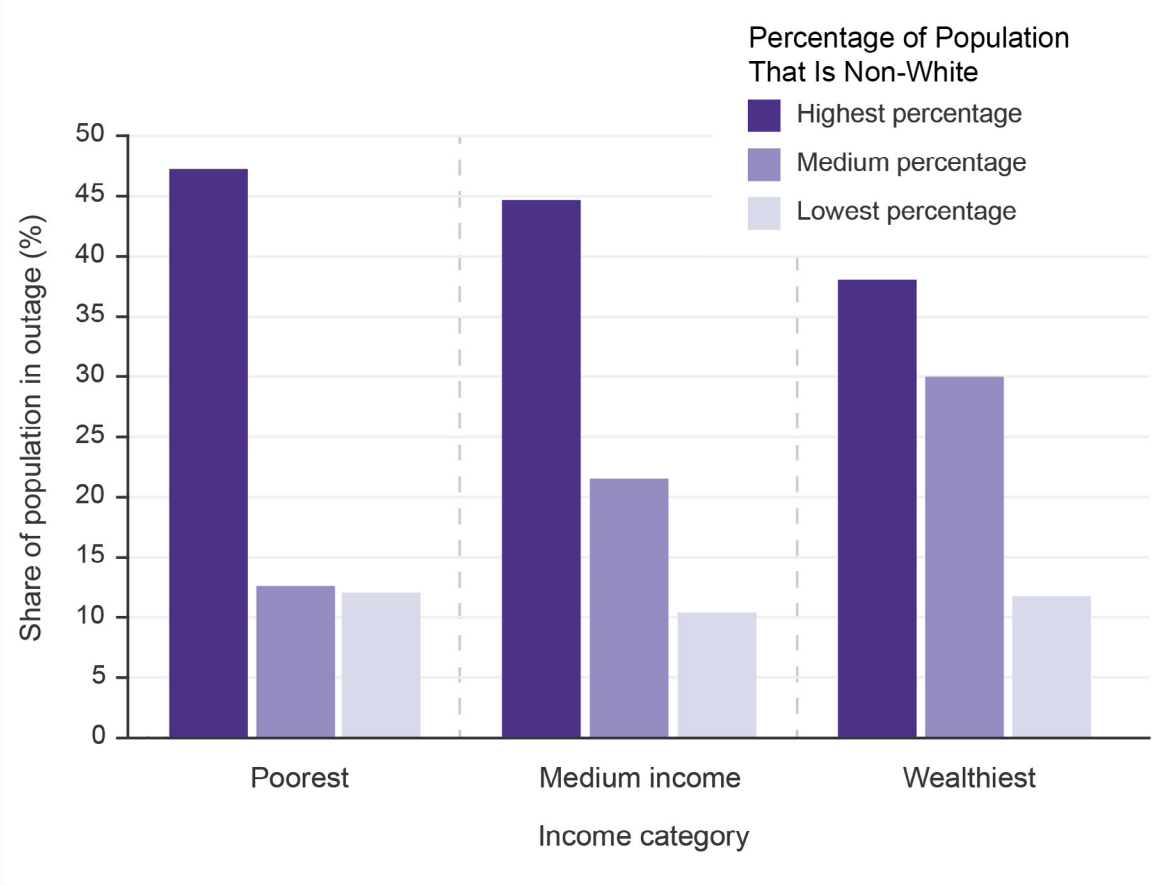
Power Generation Outages During the Cold Outbreak in February 2021



A severe cold outbreak in February 2021 led to extensive outages for electricity generation plants serving the Electric Reliability Council of Texas (ERCOT).

Figure 26.7. The map shows the maximum outage or power reduction (in megawatts, MW) by location and fuel type for electricity generation facilities serving ERCOT during February 10–24, 2021, amid the cold outbreak across portions of the south-central US. Circles are colored by fuel type; larger circles represent larger values of maximum outage or power reduction. One generation facility is in Oklahoma. Shaded counties denote the ERCOT service area. In Texas alone, loss of generation capacity caused more than 4.5 million customers to be without power at some time during the cold outbreak.[83] Figure credit: See figure metadata for contributors.

Income and Racial/Ethnic Disparities Related to Power Outages in Texas, February 2021



Regardless of income level, non-White populations experienced a disproportionate share of outages during the February 2021 cold outbreak.

Figure 26.8. This graph shows the percentage of the Texas population that experienced power outages during the February 2021 cold outbreak based on income level (poorest, medium income, and wealthiest) and race/ethnicity (lowest, medium, and highest percentage of non-White people in the population) by census block group. Non-White people are those individuals whose race was listed as other than White alone or who list their ethnicity as Hispanic or Latino. Regardless of wealth status, data indicate that areas with the highest populations of non-White people were the most likely to be impacted by power outages due to long-standing marginalization. Adapted with permission from Carvallo et al. 2021.[85]

The severe cold outbreak was not historically unprecedented, and widescale outages were avoidable.[78] To illustrate how good adaptation enhances resilience, the City of El Paso, Texas, had prepared for extreme cold following widespread energy and water disruptions in 2011. The city invested in winterization of power infrastructure and built a new power plant that could operate with different fuel types.[86] These adaptations, along with the city's connection to a different power grid, resulted in few outages during the 2021 event.

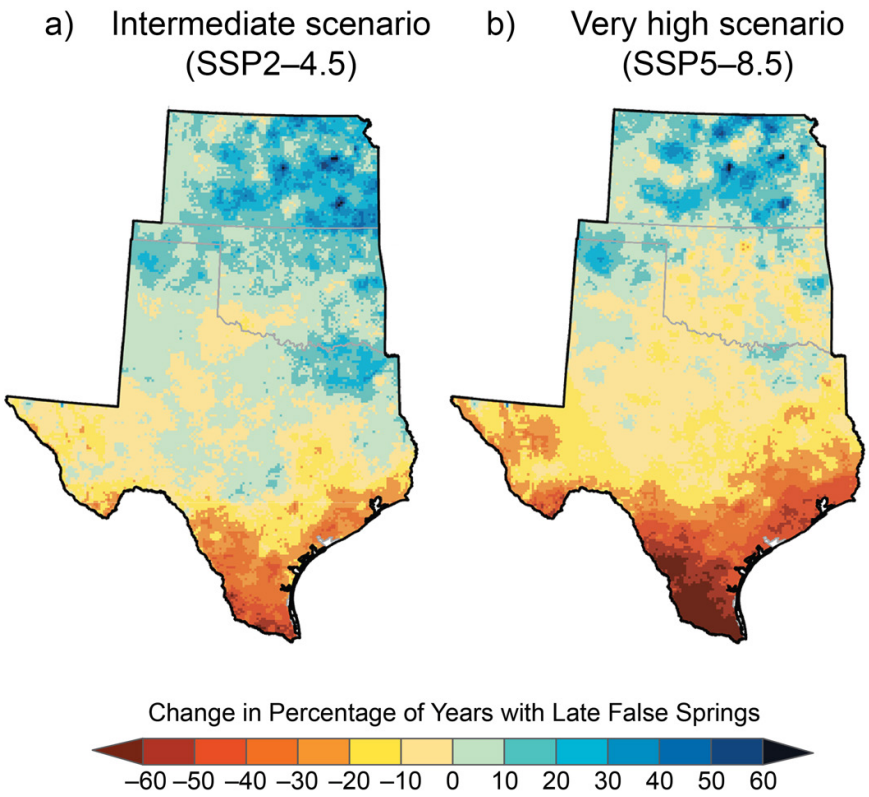
Although the effect of climate change on the jet stream's strength is an ongoing area of research[87] and extremely cold days are expected to decrease, projections indicate that the region will still experience extreme cold events in a warming world.[88] These events are expected to result in considerable costs if businesses are not adequately prepared.[78] In June 2021, the Texas legislature passed Senate Bill 3, which focused on improving emergency communication and gas infrastructure as well as other winter preparedness actions.[89] Grid operators also developed recommendations to improve energy reliability, grid operations, and communications for future winter weather events.[83]

Agriculture, including crop and livestock production and forestry, is an essential industry in the region. In 2022, Kansas led the Nation in grain sorghum production and ranked second nationally in all wheat production.[90] In 2023, Texas was first in head of cattle and calves, with Kansas and Oklahoma ranking third and fifth, respectively.[91] In 2017, the region's agricultural industry generated $60.5 billion (in 2022 dollars) in agricultural product sales, 70% of which was animal based.[92]

Agricultural producers are experiencing loss of livestock and crops, reduced income, and negative public health outcomes as climate extremes increase in magnitude and frequency (KMs 11.1, 11.2). Warmer average temperatures are leading to longer growing seasons, which affect different species differently and potentially disrupt the long-term natural connection between plants and their pollinators or between insects and their predators (KM 8.2).[93] Historical plant hardiness zones are predicted to continue migrating northward as the annual average minimum winter temperature warms (Figure 11.3). High temperatures have reduced plant growth and diminished productivity.[94] In western Kansas and the Oklahoma and Texas Panhandles, the combination of cold fronts and earlier springs is projected to increase the potential for bud burst before the last freeze (Figure 26.9),[95] threatening plant-leaf and wood-tissue damage.[96]

Compound events (Focus on Compound Events) that encompass hot, dry, and windy conditions have increased in southwest Kansas and the Panhandles of Oklahoma and Texas, reducing wheat yields proportionally to the number of hot-dry-windy hours.[97,98] Producers also are expected to experience drier conditions (Figure 26.10) and more frequent or intense drought by midcentury in western and southern parts of the region, lowering crop productivity or increasing irrigation costs.[99] By 2070 across a range of climate change scenarios (from low [RCP2.6] to very high [RCP8.5]), the Southern Great Plains is projected to lose cropland acreage, as these lands transition to pasture or grassland.[100]

Projected Change in Annual Risk of Late False-Spring Events



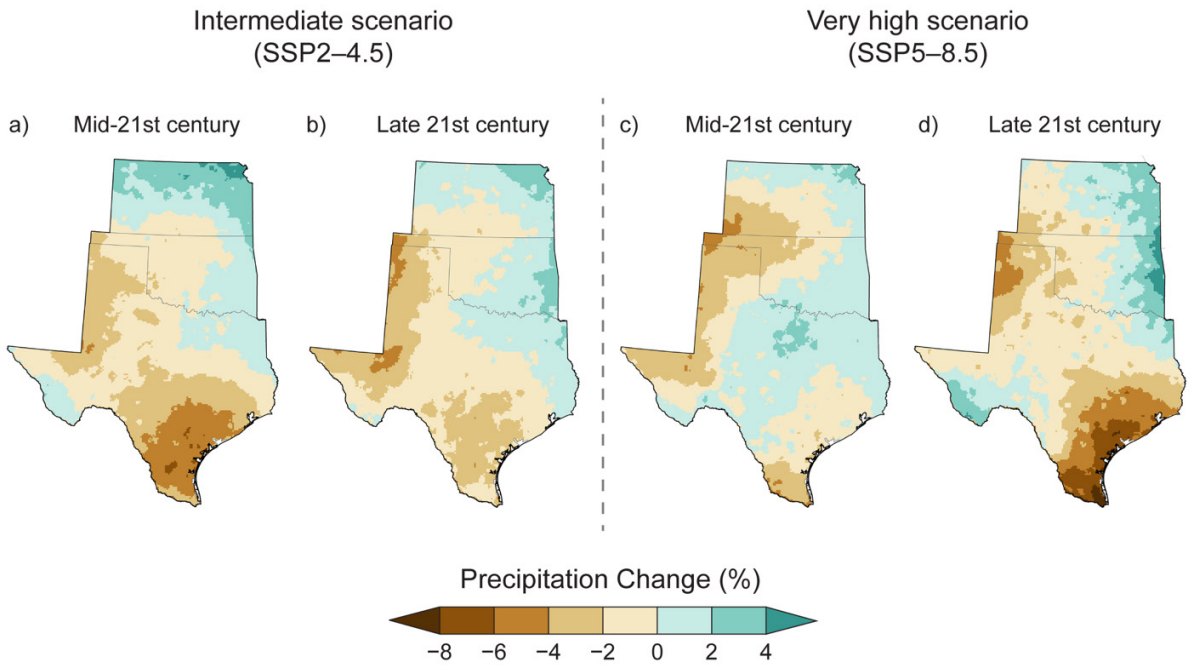
The risk of plant bud burst before the last freeze is projected to increase for the northern portion of the Southern Great Plains. The risk decreases for the southern portion of the region.

Figure 26.9. Freezing temperatures after plants begin growth in spring (late false spring) can damage crops and nursery plants. Risk of a late false spring is projected to increase in northern parts of the Southern Great Plains by the end of the century (2071–2100) as compared to the 1991–2020 average. The risk of late false springs increases by up to 20% across most of Kansas, Oklahoma, and northern Texas under an intermediate scenario (SSP2-4.5; panel **a**) and across most of Kansas, the Texas Panhandle, and parts of Oklahoma under a very high scenario (SSP5-8.5; panel **b**). Risk decreases for the remainder of the region, especially in southern and far western Texas under a very high scenario. Figure credit: See figure metadata for contributors.

Although increasing irrigation during drought can help maintain productivity, it reduces groundwater available for other ecological or societal needs and for future generations. Growers can produce similar yields using less water by adopting more efficient irrigation technologies and management practices.[101] Neighbors also can help neighbors. For example, irrigators in Sheridan and Thomas Counties (Kansas) self-imposed annual water restrictions that reduced water usage by 26%, with no reduction in crop acreage.[102]

Drought also has reduced the capacity of native rangelands and planted pastures to support livestock and has increased labor demands for feeding, forcing producers to sell genetically valuable animals. High temperatures also pose risks to animal health.[99] In June 2022, for example, thousands of cattle died in southwestern Kansas during a heatwave combined with high humidity and low wind speeds.[103,104] The additional stressors from climate change are anticipated to be especially difficult for multigenerational ranchers who strive to earn a profit while preserving the health of lands for their descendants.[105] For large-scale livestock production, successful adaptation to a changing climate includes enhancing soil health and reducing the number of animals per acre.[106]

Projected Change in Total Annual Precipitation



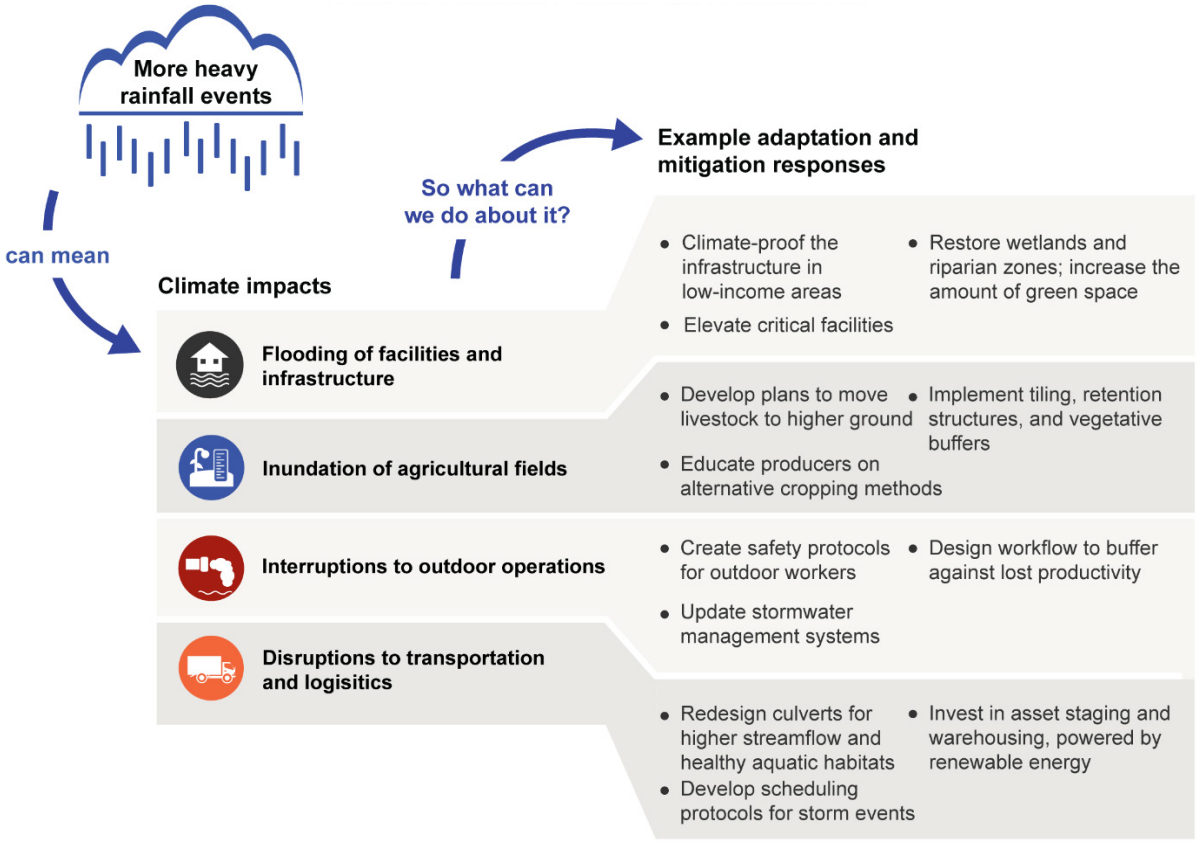
Slightly drier conditions are projected for much of the western and southern portions of the region by the end of the century.

Figure 26.10. In the future, drier conditions threaten agriculture and water supplies in parts of the Southern Great Plains (brown), while more precipitation is projected near the northern and eastern boundaries of the region (green). Under an intermediate scenario (SSP2-4.5), total annual precipitation is projected to decrease by 4% or more (as compared to the 1991–2020 average) in southern Texas by midcentury (**a**), with smaller differences expected by century's end (**b**). Under a very high scenario (SSP5-8.5), annual precipitation is projected to decline slightly in western portions of the region by midcentury (**c**) and by 4% or more in southeast and far northwest Texas by the century's end (**d**). Figure credit: See figure metadata for contributors.

More broadly, climate change–related damages to businesses have threatened the continuity of operations, increased insurance costs, disrupted supply chains, and shifted customer demand (KM 19.3). Many small businesses in the US do not have business disruption insurance, and 20%–40% of small businesses that temporarily close after a natural disaster do not reopen.[107] Small businesses owned by women, non-Whites, and veterans have a higher likelihood of closing after experiencing a natural disaster.[108] These closures have negatively affected the economy and well-being of local communities.[109]

Large and small businesses and industries have started efforts to mitigate greenhouse gas emissions. For example, in 2021 Amazon piloted an electric-vehicle fleet in Tulsa, Oklahoma, and in 2022 Frito-Lay did likewise in Carrollton, Texas. The need to reduce emissions on a worldwide scale presents economic opportunities for energy-related businesses in the region to pilot and develop new technologies. NRG Energy and JX Nippon, for example, partnered to create a commercial-scale carbon capture facility at NRG's coal-fired Petra Nova power plant in Thompsons, Texas.[110] It was the US's first and only facility to capture over one million tons of CO_2 per year. It suspended operations in 2020, however, because oil prices were too low to justify the expense of using the captured CO_2 for enhanced oil recovery.[111] Houston's Sage Geosystems is testing how to generate geothermal energy at commercial scale by repurposing an existing oil well in San Isidro, Texas,[112] and groups like Kansas Soil Health Alliance and Texas Coastal Exchange are supporting carbon storage through soil and land stewardship.[113,114] Mitigation and adaptation actions by businesses and industries promote resilience and offer long-term benefits to employers, employees, and the surrounding community (Figure 26.11).

Resilience Actions to Address the Impacts of Heavier Rainfall Events on Businesses



Resilience actions can help businesses and industries reduce the negative consequences of more heavy rainfall events.

Figure 26.11. An increased number of heavy rainfall events affects business and industry across the Southern Great Plains through flooding of facilities and infrastructure, inundation of agricultural fields, interruptions to outdoor operations, and disruptions to transportation and logistics. The example adaptation and mitigation actions can increase resilience and reduce negative impacts. Figure credit: See figure metadata for contributors.

Key Message 26.3

How We Play: Climate Extremes Are Endangering Sports, Recreation, and Leisure

Extreme climate-related events are negatively influencing how we play and participate in outdoor sport, recreation, and physical activities in the Southern Great Plains (*very high confidence*). Climate change is expected to increase heat-related illness and death, reduce outdoor physical activity, and decrease athletic performance (*very likely*, *high confidence*). Individuals, communities, and sports organizations can adapt to these hazards through strategies such as modifying the timing, location, intensity, or monitoring of activities (*high confidence*).

Sports, recreation, and leisure activities are part of life in the Southern Great Plains. Hunting, fishing, jogging, playing on the playground, and other activities help maintain participants' physical and mental

health. Organized sports, such as football, soccer, and softball, bring together spectators to cheer for their favorite athlete or team, encouraging social cohesion.[115] Climate extremes have affected many of these activities, diminishing their benefits (Figure 26.12). For example, sports fields across southeastern Texas were closed because of flooding after Hurricane Harvey in 2017.[116] Although superintendents of unaffected schools offered Harvey-displaced students the opportunity to play on their teams, these athletes were reluctant to forfeit their home-team eligibility, reducing their broader scholastic involvement.[117]

Athletes of all ages experience decreased performance, do less outdoor physical activity, and are at higher risk of severe to fatal health issues because of extreme heat, air pollution, and weather hazards.[118,119] These risks especially apply to older adults, those with chronic disease or higher body mass index, and those under prolonged environmental exposure (e.g., marathon runners) who conduct high-intensity sports or wear clothing or equipment that prevents heat loss.[120,121] Heat injuries can damage organs (e.g., liver, muscle, kidney) or disrupt the central nervous system.[122]

All dimensions of environmental injustice (i.e., recognitional, distributional, and procedural; Figure 20.1) intersect with climate change to disproportionately harm people who have been marginalized (KM 15.2), reducing their participation in and health benefits from outdoor physical activities. These people include low-income populations, those living in areas with higher levels of air pollution, and those with less access to places to engage in sports, recreation, and leisure.[123,124] Non-English-speaking recreationists are at increased risk because health communication about climate-related hazards (such as the dangers of swimming in a harmful algal bloom) likely is not presented in their native language.[125]

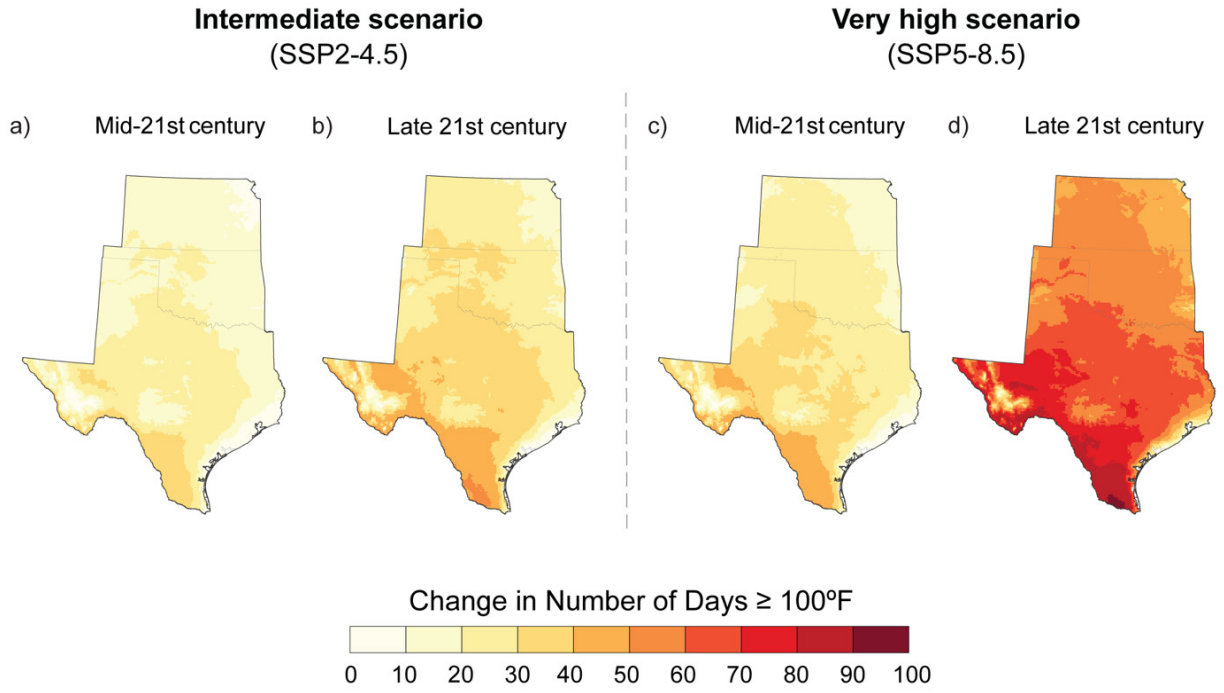
Climate Change Impacts on Outdoor Activities

Climate change is expected to affect many outdoor sports, recreational, and leisure activities.

Figure 26.12. Outdoor sports, recreational, and leisure activities for people of all ages are being affected by climate extremes. Heavy rainfall, poor air quality, and extreme heat are expected to increase with climate change. These stressors impair athletic performance, damage sports facilities, and alter landscapes for recreation and tourism. Figure credit: See figure metadata for contributors.

Nationally, heat-related illnesses are the third-highest cause of death among high school athletes[126] and are the most preventable cause of death in youth sports.[127] Heat-related deaths can occur outside of a typical heatwave. For players of organized football at any level, these types of death occurred most often in the south-central and southeastern United States.[128] These risks apply to any outdoor sport, especially those that involve training or competition during summer and fall. Future increases in the number of very hot days and warm nights are expected to exacerbate health concerns (Figure 26.13). For example, the number of 100-degree days is projected to increase by the end of the century under a very high scenario (SSP5-8.5) by 30–60 days in Kansas and Oklahoma and more than 80 days in parts of southwestern Texas (Figure 26.13c, d). By contrast, under an intermediate scenario (SSP2-4.5), the number of 100-degree days per year would remain close to the recent average (Figure 26.13a, b).

Projected Change in Annual Number of Days of 100°F or Higher



The number of extreme-heat days is projected to increase.

Figure 26.13. Outdoor physical activity becomes more dangerous in extremely hot temperatures. By midcentury, the number of days per year with temperatures at or above 100°F across the Southern Great Plains is projected to increase (**a**) by 10–40 days under an intermediate scenario (SSP2-4.5) and (**c**) by 10–60 days under a very high scenario (SSP5-8.5) above the 1991–2020 average. By late century, projections indicate that the number of these extreme-heat days would increase (**b**) by 10–60 days (SSP2-4.5) or (**d**) by 30–90 days (SSP5-8.5), depending on scenario. The historical average ranges from fewer than 10 days per year in Kansas to fewer than 20 days across most of Oklahoma and Texas, with 40–60 days along the Mexican border. Figure credit: See figure metadata for contributors.

Extreme temperatures have threatened the health of young athletes and their ability to practice and compete outdoors in sports like cross-country, track and field, tennis, golf, softball, soccer, and lacrosse.[129,130,131] In schoolyards or playgrounds, the time spent playing in warm or hot environments and the physical environment (e.g., shade, vegetation) have affected the perceived discomfort of youth while they are active outdoors.[132] Unhealthy heat stress is occurring even at ambient temperatures of 80°–85°F where play areas are unshaded and have artificial surfaces (e.g., asphalt or artificial turf).[133] Children from non-White and lower-income families have less access to high-quality, sizeable urban parks,[134] putting them at higher risk of heat illness and other adverse health outcomes (i.e., physical and mental health problems).[123]

Heavy rainfall and extreme temperatures cause sports teams to depend more on artificial or indoor environments, increasing participation costs and decreasing access to sports, especially for lower-income populations.[120] The Texas Rangers replaced their structurally sound stadium earlier than expected because extreme temperatures suppressed attendance.[135] The new stadium has a retractable roof for a climate-controlled environment. Sports events across all levels—from youth and interscholastic to collegiate and professional—have been halted or moved because of the unusual timing or intensity of storms (Figure 26.14, left), resulting in scheduling challenges, economic costs, and reduced social interactions.[136,137] All people who enjoy the outdoors as part of their healthy lifestyle are expected to face more days with dangerous extreme heat (Figure 26.14, right).

Extreme Event Impacts on Sports and Recreation

Outdoor sports and recreation of all kinds are challenged by extreme events.

Figure 26.14. (**left**) University of Oklahoma staff paint the Green Wave of Tulane University on their football field for a September 4, 2021, matchup. The game was relocated after Hurricane Ida left Tulane's stadium powerless and damaged. (**right**) As people enjoy the outdoors as part of a healthy lifestyle, warmer temperatures are expected to cause them to adapt by drinking cool liquids, reducing strenuous exercise, or exercising during cooler times of the day. Photo credits: (left) ©University of Oklahoma Athletics; (right) ©Emma Kuster.

Lakes, streams, and reservoirs support fishing, hunting, and other outdoor recreation; however, more variable or heavier rainfall, flash or prolonged droughts, and higher temperatures have jeopardized recreation by reducing the quality and quantity of water.[138] In 2019, for example, southeast Kansas and northeast Oklahoma experienced historic spring flooding after multiple storm systems brought almost 2 feet of rain.[139] The flooding caused more than $12.5 million (in 2022 dollars) in damages for the Kansas Department of Wildlife, Parks, and Tourism (Figure 26.15), primarily through lost revenues from park closures.[140] Texas State Parks amassed a $5.9 million (in 2022 dollars) funding deficit when drought, wildfires, and record heat prompted fewer visitors in 2011–2012.[141]

Flooding of Park in Kansas, Spring 2019

Historic spring flooding in 2019 closed parks and recreational areas in southeastern Kansas.

Figure 26.15. Sandstone Bluff Cabin along Toronto Lake in Cross Timbers State Park was flooded from spring 2019 storms, as the lake level exceeded prior historic records. The extreme rainfall closed parks and created an estimated $12.5 million (in 2022 dollars) in damages. Photo credit: ©Kansas Department of Wildlife and Parks.

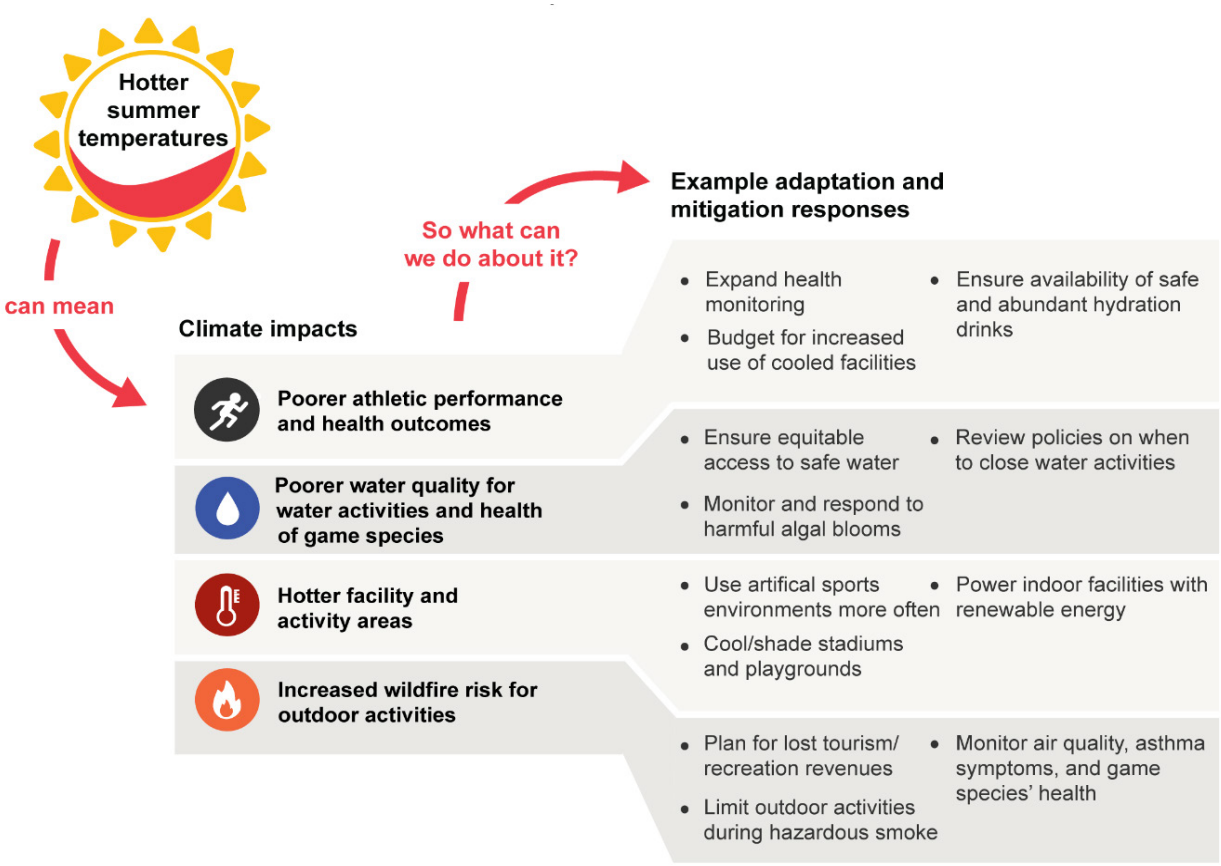
Along the Texas Coast, recreational opportunities are expected to change as coastal ecosystems transform, degrade, or disappear as a result of sea level rise (KM 9.1), warming temperatures,[142] and more powerful or rainier tropical cyclones.[143] After the destruction from Hurricane Harvey (2017), coastal ecotourism collapsed across the Coastal Bend, where ecotourism supports 8% of the local workforce and generates over a billion dollars in economic value annually.[144] Sea level rise has caused erosion of coastal beaches. Sand erosion on Galveston Island, for instance, has increased by 45% in comparison to geologic rates.[145] Sea level rise is also increasing saltwater inundation of coastal marshes that support birdwatching and angling.[146]

Changes in the timing and amount of precipitation have affected freshwater runoff and its associated salinity of bays and coastal ecosystems.[147] In the winter of 2008–2009 at the Aransas National Wildlife Refuge, a combination of inundation, drought, and upstream water use resulted in the loss of 10% of blue crabs, the main food source for the whooping cranes that draw legions of birdwatchers to the refuge.[148] Other impacts are favorable for coastal fisheries. Fewer extreme freeze events have caused the northward expansion of mangroves,[142] increasing fish diversity in Texas bays.[149] The diversity and prevalence of marine fish for sport fishing has also increased along Texas coasts as tropical fish expand their range northward.[150]

In 2020, hunting, shooting, and trapping generated $1.3 billion (in 2022 dollars) in Texas, ranking it first in the Nation.[151] Competition for limited food and water resources during drought is anticipated to alter animal migration, reproduction, and behavior (e.g., Cady et al. 2019;[152] Porro et al. 2020[153]). As a result, with warming temperatures, hunters are expected to see shifts in wildlife habitats and species ranges and decreases in the size and weight of prey.[154,155] For example, the Texas Parks and Wildlife Department has noted a decline in wintering mallard duck populations because open waters and food remain available farther north as winters warm.[156]

Sport, recreation, fish, and wildlife managers can plan for climate change by considering ways to alleviate negative impacts or enhance benefits (Figure 26.16). For example, to reduce health risks resulting from extreme heat, athletes can acclimatize to heat by slowly increasing the duration and intensity of exercise, scheduling strenuous outdoor activities during cooler hours, and reducing their core body temperature by applying ice packs and drinking cold water.[122] To maximize public outreach, communication of these risk-reduction methods should reflect the languages spoken throughout the community. Communities can support local sports, leisure, and recreation through landscape design by adding shaded green spaces as shelter from extreme heat. Park amenities, such as trees and splash pads, can also cool people on hot days. Despite the potential for temporary closures, siting parks and recreational areas along streambeds can reduce flood losses by buffering floodwaters in downstream developed areas.[157]

Resilience Actions to Address the Impacts of Hotter Summer Temperatures on Outdoor Activities



Resilience actions can alleviate the effects of hotter temperatures on outdoor activities.

Figure 26.16. Hotter temperatures affect athletic, recreational, and leisure activities outdoors across the Southern Great Plains, leading to poorer athletic performance and health outcomes, poorer water quality, hotter facilities and activity areas, and increased wildfire risk. The example adaptation and mitigation actions can increase resilience and reduce negative impacts. Figure credit: See figure metadata for contributors.

Key Message 26.4

How We Heal: Climate Change Is Exacerbating Existing Social and Environmental Disparities

Some neighborhoods and communities in the Southern Great Plains are suffering disproportionately from climate-related hazards because of long-standing marginalization, discrimination, and governmental policies (*very high confidence*). As a result, climate change will compound existing social and environmental burdens on the people, neighborhoods, and communities with the fewest resources to prepare and adapt (*very high confidence*). Our institutions and governments can play a role in improving outcomes for these people and places by adopting climate adaptation and hazard-mitigation practices and policies that prioritize social equity and justice, aim to reduce community risks, build resilience, and repair past injustices (*medium confidence*).

Climate change does not affect all people in the same ways; society's most under-resourced and overburdened face harsher experiences (KMs 15.2, 20.1)[158] and have less access to climate-resilient infrastructure and recovery support,[159,160] typically as a result of power imbalances or discriminatory policies and practices.[161,162] This unequal distribution of harms and benefits is climate injustice. Those most impacted by climate inequities and injustices include people with low incomes; rural residents; disabled persons; older adults; Black, Indigenous, and People of Color; those who identify as other than cis, straight men; immigrants; those living in *colonias* (Texas-border housing developments lacking basic infrastructure and services); and unhoused individuals (KM 15.2).

Governments and organizations trying to heal historical traumas, injustices, and disparities are expected to face increasing urgency for equitable solutions and resources, as exposure to climate change impacts is projected to increase by midcentury. Lack of resources, political power, and technical expertise inhibit effective planning for and implementation of climate mitigation and adaptation.[3,163] Without intervention, climate change is expected to continue limiting equitable access to resources, services, and economic opportunities.

In many cases, housing stocks that serve low-income communities and communities of color lack adequate weatherization, air-conditioning, structural resistance to high winds, or adequate tree canopy, shade, and green spaces to provide heat relief due to long-standing under-resourcing and marginalization.[164,165] Lack of access to reliable and affordable energy increases the vulnerability of low-income communities to intense heat events. Severely marginalized groups, such as unhoused, detained, or incarcerated people, have experienced considerable suffering during extreme heat events with little relief.[166,167] For example, Texas inmates and correctional officers have endured heat stress or heat mortality from lack of air-conditioning and proper ventilation.[168]

Low-income communities and communities of color often lack access to adequate and maintained flood infrastructure, which reduces resilience, limits recovery, and contributes to increased flood vulnerability.[169,170] In Houston and other Gulf Coast communities, for example, these populations often live in lower-quality housing in flood-prone areas, placing them at a higher risk than those living in surrounding areas.[171]

In addition, low-income residential areas and residents of color tend to be in closer proximity to petrochemical plants or chemical storage facilities than their higher-income or White counterparts,[172] putting them at higher risk of industrial accidents caused by extreme weather events that release toxins into the air

and water (KM 15.2).[173] For instance, facilities that reported chemical releases after Hurricane Harvey tended to be near predominantly Hispanic neighborhoods and revealed patterns of societal inequity.[174] Exposure is particularly acute near Superfund sites[175] and across industrial areas of the Texas Gulf Coast (Figure 26.17).[176]

After a disaster, many people who are poor, uninsured, and without access to climate recovery and adaptation programs, such as voluntary buyouts, have not rebuilt.[159,177] Efforts to recover from compounding hazards (Focus on Compound Events) can quickly exhaust resources and strain mental well-being in low-income populations (KM 15.1).[178]

Increased Climate Risks in Port Arthur, Texas

Historically underserved communities near chemical facilities face increased risks from weather hazards associated with climate change.

Figure 26.17. These scenes from Port Arthur, Texas, reveal (**top**) a low-lying landscape of petrochemical facilities and residential neighborhoods, representative of many communities along the Texas Gulf Coast. After Hurricane Harvey (2017) made landfall near Port Aransas, Texas, neighborhoods (**bottom left**) and transportation infrastructure and petrochemical facilities (**bottom right**) were flooded, exposing residents to contaminated waters spreading across the landscape. With climate change projected to intensify hurricanes and bring heavier rainfall, the risks to communities along the Gulf Coast are even higher when hazardous facilities, such as petrochemical plants, are nearby. Photo credits: (top) halbergman/iStock via Getty Images Plus; (bottom left) US Air National Guard Staff Sergeant Daniel J. Martinez; (bottom right) ©Alison A. Tarter.

Communities with insufficient capacity to evacuate prior to coastal storms are at greater risk from tropical cyclones, which are projected to be stronger by midcentury (KM 2.2). These communities also face increased likelihood of house abandonment as Gulf waters rise and rainfall becomes more intense.[160] After Hurricane Ike (2008), for example, over half of Galveston's public-housing apartments sustained damages, displacing

almost 600 households. Most of these apartments were demolished and not replaced, and displaced residents confronted barriers to participating in post-disaster decision-making.[179]

Settler colonialism and policies to eradicate Indigenous Peoples, cultures, and practices have contributed to current inequalities in climate mitigation and adaptation resources (KMs 15.2, 16.2, 20.2).[3] Through the Indian Removal Act and treaties with the United States,[180] Tribes became bound geographically to predetermined jurisdictions, often in areas now at higher risk of climate change impacts (KM 16.2) or more exposed to climate hazards than their historical lands.[181] Self-determination, sovereignty, and self-governance, however, empower Tribes in the region to lead their own climate adaptation planning, transforming themselves into thriving communities of their own design (Box 26.3). Indigenous Peoples have knowledges and experiences to share with all peoples about how to live sustainably and adapt to climate changes.[182]

Box 26.3. Adaptation Planning Led by the Tribes of Kansas, Nebraska, and Iowa

The Iowa Tribe of Kansas and Nebraska, Kickapoo Tribe in Kansas, Meskwaki Nation, Omaha Tribe of Nebraska, Ponca Tribe of Nebraska, Prairie Band Potawatomi Nation, Sac and Fox Nation of Missouri, Santee Sioux Nation, and Winnebago Tribe of Nebraska recognized the need to be #Rezilient (the social-media notation for Tribal resilience) in the face of climate change. Using grant funding obtained by the Sac and Fox Nation of Missouri, the Tribes worked to blend their cultural values, Indigenous Knowledges, and adaptation experience with Western science to create Tribal climate adaptation plans. They convened a series of workshops (Figure 26.18) to guide Tribal environmental professionals to customize plans for their unique communities. Beginning in 2019, Tribal elders, council members, environmental professionals, and subject-matter experts initiated Tribal Technical Teams to identify knowledge sources and prioritize risks.

Collaboration to Develop Tribal Climate Adaptation Plans

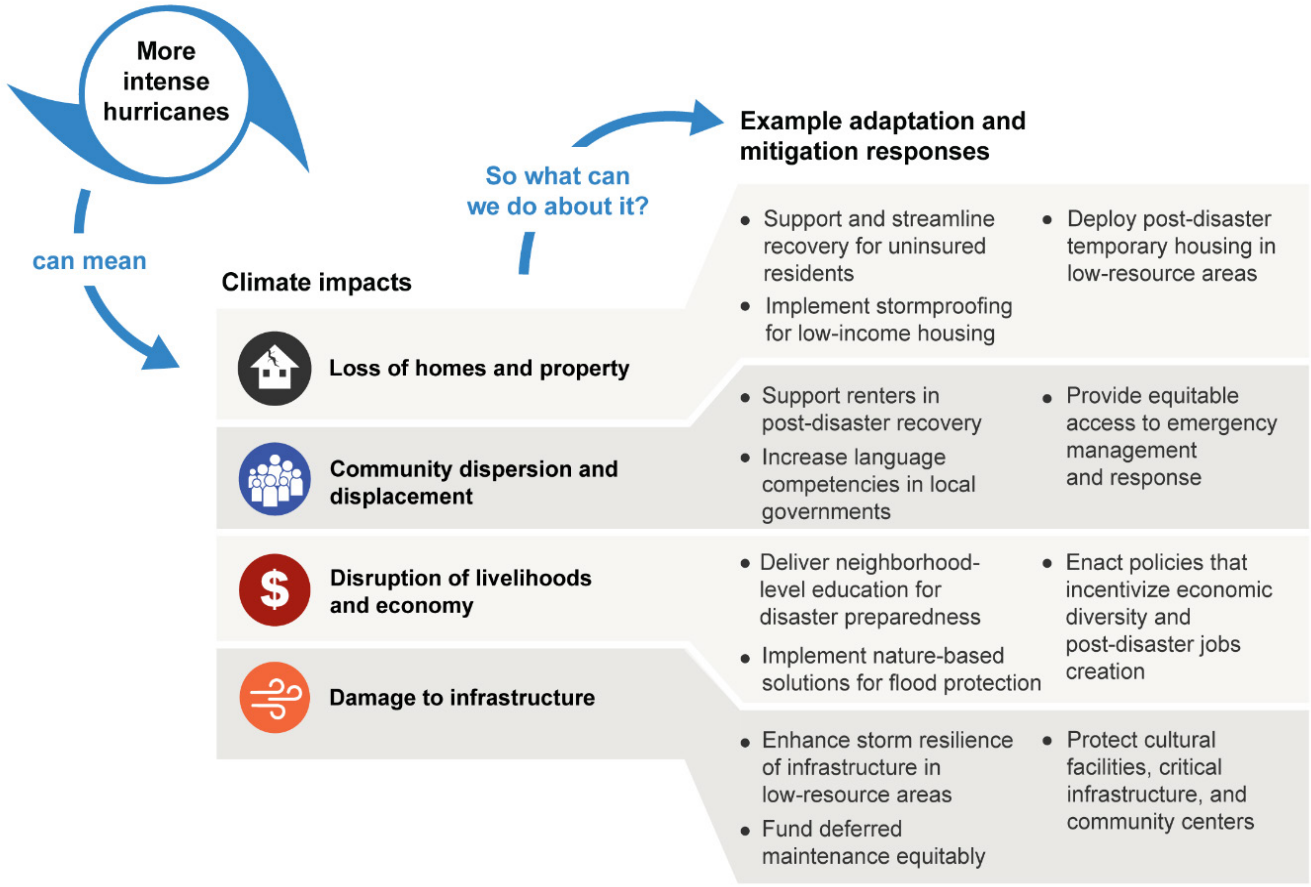
Nine Tribes of Kansas, Nebraska, and Iowa work together to create customized climate action plans for their individual communities.

Figure 26.18. (**top**) In 2022 Mayetta, Kansas, was the site of a climate resilience workshop for the nine Tribes of Kansas, Nebraska, and Iowa. (**bottom**) Technical teams worked together to create and present specific climate adaptation plans for each Tribe and to share their experiences with one another. Photo credit: ©Mark Junker.

Then the Tribes developed a drought early-warning system for each Tribe. The systems focused on more than 20 drought-related indicators, including precipitation, soil moisture, fire danger indices, and evapotranspiration. Next, the teams wrote summaries of their individual regions' climates in the Winnebago language. They discussed how to communicate local climate change impacts in relevant ways for the people on and near the reservations. The teams also met to create maps showing what areas were projected to be most at risk. By 2022, the groups were sharing how they collected data, analyzed trends, and researched impacts and solutions to climate change on their lands and peoples. The resulting nine climate adaptation plans will strengthen resilience of the Tribes of Kansas, Nebraska, and Iowa for years to come.

Residents, businesses, organizations, and governments in the Southern Great Plains can work together to repair prior societal damage and build community resilience by incorporating justice and equity principles in climate resilience strategies and actions (Figure 26.19).[183] For example, the Resilient El Paso strategy includes social stability, security, and justice among the 12 drivers in its resilience framework.[184] The strategy recognizes El Paso's unique attributes, including one-quarter of El Pasoans living in poverty, a large bilingual population, and its location in the largest binational metroplex in the Western Hemisphere. Development of the strategy involved 70,000 residents participating in 95 community engagement events, ensuring that a range of voices were at the table. These adaptation efforts are complicated, however, by historical trauma, which has diminished trust in government, and the marginalization of various populations (e.g., Norton-Smith et al. 2016[185]).

Resilience Actions to Address Equity and Justice Issues Related to Increasing Hurricane Risk



Resilience actions centered on justice and equity can help overburdened communities respond to increasing hurricane risks.

Figure 26.19. More intense hurricanes increase challenges for justice and equity actions across the Southern Great Plains, including loss of homes and property, community dispersion and displacement, disruption of livelihoods and economy, and damage to infrastructure. The example adaptation and mitigation actions can align justice and equity work with climate resilience. Figure credit: See figure metadata for contributors.

Key Message 26.5

How We Serve: Climate Change Is Straining Public Infrastructure and Services

The institutions that serve our communities have been challenged to respond and adapt to more frequent and intense weather events (*medium confidence*). Without significant adaptation, climate change is expected to strain water supplies, transportation infrastructure, and emergency services across the Southern Great Plains (*high confidence*). Actions that can enhance our community resilience include substantially reducing greenhouse gas emissions, installing or retrofitting climate-resilient infrastructure, educating students and the public on climate change, and cultivating the capacity of faith- and volunteer-based aid organizations to assist hazard planning, response, and recovery (*medium confidence*).

Communities throughout the Southern Great Plains rely on basic physical infrastructure and public services, from roads and water treatment facilities to healthcare and education. However, the efficiency, effectiveness, and equitable distribution of these fundamental services are being affected by climate change.[186] These services are not available equally across the region. For example, in 2018 along the Texas–Mexico border, only 77% of the Texas *colonia* population had wastewater service.[187] Although *colonia* residents may have access to an electrical connection, many households remain without energy services because of limited income.[188]

Public utilities depend on reliable, safe, and abundant surface water and groundwater. These sources are at risk from increasing air and water temperatures, more frequent and severe drought, more intense rainfall events, and changes in rainfall frequency and timing (Figure 4.2; KM 4.2).[189,190] For example, heavy rainfall events have caused higher concentrations of pollution[191] and more sedimentation in reservoirs.[192] Winter storms have led to the loss of water pressure and electricity at utility facilities (Box 26.2). The average annual number of boil-water notices and sanitary-sewer overflows across Texas increased substantially between 2011 and 2016, mostly because of infrastructure damage following extreme drought that caused clay-soil contraction.[193]

Along the Texas coast, massive water withdrawals from coastal aquifers currently cause most of local sea level rise.[194] Precipitation carrying salt spray remains the major source of brackish waters in the Gulf Coast aquifer, as rising seas have yet to cause significant saltwater intrusion.[195] However, rates of average sea level rise from global warming have accelerated since 1992,[196] and western Gulf Coast sea levels are projected to rise 19–27 inches by 2050 using the full range (low to high) of global mean sea level rise scenarios.[197] The resulting saltwater intrusion is expected to pose challenges for drinking-water suppliers, as costs for desalinating seawater are twice those for brackish groundwater.[195]

The region's transportation systems, including its major airport hubs, ports, and highways, are critical for international and domestic commerce. Transportation infrastructure—much of which is aging and in significant need of repair—has been damaged by extreme weather events associated with climate change (KM 13.1).[198] Extreme heat has reduced passenger and cargo loads for aircraft and buckled roadways and railways; heavy rainfall has eroded road, bridge, and rail foundations (Figure 26.20); and coastal storms have interrupted shipping and caused mass evacuations on roadways. When transportation systems fail, the impacts have been particularly devastating for people living in systematically underserved and under-resourced neighborhoods.[171] As of 2022, Oklahoma's and Texas's state transportation plans do not address threats to transportation services or infrastructure from climate change impacts;[199,200] Kansas's plan does include threats to infrastructure from extreme weather.[201]

Extreme Rainfall Impacts on Transportation

Heavy downpours associated with Hurricane Harvey (2017) caused bridge damage.

Figure 26.20. Extreme events associated with climate change are expected to threaten transportation infrastructure, as demonstrated by past experiences. Here, widespread heavy rains associated with Hurricane Harvey (2017) caused the collapse of a section of Farm to Market Road 762 in Fort Bend County, Texas. Photo credit: Kevin Stillman, Texas Department of Transportation.

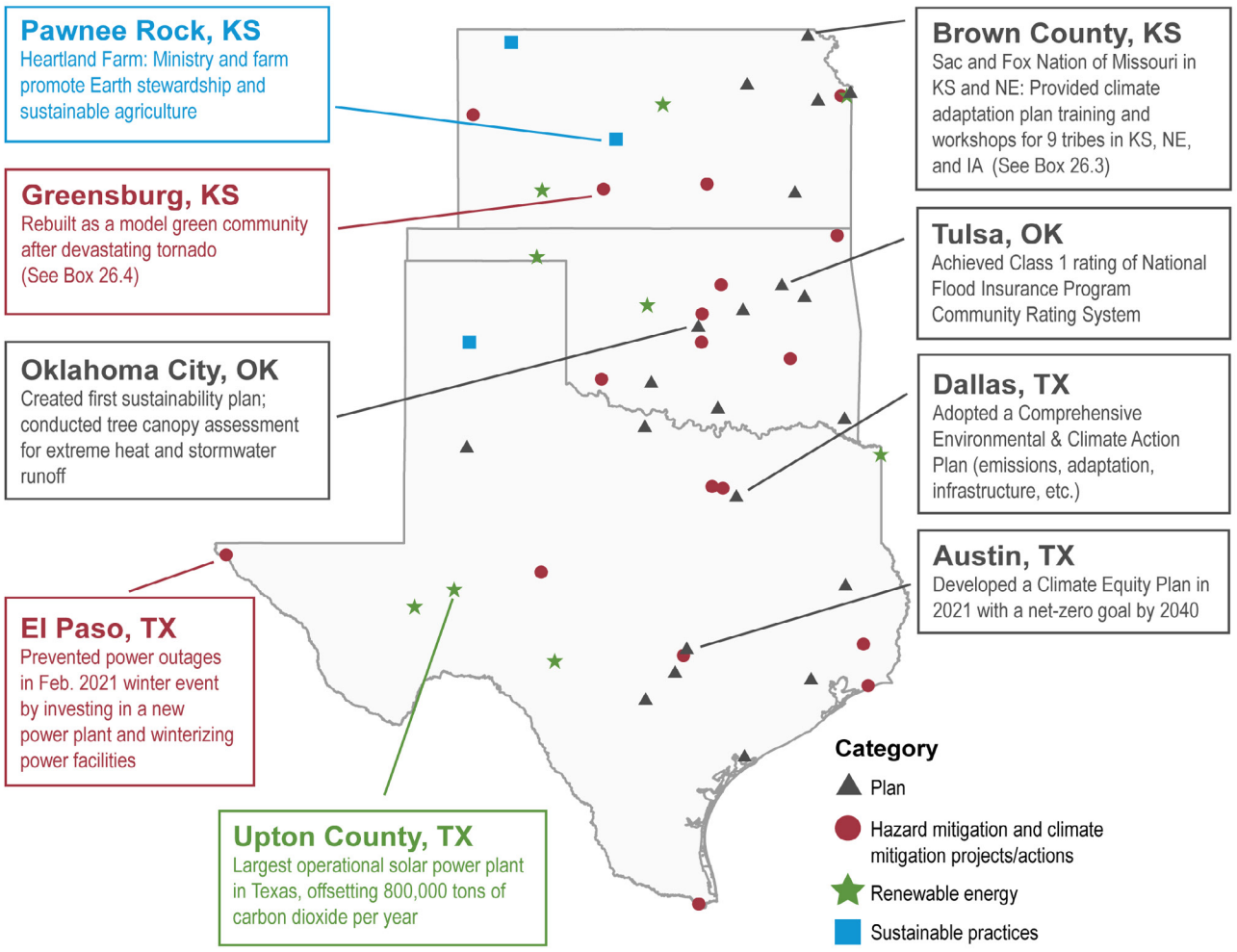
Climate change is also affecting public safety systems and their ability to serve community members. For example, during extreme heat events in 2018, the San Antonio Fire Department received significantly more requests for emergency medical services from neighborhoods with higher rankings on social vulnerability indices.[202] From 2000 to 2018, firefighters in the Southern Great Plains fought 16 megafires—fires that encompass over 100,000 acres, overwhelm local response capacity, and are extinguished only when weather conditions become favorable.[203] These fires are associated with extremely dry vegetation,[204] unusually warm temperatures, and strong winds aloft[203]—conditions projected to become more prevalent as the region warms and soil water evaporates more quickly.

In addition to providing resources for infrastructure, utilities, and public safety, local communities support public education systems. These systems serve learners of all ages and support scientific literacy and social cohesion while serving meals and providing other community services—key steps in enabling public engagement solutions.[205] As of 2022, only Kansas clearly incorporates human-caused climate change in its K–12 state curriculum standards.[206,207,208] Educators rarely receive formal education on the subject, leading many K–12 science teachers to have misconceptions and critical gaps in climate change knowledge. In a survey of teachers and education students in Dallas–Fort Worth,[209] for example, most educators were neutral regarding whether climate scientists disagree about the causes of global warming, even though 97% of these scientists agree (KM 2.1).[210] Informal education programs fill some climate change literacy gaps left by public education through short courses online (e.g., Martin et al. 2020[211]) and Tribal youth education programs.[3] Educators can apply successful strategies for teaching the complexities of climate change by actively engaging learners[212] and infusing lessons with place-based knowledge.[213]

Environmental monitoring and associated data quality assurance and sharing are important to track changes in climate over time, support evidence-based decisions, and warn people of imminent danger. High-resolution, regional weather and water monitoring networks[214,215,216,217] supply critical local measurements for decision-makers. However, understanding local impacts of climate extremes and how to adapt is hampered by a lack of systematic, region-wide observations of species, habitats, economic costs and damages, resource demand and consumption, decision processes, and adaptation and mitigation strategies.[218,219,220,221] Such data would help researchers better understand complex systems and managers develop better local management strategies.

Even without these regional data, cities across the Southern Great Plains are addressing risks to public services through hazard mitigation work and climate adaptation and mitigation actions (Figure 26.21; KM 12.3). Greenburg, Kansas, for example, chose environmentally resilient designs for rebuilding after it was hit by a violent tornado on May 4, 2007 (Box 26.4). In 2020, Oklahoma City produced its first sustainability plan, known as adaptokc, which addressed climate change.[222] Austin, San Antonio, and Dallas also adopted plans that included both mitigation and adaptation actions and have started to address local equity issues as related to climate change impacts (Climate Resilience Action Plan;[223] Climate Ready, Action and Adaptation Plan;[224] and Comprehensive Environmental and Climate Action Plan[225]). Smaller communities that lack resources for stand-alone climate plans are integrating actions into hazard mitigation or comprehensive plans. Results of city actions are becoming evident. For example, in response to frequent flooding that occurred prior to the 1990s, Tulsa enacted flood management actions that resulted in the National Flood Insurance Program awarding Tulsa its highest rating under the Community Rating System, reducing flood insurance premiums by 45%.[226]

Mitigation and Adaptation Actions Across the Southern Great Plains



A wide array of actions are being conducted across the region to address the impacts of climate change.

Figure 26.21. Communities and Tribes across the Southern Great Plains are acting in response to the challenges associated with climate variability and change. Actions include developing plans for hazard mitigation, climate action, and climate resilience (black triangles) or undertaking activities related to hazard mitigation (e.g., building resilient infrastructure) and climate mitigation (e.g., reducing energy usage; red circles). Renewable energy projects (green stars) and agricultural or environmental practices that support sustainability (blue squares) are also beginning. For actions under multiple categories, the main category was mapped. These actions aim to increase community resilience to hazards now and in the future. The mapped examples are representative of others occurring elsewhere across the region. See details at https://arcg.is/0yGjKm. Figure credit: See figure metadata for contributors.

The water policies of the three states encourage consumptive use, generally exclude the physical interactions between groundwater and surface waters, and are overseen by multiple agencies across different levels of government. These constraints make water resource solutions difficult in a rapidly changing climate. Nonetheless, Kansas's 2022 statewide water plan includes climate change, its impacts, and associated recommendations, providing a scientifically credible guide for adaptation and mitigation options.[227] The 2012 Oklahoma Comprehensive Water Plan went further by incorporating quantitative climate projections to assess future streamflow, municipal and industrial demand, crop irrigation demand, and water storage.[228] The resulting information was applied in the plan's recommendations. For Texas,

however, the 2022 State Water Plan did not consider climate change.[229] Researchers have spotlighted this crucial omission in Texas's water planning process, especially its lack of planning for droughts worse than the previous record drought.[190]

Communities are beginning to welcome nature-based or green infrastructure solutions for water resource challenges. The City of Austin has implemented water catchment systems, bioswales, and other green infrastructure at libraries, schools, and other city properties to reduce stormwater flows.[230] In Norman, Oklahoma, the Division of Utilities is testing how to augment water supplies during drought by returning highly treated water from its water reclamation facility to a nearby reservoir (Figure 26.22).[231] Cities of all sizes, from Houston (see Box 26.1) to Lenexa, Kansas (population under 50,000),[232] are adopting green infrastructure programs.[233]

Water Treatment Plant in Norman, Oklahoma

Wastewater treatment services in the region are addressing water resource challenges.

Figure 26.22. The City of Norman's wastewater treatment facility is testing how to supplement water during drought by returning highly treated water from its water reclamation facility to its nearby reservoir. Water reuse is a well-established adaptation method that is especially useful in semiarid climates. Photo credit: ©City of Norman, Oklahoma.

Faith-based organizations also are responding to climate impacts by raising charitable donations, serving as communication and distribution centers, and recruiting volunteers to assist with both physical and emotional disaster recovery.[234] After Hurricane Harvey (2017), for example, faith communities provided over $242 million (in 2022 dollars) to help flood victims.[235] Interfaith and ecumenical organizations, denominational bodies, local worshipping communities, and individual believers are teaching about climate change and environmental stewardship with their sacred texts or oral traditions[236] and leading environmental actions such as recycling and tree planting.[237] Sharing spiritual beliefs within a local community is an important way to increase social capital for climate adaptation.[238]

Box 26.4. Building a Sustainable City: Greensburg, Kansas

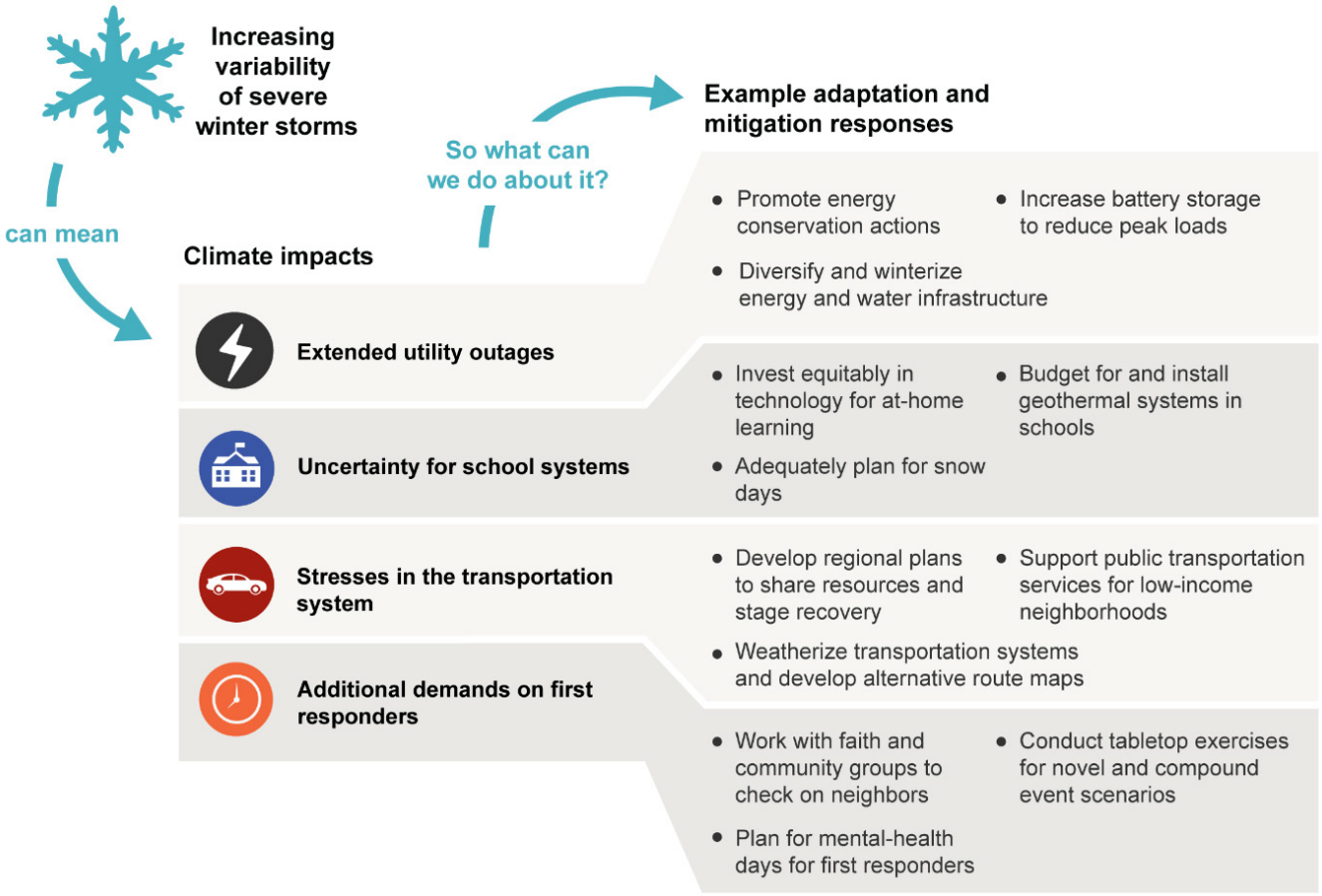
After 90% of the structures in Greensburg, Kansas (population: 1,400), were destroyed by a 2007 tornado, the town's residents rebuilt with an emphasis on resilience and sustainability—elements important to climate change adaptation. The community planned to "green Greensburg" following four visioning meetings that averaged 400 participants each.[239] The resulting 2008 Sustainable Comprehensive Plan reflected their discussions through a focus on children and future generations, a strong community and sustainable economy, and living off and with the land.[240]

Rescoping and rebuilding the city required support from federal, state, university, private, and nonprofit organizations, as well as community groups and individual leaders.[241] The city council provided backing through a resolution requiring that city-owned buildings of 4,000 square feet or larger adhere to "platinum" building standards of the Leadership in Energy and Environmental Design program.[239] This decision led to the creation of a platinum-certified city hall, county school, public hospital, county commons, arts center, and business incubator.[242] Energy-efficient lighting along Main Street reduced energy and maintenance costs; a 10-turbine wind farm generated enough power for 4,000 homes; and native plants, green roofs, and bio-retention areas reduced stormwater runoff.[243] Attracting sustainable businesses to the remote city, however, remains challenging.[241]

During the transformation process, residents' attitudes have changed about sustainability. Many who were initially reluctant found that environmental stewardship was consistent with their values and made common sense, leading them to adopt sustainable practices and technologies for their own homes and landscapes.[243]

Overall, actions in the region have been too slow in pace, and investments have been inadequate in scale and scope, compared to what would be needed[244] to minimize strongly negative consequences of climate change by midcentury (KM 32.1), within the lifetimes of today's young adults. For mitigation, calculations indicate that CO_2 emissions would have to decline by about 25% from 2010 levels by 2030 and reach net zero around 2070.[244] While Kansas and Oklahoma reduced carbon emissions 14%–17% between 2010 and 2019, Texas increased emissions by 11%.[245] Transformative adaptation (KM 31.3) and climate equity and justice (KMs 20.1, 20.3) provide holistic frameworks for climate adaptation actions. Many actions that enhance the resilience of public services and infrastructure (Figure 26.23) also are expected to reduce future financial costs from extreme events.

Resilience Actions to Address the Impacts of Severe Winter Storms on Public Services



Resilience actions can reduce risks to public services caused by increasingly variable severe winter storms.

Figure 26.23. The increasing variability of severe winter storms causes uncertainty and increases risk in public services and infrastructure across the Southern Great Plains, including extended utility outages, uncertainty for school systems, stresses in the transportation system, and additional demands on first responders. The example adaptation and mitigation actions can increase resilience and reduce negative impacts. Figure credit: See figure metadata for contributors.

Traceable Accounts

Process Description

The author team for the Southern Great Plains chapter was selected using a standardized rubric on candidate biographies acquired from nominations and an internet search. Rubric elements were 1) subject-matter expertise relevant to the Southern Great Plains; 2) diversity in discipline or type of experience to ensure breadth in chapter content; 3) role that reduced the risk of chapter structural problems, including breadth of perspectives (e.g., gender, ethnicity, race, organization type, career stage, and geographical location); and 4) experience engaging with partners across the region (e.g., government agencies, nongovernmental organizations, practitioners, academics, churches, businesses). Candidate authors were screened by their willingness and ability to work on a team, write well, and commit the necessary time. A few original authors left the team during the Zero Order and First Order Draft stages (either to transfer to another chapter or to address changes in their jobs) and were not replaced.

The author team met virtually for an hour at least biweekly during writing periods to discuss assignments, answer questions, prepare for stakeholder workshops, discuss figures, and reach consensus on topics and written text. The coordinating lead author, chapter lead author, and point of contact met virtually, typically weekly during writing periods, to review due dates, answer questions, and ensure that the team was progressing adequately.

Chapter authors developed initial chapter themes by brainstorming a list of values and interests demonstrated by people living and working across the diverse landscapes of the region. Impact-based statements focused on these values and were clustered by common attributes to reduce redundancy.

Consensus-building occurred through deliberations and by addressing questions during author meetings and through discussions using the comments feature in the shared online draft of the chapter. The lead author checked regularly with the author team for concurrence on any statements drafted by one or more team members. Disagreements on priorities or wording were discussed openly. Confidence was determined through initial, independent assessments of several author team members and finalized after oral discussion during a virtual meeting of the full author team. Concerns were debated until no one disagreed with the stated confidence level. All members of the author team approved of the document for each draft through the Fourth Order Draft. The lead author finalized the Fifth Order Draft, with minimal changes from the Fourth Order Draft, to respond to three minor reviewer comments, suggest copy edits, add missing citations, and address inconsistent figure captions.

The author team chose to hold four 90-minute online stakeholder workshops over two days to provide opportunities for people with different work schedules to participate. Workshops were held at various times of day, including during the noon lunch hour (Central Time) and at 5:30 p.m. for those unable to join during the normal workday. Each workshop began with a 30-minute overview of the full National Climate Assessment (NCA) process and the specific chapter content, followed by six concurrent one-hour breakout sessions—one for each of the five sections of the chapter and one additional session open for any discussion. The author team facilitated the breakout sessions using specific questions to engage participants and obtained feedback through interactive presentations and discussion.

Input from the stakeholder meetings, agency reviews, and internal reviews by the Technical Support Unit (TSU) were addressed through the consensus-building process noted above. The author team discussed content of newly developed graphics during regular meetings and iterated on design with the TSU. Metadata for all graphics and images were collected and documented by the chapter lead author and approved by the TSU. Technical contributors provided specific expertise in the following ways: 1) to alert the author team of local examples of impacts of, adaptation to, or mitigation of climate change; 2) to suggest peer-reviewed

literature in areas where the author team had a disciplinary gap; or 3) to aid in the description of an author-selected figure. Climate projections were available only to 2100; as a result, the author team was not able to assess the impacts of climate change out 100 years, as required by the Global Change Research Act of 1990.[246]

Key Message 26.1

How We Live: Climate Change Is Degrading Lands, Waters, Culture, and Health

Description of Evidence Base

Several topics have an extensive research base both nationwide and within the Southern Great Plains. For these, the author team selected citations that were most relevant for the region. Physical impacts, such as species range shifts, changes in water quality, and stormwater runoff, have sufficient evidence within the region to make well-documented statements (e.g., Howell et al. 2019;[23] Bragg et al. 2003;[24] Moore et al. 2016;[25] Will et al. 2013;[26] Whyte et al. 2021[31]). Literature on human health and climate change was relatively abundant (e.g., Anderegg et al. 2021;[49] Levetin 2021;[50] Neumann et al. 2019;[51] Johnson et al. 2016;[52] Mallen et al. 2019;[53] Bell et al. 2018;[54] Caminade et al. 2019;[56] Raghavan et al. 2021;[57] Hotez 2018;[58] Gorris et al. 2019[59]). The body of literature in climatic regions similar to the Southern Great Plains also supports the statements (e.g., Chs. 6, 8). Studies of human and societal impacts, such as climate impacts to culture, or the intersection of climate and other ecological or human drivers of the system, such as woody encroachment or racial disparities, were more difficult to find. In these cases, the members of the author team used their expert judgment to develop the section text.

Studies for Houston, Dallas, and Austin, Texas, were relatively abundant, as was research on impacts of climate change on both natural ecosystems and agroecosystems in Texas. Research for the case study on Houston was abundant and consistent, although the diversity of peoples and environments across the metropolitan area was extremely broad and had to be condensed in a manner that did not capture the city's nuances to the degree that the authors preferred.

Major Uncertainties and Research Gaps

Major gaps included lack of research on 1) a wide variety of communities (i.e., the same handful of cities are well documented and others are not), 2) human impacts outside of human morbidity and mortality (e.g., what traditions or cultural practices are changing because of climate change), 3) attribution of climate change to impacts that were driven by multiple stressors (e.g., urban flooding caused by heavier rainfall, changes in land use, and water management practices), and 4) long-term signals of climate change along the Gulf Coast and in Gulf waters (i.e., insufficient observational data over time and space).

There are major uncertainties in individual, family, neighborhood, and community responses to different climate-related impacts, such as higher temperatures, heavier rainfall events, or more intense hurricanes. Adaptation methods are not commonly measured throughout the region, so the circumstances under which different adaptation strategies are most beneficial are highly uncertain (KMs 31.1, 31.3). Although specific Tribes are knowledgeable about climate-related impacts to their relatives and culture, many understandably choose to protect their intellectual property as sovereign nations; thus, some impacts to Tribes are uncertain.

Documentation of impacts and actions for Kansas and Oklahoma was substantially limited in comparison to inland Texas. In fact, peer-reviewed literature focused on or inclusive of Kansas was limited outside of the Kansas City metropolitan area. Literature on changes in waters along the Texas Gulf Coast as related to climate change was sparse, and data sampling was insufficient in space and time to determine long-term

trends in red tide harmful algal blooms, mass mortalities of aquatic organisms (e.g., from cold outbreaks), or freshwater discharge.

Description of Confidence and Likelihood

For the first statement in the Key Message, the author team had *very high confidence* in risks associated with degradation of lands, waters, and health. However, a lack of data for privately owned areas within the region, notably in Texas, where 93% of land is privately owned,[247] limits the authors' confidence slightly for these areas. The author team had lower confidence in risks associated with quality of life, well-being, and cultural interconnectedness. As a result, the team lowered the confidence level from *very high* to *high*. Confidence in future projections of temperature-related hazards (e.g., extreme heat days) is *very high*; however, confidence is substantially lower (i.e., *medium*) for precipitation-related hazards because projections are mixed on the trends, depending on location. As a result, the team lowered the confidence level from *very high* to *high*. In the third sentence, the author team agreed that all actions were viable and well documented in the literature as resilience activities, but the effectiveness of the actions has not been vetted thoroughly, leading to an assessment of *medium confidence*.

The evidence base was not sufficient to determine quantitative probabilities for the first and third statements in this Key Message; thus, no likelihood is specified. For the second statement, there is sufficient evidence from multiple sources of climate projections across the region to indicate that it is *very likely* that weather hazards will increase (in size, number, or intensity). There also is sufficient evidence in the literature to indicate that these types of changes generally result in negative consequences for human lives, because most US families, neighborhoods, and communities are equipped to handle average climate conditions, but they struggle to be resilient during extremes.

Key Message 26.2

How We Work: Climate Changes Are Creating Economic Challenges and Opportunities

Description of Evidence Base

Impacts of, and mitigations and adaptations for, climate change in the energy and agriculture industries have an extensive research base both nationwide and within the Southern Great Plains (e.g., see Chs. 5, 11; Challinor et al. 2014;[94] Miller et al. 2021;[248] Rojas-Downing et al. 2017;[249] Shoeib et al. 2021;[76] Wimhurst and Greene 2019[77]). For these topics, the author team selected citations that were most relevant for the region. Robust literature was not available for many other businesses and industries across the region. In these cases, the author team selected examples specifically from the region. Research that focused on other regions of the country, even if robust, was not used because the context for resources, culture, and values of the Southern Great Plains differs from other regions of the United States. Thus, the author team chose to respect the place-based nature of impacts and solutions.

Literature on the February 2021 winter storm and its impacts has grown rapidly, and the author team assessed sufficient documentation to discuss the event (e.g., Bolinger et al. 2022;[78] Busby et al. 2021;[86] Doss-Gollin et al. 2021;[250] FERC 2021;[83] Ghosh et al. 2021[84]). Figure 26.8 applied the first, third, and fifth quintiles of the data for both income level (poorest, medium income, wealthiest) and race (low, medium, and high non-White) to demonstrate inequities related to the percentage of power outages during the event.[46] Employment statistics for the fossil fuel industry were calculated for September 2022 using the following categories from the North American Industry Classification System: 211, 2121, 213112, 213113, 22112, 2212, and 3241.[73]

The literature on topics such as geothermal energy production and carbon capture and storage has grown in academic and federal government publications; however, commercial-scale implementation of these technologies was considered of more interest to the chapter audience even though the literature was scarce.

Major Uncertainties and Research Gaps

In addition to government services (KM 26.5), energy, and agriculture, major economic sectors in the region that may be affected by climate change include manufacturing, retail services, construction, hospitality, real estate, insurance, wholesale trade, and social assistance. Little to no peer-reviewed literature was found related to impacts, adaptation, or mitigation for these sectors.

As in other sections, literature was substantially sparser for Kansas and Oklahoma than for Texas. Most of the literature on climate-change impacts and actions related to business and industry, except for agriculture, was focused on major metropolitan areas; thus, rural areas were less studied. The literature on climate impacts to women- or minority-owned businesses or small businesses in the region was minimal. Research was limited on adaptation and mitigation actions in the region, including the evaluation of their effectiveness.

Peer-reviewed literature on the impacts of the February 2021 winter storm was limited except for the storm's impact on energy generation, transmission, and distribution. News articles discussed a wide range of other impacts, from transportation and the economy to recreation and mental health, but few studies analyzing non-energy impacts were available in the literature at the time of writing.

Description of Confidence and Likelihood

In the first statement for the Key Message, the author team determined that the literature was limited regarding how business and industry experience new employment opportunities as climate conditions change across the Southern Great Plains. Thus, the author team lowered the confidence level from *very high* (i.e., the level that would be assigned to the US as a whole) to *high* (for the Southern Great Plains region). For the second statement, confidence was assessed as *high* based on substantial evidence from available climate projections but less evidence for costs to businesses and industry. For the third statement, the literature was thin with respect to how actions by business and industry result in positive economic outcomes; hence, the team concluded that *medium confidence* was most appropriate.

The evidence base was not sufficient to determine quantitative probabilities for the first and third statements in this Key Message; thus, no likelihood is specified. For the second statement, there is sufficient evidence from multiple sources of climate projections to indicate that it is *very likely* that warmer temperatures, more erratic precipitation, and sea level rise will occur across the region in the future. These types of changes are linked to costs and losses in business and industry.

Key Message 26.3

How We Play: Climate Extremes Are Endangering Sports, Recreation, and Leisure

Description of Evidence Base

The author team considered the topic of climate change and sports (i.e., sports ecology) to be an emerging area that will be of great interest to readers in the Southern Great Plains. Discussion about climate change and organized sport, from youth to professional, has been limited in prior NCAs. Yet the literature on how

climate affects health outcomes in sports and other physical activities has been growing (e.g., Bernard et al. 2021;[120] Bergeron et al. 2011;[130] Yeargin et al. 2017;[127] Vanos et al. 2017;[132] Orr et al. 2022;[118] Thomas et al. 2013;[141] Brocherie et al. 2015[122]). The lack of access to parks is a major theme in environmental justice and public health literature (e.g., Heynen et al. 2006;[251] Sister et al. 2010;[252] Rigolon 2016;[134] Mullenbach and Wilhelm Stanis 2022[253]). Negative impacts of climate change on ecosystem services, including hunting, fishing, and other types of recreation, also are well documented (KM 8.3); however, positive impacts are less studied. Studies in the Southern Great Plains are abundant on health outcomes and ecosystem services in the face of climate change.

Literature on the economic impacts of specific extreme events on recreation can be found, especially for Texas, but comprehensive literature on these impacts across the region or across recreation, sports, and leisure does not exist. In these cases, the author team gave examples from specific activities, events, and locations from the literature or provided examples from multiple news reports. As in other sections, peer-reviewed literature related to this section was most abundant for Texas, especially the Texas Gulf Coast, and least abundant for Kansas. Although examples were available for specific adaptation actions, literature evaluating the effectiveness of these actions was limited.

Major Uncertainties and Research Gaps

Documentation of how climate change affected the amount, timing, and intensity of physical activity on a community or larger scale is limited. Prior research focused primarily on the impacts of climate on football players. Research remains lacking on the impacts on other sports (e.g., soccer, lacrosse, cross-country). Comparative studies across the region are rare for impacts of climate change on sports, recreation, and leisure activities. Literature regarding climate change impacts and adaptation actions for recreational activities in Texas Gulf waters is minimal.

Research is limited on the convergence of environmental justice, climate, and sports and recreation, especially among Indigenous communities and in rural settings. Economic impact studies tend to focus on singular extreme events in limited regions and thus do not provide a comprehensive understanding from state to state, activity to activity, or sport to sport. Research is limited on the climate adaptations of sports organizations to reduce climate vulnerabilities, as well as on the outcomes (positive or negative) of those adaptations.

Description of Confidence and Likelihood

Peer-reviewed literature was abundant and consistent, leading the author team to an assessment of *very high confidence* for the first statement in the Key Message. The other two statements were assessed at *high confidence* based on a smaller evidence base on climate change impacts on reduction of outdoor physical activity and on the types of adaptation strategies used by individuals, communities, or sport organizations.

The evidence base was not sufficient to determine quantitative probabilities for the first and third statements in this Key Message; thus, no likelihood was specified. For the second statement, there was sufficient evidence from multiple sources of climate projections to indicate that it is *very likely* that heat extremes will increase across the region in the future. The literature is sufficient to recognize that heat extremes are linked to heat-related illness and death and that they also result in a reduction of outdoor physical activity.

Key Message 26.4

How We Heal: Climate Change Is Exacerbating Existing Social and Environmental Disparities

Description of Evidence Base

Social science literature regarding justice and equity as related to climate hazards was abundant and consistent, especially as related to extreme heat, flooding, and tropical cyclones (e.g., Benevolenza and DeRigne 2019;[68] Flores et al. 2021;[254] Maldonado et al. 2016;[255] Prudent et al. 2016;[256] Smiley et al. 2022[257]). Research on low-income communities and communities of color was extensive for many metropolitan and industrial areas in the region (e.g., Collins et al. 2019,[258] 2013;[259] Flores et al. 2021;[254] Li et al. 2022[260]). There is a cluster of research on tropical cyclones, sea level rise, and infrastructural disparities in marginalized communities in Texas coastal metropolitan and industrial areas, with some studies focusing on South Texas, where many *colonias* are located (e.g., Atisa and Racelis 2022;[261] Martinich et al. 2013;[160] Flores et al. 2021;[254] Chakraborty et al. 2019[169]). The *Status of Tribes and Climate Change Report*[3] provided extensive examples and documentation of challenges and opportunities, and it was useful for content and context across the entire chapter. Evidence-based solutions were limited, especially those over a sufficient time period to evaluate long-term effectiveness.

Major Uncertainties and Research Gaps

In comparison to research on the physical impacts of climate change, there is significantly less research in the Southern Great Plains on climate change through the lens of justice and equity. Those most impacted include people and families with low incomes; rural residents; historically marginalized populations; disabled persons; older adults; Black, Indigenous and People of Color; those who do not identify as cis, straight male; immigrants; those living in *colonias*; and unhoused individuals; however, the author team found no studies that analyze the impacts on these populations systematically across any of the three states. In addition, although there are several studies assessing challenges for Spanish-speaking individuals, those who speak other non-English languages generally are not included. In some cases, literature diagnoses disparities without explaining the reasons for them (e.g., Carvallo et al. 2021[85]), indicating that additional research is needed to analyze the root causes so that they can be addressed alongside climate adaptation and mitigation actions (i.e., to avoid maladaptation; KM 31.4).

Peer-reviewed research has tended to focus on cities, with less emphasis on rural communities or small- to medium-sized cities in the region. Even for locations near the Southern Great Plains, there is little literature on climate justice as it relates to rural communities (e.g., Gutierrez and LePrevost 2016[262]). Knowledge is limited regarding the evaluation of climate mitigation and adaptation strategies that seek to incorporate climate justice and equity (e.g., Mullenbach and Wilhelm Stanis 2022[253]). Because of their sovereignty, Tribes have chosen, in many circumstances, to document their work through oral traditions, which are not shared with outsiders.[3]

Description of Confidence and Likelihood

Based on the abundance of research and consistency of results across the US and within the region, the author team assessed the first two Key Message statements with *very high confidence*. How the specific demographics or location of the neighborhoods and communities relate to a higher risk of impacts remains to be studied more completely, but the first two statements were intentionally general to highlight what is known from the literature. The third statement was assessed with *medium confidence* because rigorous evaluation of outcomes from policies, practices, and programs is more limited in the literature.

Although the literature is compelling for many of the physical impacts of climate change, impacts to individuals, neighborhoods, and communities were not as robustly documented and certainly did not cover the entire region. Hence, no likelihood is specified for any statement, as the author team could not assess quantitative probabilities through case studies or analyses of small regions within the Southern Great Plains.

Key Message 26.5

How We Serve: Climate Change Is Straining Public Infrastructure and Services

Description of Evidence Base

Public infrastructure and services topics related to water supply (KM 4.2), infrastructure (KMs 12.2, 13.1), public health and safety (KM 15.1), and education[212] had an extensive research base nationwide and across specific regions of the United States. Research in the Southern Great Plains was less robust. In this case, the authors, many of whom have worked for or with municipalities across the region for decades, used their expert judgment to communicate the message and to select the most relevant citations. Other evidence for this Key Message included state water plans,[227,247,263] state transportation plans,[199,200,201] and state science curriculum standards[207,208,264] for each of the three states.

Scholarship is abundant regarding agricultural water needs and uses across the Southern Great Plains; however, peer-reviewed literature regarding climate change and municipal water supplies or water sustainability was sparse for all three states. How climate change affects public infrastructure and services in the region is an emerging topic, with much of the research done only in the past decade. News media covered local impacts after extreme events, including the damage to public infrastructure and response by service agencies and organizations. Because cities and towns are important locations where climate mitigation and adaptation occur, the author team chose to cover this topic even though the evidence base was smaller than that for the other sections.

In addition, the author team chose to discuss the emergent topic of the role of faith-based organizations, as it was well aligned with values in the region. These organizations also can use content in this report to plan for community service before, during, and after climate hazards. Although major religions have statements regarding climate change (e.g., *Laudato si'* encyclical from Pope Francis, "Islamic Declaration on Climate Change," "Buddhist Climate Change Statement to World Leaders," and "Interfaith Climate Statement"),[265] literature regarding the interactions of faith, religion, and climate change is limited.[238,266] Peer-reviewed literature was sparse on how faith-based organizations conduct adaptation or mitigation actions or the scope and effectiveness of these activities.

Information about what actions communities were taking in the region was primarily documented in state or municipal reports rather than the peer-reviewed literature (e.g., City of San Antonio 2019;[224] City of Oklahoma City 2020[222]). Hence, no evaluation of the effectiveness of or public support for the actions was available. State transportation plans did not have detailed articulation of threats to transportation services or infrastructure as related to climate change. The 2020–2045 Kansas Long Range Transportation Plan;[201] Oklahoma Long Range Transportation Plan: 2020–2045;[199] and the Texas Transportation Plan 2050[200] did not provide goals or objectives that addressed climate-change impacts. Although Kansas and Oklahoma acknowledged the need to support electric-vehicle charging stations, climate-change adaptation and mitigation were minimal elements of these plans and provided little context for the author team. For water resources management, significant content was available in the 2022 Kansas Water Plan[227] and the 2012 Oklahoma Comprehensive Water Plan.[263] Conversely, the Texas Water Development Board[229] did not

acknowledge climate change or plan for its impacts on water resources management, thus limiting the content for Texas.

Major Uncertainties and Research Gaps

Data for and analyses of climate change impacts on public services and infrastructure in the region were sporadic, even though research, data, and projections for temperature, precipitation, and other physical climate indicators over land were generally plentiful. Also, although coastal and offshore data were available for the Gulf of Mexico from the Gulf of Mexico Coastal Ocean Observing System[267] and Texas Automated Buoy System,[268] these observing systems were not established to monitor long-term climate trends (e.g., ocean acidification, saltwater intrusion), and thus there was a scarcity of literature on how these observing systems aided decision support for climate change.

Few studies on public infrastructure and services focused on Kansas and Oklahoma, with most research in Texas. Of those on Kansas and Oklahoma, many were decades old. For all states, most studies examined specific facilities or communities; there were few synthesis or comparison studies that helped present a larger picture of climate change impacts across the region. Documentation of how climate change is projected to affect the healthcare system or healthcare facilities was sparse, although research on climate change and public health was relatively abundant (see Traceable Account for KM 26.1). Similarly, broad syntheses across the region of the impacts of climate change on roadways, railways, ports, pipelines, and airports, or the reliability and safety of transportation systems, were unavailable. In addition, with the region's residents and visitors heavily dependent on automobiles and trucks, there was a large gap in the research on what mitigation and adaptation measures were recommended for moving into a next-generation, climate-smart transportation system.

Few peer-reviewed publications existed, specific to the region, regarding the intersection of public safety and climate change, including current planning processes, effective adaptation, and economic costs. The documentation available primarily focused on historical events and rarely on projections into the future. Similarly, information was minimal regarding how climate change was incorporated into the curriculum at various education levels across all three states, whether in formal or informal programs.

Even though faith-based organizations play significant roles locally, regionally, and globally when crises occur, most of the literature on climate change and faith focused on individual knowledge, opinions, or actions based on religious affiliation. The scope of what these organizations were doing (or not doing) and how they were accomplishing their works were unclear.

Description of Confidence and Likelihood

Confidence was assessed to be *medium* for the first statement, which was the consensus after acknowledging both the dearth of peer-reviewed literature (which would have led to *low confidence*) and the experience of members of the author team who served one or more communities and networked with others who do the same (which would have led to *high confidence*). In this case, much of the work being conducted across the region is relatively recent (e.g., since the publication of NCA4 in 2018); thus, ongoing research has yet to reach publication stage. For the second statement, the *high confidence* level was chosen primarily because of the authors' knowledge of the climate projections and those events that have most affected public infrastructure and services in the past. As with other sections, evaluation of mitigation and adaptation options in the region is sparse (KM 31.1). The effectiveness of solutions is generally place-based, so the author team chose *medium confidence* based on these uncertainties.

Although climate projections indicate that more frequent and intense climate-related events are *very likely* in the future for the region, the author team did not find sufficient literature on the reliability, cost, and

distribution of community services to generate quantitative probabilities of likelihood. Thus, no likelihood is specified for any statement in the Key Message.

References

1. EPA, 2013: Level III Ecoregions of the Continental United States. U.S. Environmental Protection Agency, National Health and Environmental Effects Research Laboratory. https://gaftp.epa.gov/epadatacommons/ord/ecoregions/us/eco_level_iii_us.pdf

2. IPBES, 2019: *Summary for Policymakers of the Global Assessment Report on Biodiversity and Ecosystem Services of the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services*. Díaz, S., J. Settele, E.S. Brondízio, H.T. Ngo, M. Guèze, J. Agard, A. Arneth, P. Balvanera, K.A. Brauman, S.H.M. Butchart, K.M.A. Chan, L.A. Garibaldi, K. Ichii, J. Liu, S.M. Subramanian, G.F. Midgley, P. Miloslavich, Z. Molnár, D. Obura, A. Pfaff, S. Polasky, A. Purvis, J. Razzaque, B. Reyers, R. Roy Chowdhury, Y.J. Shin, I.J. Visseren-Hamakers, K.J. Willis, and C.N. Zayas, Eds. IPBES Secretariat, Bonn, Germany, 56 pp. https://www.ipbes.net/sites/default/files/inline/files/ipbes_global_assessment_report_summary_for_policymakers.pdf

3. STACCWG, 2021: The Status of Tribes and Climate Change Report. Marks-Marino, D., Ed. Northern Arizona University, Institute for Tribal Environmental Professionals, Flagstaff, AZ. http://nau.edu/stacc2021

4. Lavin, S.J., F.M. Shelley, and J.C. Archer, 2011: *Atlas of the Great Plains*. University of Nebraska Press, 352 pp. https://www.nebraskapress.unl.edu/nebraska/9780803215368/

5. Collins, S.D., L.J. Heintzman, S.M. Starr, C.K. Wright, G.M. Henebry, and N.E. McIntyre, 2014: Hydrological dynamics of temporary wetlands in the southern Great Plains as a function of surrounding land use. *Journal of Arid Environments*, **109**, 6–14. https://doi.org/10.1016/j.jaridenv.2014.05.006

6. Matthews, W.J., C.C. Vaughn, K.B. Gido, and E. Marsh-Matthews, 2005: Ch. 7. Southern Plains rivers. In: *Rivers of North America*. Benke, A.C. and C.E. Cushing, Eds. Academic Press, Burlington, MA, 282–325. https://doi.org/10.1016/b978-012088253-3/50010-9

7. Lovelace, J.K., M.G. Nielsen, A.L. Read, C.J. Murphy, and M.A. Maupin, 2020: Estimated Groundwater Withdrawals from Principal Aquifers in the United States, 2015. Circular 1464. U.S. Geological Survey, Reston, VA, 70 pp. https://doi.org/10.3133/cir1464

8. Costigan, K.H. and M.D. Daniels, 2012: Damming the prairie: Human alteration of Great Plains river regimes. *Journal of Hydrology*, **444-445**, 90–99. https://doi.org/10.1016/j.jhydrol.2012.04.008

9. Heidari, H., M. Arabi, and T. Warziniack, 2021: Vulnerability to water shortage under current and future water supply-demand conditions across U.S. river basins. *Earth's Future*, **9** (10), 2021EF002278. https://doi.org/10.1029/2021ef002278

10. EIA, 2020: Map of Fossil Fuel Resources in the U.S. U.S. Energy Information Administration. https://atlas.eia.gov/apps/fossil-fuels/explore

11. EIA. 2022: Electricity: Capacity of Electric Power Plants, Annual: Existing Capacity by Energy Source, by Producer, by State Back to 2000 (Annual Data From the EIA-860). U.S. Energy Information Administration. https://www.eia.gov/electricity/data.php

12. Frankson, R., K.E. Kunkel, L.E. Stevens, D.R. Easterling, X. Lin, M. Shulski, N.A. Umphlett, and C.J. Stiles, 2022: Kansas State Climate Summary 2022. NOAA Technical Report NESDIS 150-KS. National Oceanic and Atmospheric Administration, National Environmental Satellite, Data, and Information Service, Silver Spring, MD. 5 pp. https://statesummaries.ncics.org/chapter/ks/

13. Runkle, J., K.E. Kunkel, J. Nielson-Gammon, R. Frankson, S.M. Champion, B.C. Stewart, L. Romolo, and W. Sweet, 2022: Texas State Climate Summary 2022. NOAA Technical Report NESDIS 150-TX. National Oceanic and Atmospheric Administration, National Environmental Satellite, Data, and Information Service, Silver Spring, MD, 5 pp. https://statesummaries.ncics.org/chapter/tx/

14. Frankson, R., K.E. Kunkel, L.E. Stevens, S.M. Champion, B.C. Stewart, and J. Nielsen-Gammon, 2022: Oklahoma State Climate Summary 2022. NOAA Technical Report NESDIS 150-OK. National Oceanic and Atmospheric Administration, National Environmental Satellite, Data, and Information Service, Silver Spring, MD. 5 pp. https://statesummaries.ncics.org/chapter/ok/

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

16. NDMC, 2023: U.S. Drought Monitor: Data Tables. University of Nebraska-Lincoln, National Drought Mitigation Center, Lincoln, NE, accessed May 21, 2023. https://droughtmonitor.unl.edu/dmdata/datatables.aspx

17. NCEI, 2023: U.S. Billion-Dollar Weather and Climate Disasters. National Oceanic and Atmospheric Administration, National Environmental Satellite, Data, and Information Service, National Centers for Environmental Information. https://www.ncei.noaa.gov/access/billions/

18. EIA, 2023: Electricity Data Browser. U.S. Energy Information Administration, accessed May 3, 2023. https://www.eia.gov/electricity/data/browser/

19. EPA, 2023: Greenhouse Gas Inventory Data Explorer. U.S. Environmental Protection Agency, Washington, DC, accessed May 26, 2023. https://cfpub.epa.gov/ghgdata/inventoryexplorer/index.html#allsectors/allsectors/allgas/gas/all

20. Ansley, R.J., V.H. Rivera-Monroy, K. Griffis-Kyle, B. Hoagland, A. Emert, T. Fagin, S.R. Loss, H.R. McCarthy, N.G. Smith, and E.F. Waring, 2023: Assessing impacts of climate change on selected foundation species and ecosystem services in the South-Central USA. *Ecosphere*, **14** (2), e4412. https://doi.org/10.1002/ecs2.4412

21. Archer, S.R., E.M. Andersen, K.I. Predick, S. Schwinning, R.J. Steidl, and S.R. Woods, 2017: Ch. 2. Woody plant encroachment: Causes and consequences. In: *Rangeland Systems: Processes, Management and Challenges*. Briske, D.D., Ed. Springer, Cham, Switzerland, 25–84. https://doi.org/10.1007/978-3-319-46709-2_2

22. Twidwell, D., W.E. Rogers, S.D. Fuhlendorf, C.L. Wonkka, D.M. Engle, J.R. Weir, U.P. Kreuter, and C.A. Taylor, Jr., 2013: The rising Great Plains fire campaign: Citizens' response to woody plant encroachment. *Frontiers in Ecology and the Environment*, **11** (s1), 64–71. https://doi.org/10.1890/130015

23. Howell, N.L., E.B. Butler, and B. Guerrero, 2019: Water quality variation with storm runoff and evaporation in playa wetlands. *Science of The Total Environment*, **652**, 583–592. https://doi.org/10.1016/j.scitotenv.2018.10.298

24. Bragg, D.C., M.G. Shelton, and B. Zeide, 2003: Impacts and management implications of ice storms on forests in the southern United States. *Forest Ecology and Management*, **186** (1), 99–123. https://doi.org/10.1016/s0378-1127(03)00230-5

25. Moore, G.W., C.B. Edgar, J.G. Vogel, R.A. Washington-Allen, Rosaleen G. March, and R. Zehnder, 2016: Tree mortality from an exceptional drought spanning mesic to semiarid ecoregions. *Ecological Applications*, **26** (2), 602–611. https://doi.org/10.1890/15-0330

26. Will, R.E., S.M. Wilson, C.B. Zou, and T.C. Hennessey, 2013: Increased vapor pressure deficit due to higher temperature leads to greater transpiration and faster mortality during drought for tree seedlings common to the forest-grassland ecotone. *New Phytologist*, **200** (2), 366–374. https://doi.org/10.1111/nph.12321

27. Zhang, W., G. Villarini, G.A. Vecchi, and J.A. Smith, 2018: Urbanization exacerbated the rainfall and flooding caused by Hurricane Harvey in Houston. *Nature*, **563** (7731), 384–388. https://doi.org/10.1038/s41586-018-0676-z

28. Texas GLO, 2019: Texas Coastal Resiliency Plan. Texas General Land Office. https://coastalstudy.texas.gov/resources/files/2019-coastal-master-plan.pdf

29. Cozzetto, K., K. Chief, K. Dittmer, M. Brubaker, R. Gough, K. Souza, F. Ettawageshik, S. Wotkyns, S. Opitz-Stapleton, S. Duren, and P. Chavan, 2014: Ch. 6. Climate change impacts on the water resources of American Indians and Alaska Natives in the U.S. In: *Climate Change and Indigenous Peoples in the United States: Impacts, Experiences and Actions*. Maldonado, J.K., R.E. Pandya, and B.J. Colombi, Eds. Springer, Cham, Switzerland, 61–76. https://doi.org/10.1007/978-3-319-05266-3_6

30. Pearson, J., G. Jackson, and K.E. McNamara, 2023: Climate-driven losses to Indigenous and local knowledge and cultural heritage. *The Anthropocene Review*, **10** (2), 343–366. https://doi.org/10.1177/20530196211005482

31. Whyte, K., C. Avery, E. Azzuz, J. Breckinridge, C. Cooley, K. Cozzetto, R. Croll, M. Cruz, P. Ezcurra, P. Hardison, C. Jones, F. Lake, C. Magee, D.M. Marks-Marino, D., H. Mullen, C. Nelson, A. Pairis, H. Panci, B. Rodriguez, H. Sorensen, C. Spriggs, and A. Warneke, 2021: Ch. 4. Ecosystems & biodiversity. In: *Status of Tribes and Climate Change Report*. Marks-Marino, D., Ed. Institute for Tribal Environmental Professionals, 56–80. http://nau.edu/stacc2021

32. Reeder-Myers, L.A. and M.D. McCoy, 2019: Preparing for the future impacts of megastorms on archaeological sites: An evaluation of flooding from Hurricane Harvey, Houston, Texas. *American Antiquity*, **84** (2), 292–301. https://doi.org/10.1017/aaq.2018.85

33. Berlemann, M. and M.F. Steinhardt, 2017: Climate change, natural disasters, and migration—A survey of the empirical evidence. *CESifo Economic Studies*, **63** (4), 353–385. https://doi.org/10.1093/cesifo/ifx019

34. Chort, I. and M. de la Rupelle, 2022: Managing the impact of climate on migration: Evidence from Mexico. *Journal of Population Economics*, **35** (4), 1777–1819. https://doi.org/10.1007/s00148-022-00894-1

35. McLeman, R.A., J. Dupre, L. Berrang Ford, J. Ford, K. Gajewski, and G. Marchildon, 2014: What we learned from the Dust Bowl: Lessons in science, policy, and adaptation. *Population and Environment*, **35** (4), 417–440. https://doi.org/10.1007/s11111-013-0190-z

36. Shen, X., C. Cai, Q. Yang, E.N. Anagnostou, and H. Li, 2021: The US COVID-19 pandemic in the flood season. *Science of The Total Environment*, **755**, 142634. https://doi.org/10.1016/j.scitotenv.2020.142634

37. Coffey, R., M.J. Paul, J. Stamp, A. Hamilton, and T. Johnson, 2019: A review of water quality responses to air temperature and precipitation changes 2: Nutrients, algal blooms, sediment, pathogens. *JAWRA Journal of the American Water Resources Association*, **55** (4), 844–868. https://doi.org/10.1111/1752-1688.12711

38. Schlinger, C., O. Conroy-Ben, C. Cooley, N. Cooley, M. Cruz, D. Dotson, J. Doyle, M.J. Eggers, P. Hardison, M. Hatch, C. Hogue, K. Jacobson Hedin, C. Jones, K. Lanphier, D. Marks-Marino, D. Mosley, F. Olsen Jr., and M. Peacock, 2021: Ch. 4.2. Water. In: *Status of Tribes and Climate Change Report*. Marks-Marino, D., Ed. Institute for Tribal Environmental Professionals, Flagstaff, AZ, 98–141. http://nau.edu/stacc2021

39. U.S. Census Bureau, 2020: City and Town Population Totals: 2010-2020. U.S. Department of Commerce, U.S. Census Bureau. https://www.census.gov/programs-surveys/popest/technical-documentation/research/evaluation-estimates/2020-evaluation-estimates/2010s-cities-and-towns-total.html

40. U.S. Census Bureau. 2021: Annual Estimates of the Resident Population for Metropolitan Statistical Areas in the United States and Puerto Rico: April 1, 2020 to July 1, 2021. U.S. Department of Commerce, U.S. Census Bureau. https://www2.census.gov/programs-surveys/popest/tables/2020-2021/metro/totals/cbsa-met-est2021-pop.xlsx

41. Muir, A.F., 1943: The destiny of Buffalo Bayou. *The Southwestern Historical Quarterly*, **47** (2), 91–106. https://www.jstor.org/stable/30236015

42. Feagin, J.R., 1997: *The New Urban Paradigm: Critical Perspectives on the City*. Rowman & Littlefield, 384 pp. https://rowman.com/isbn/9780847684991/the-new-urban-paradigm-critical-perspectives-on-the-city

43. U.S. Census Bureau, 2020: American Community Survey (ACS). U.S. Department of Commerce, U.S. Census Bureau. https://www.census.gov/programs-surveys/acs

44. Klineberg, S.L., R. Bozick, and Kinder Institute for Urban Research, 2021: The Fortieth Year of the Kinder Houston Area Survey: Into the Post-Pandemic Future. Rice University, Kinder Institute for Urban Research, Houston, TX. https://doi.org/10.25611/hz81-gt44

45. Hayden, M.H., O.V. Wilhelmi, D. Banerjee, T. Greasby, J.L. Cavanaugh, V. Nepal, J. Boehnert, S. Sain, C.Burghardt, and S. Gower, 2017: Adaptive capacity to extreme heat: Results from a household survey in Houston, Texas. *Weather, Climate, and Society*, **9** (4), 787–799. https://doi.org/10.1175/wcas-d-16-0125.1

46. Rice University Kinder Institute for Urban Research, 2022: Harris County Winter Storm Uri Resilience Assessment in Harris County. Rice University, Kinder Institute for Urban Research, Houston, TX. https://doi.org/10.25611/yt6s-k856

47. City of Houston, 2020: Resilient Houston. City of Houston. https://www.houstontx.gov/mayor/Resilient-Houston-20200518-single-page.pdf

48. Stoner, A. and K. Hayhoe, 2020: Climate Impact Assessment for the City of Houston. ATMOS Research and Consulting, 69 pp. https://www.houstontx.gov/mayor/Climate-Impact-Assessment-2020-August.pdf

49. Anderegg, W.R.L., J.T. Abatzoglou, L.D.L. Anderegg, L. Bielory, P.L. Kinney, and L. Ziska, 2021: Anthropogenic climate change is worsening North American pollen seasons. *Proceedings of the National Academy of Sciences of the United States of America*, **118** (7), e2013284118. https://doi.org/10.1073/pnas.2013284118

50. Levetin, E., 2021: Aeroallergens and climate change in Tulsa, Oklahoma: Long-term trends in the south central United States. *Frontiers in Allergy*, **2**, 726445. https://doi.org/10.3389/falgy.2021.726445

51. Neumann, J.E., S.C. Anenberg, K.R. Weinberger, M. Amend, S. Gulati, A. Crimmins, H. Roman, N. Fann, and P.L. Kinney, 2019: Estimates of present and future asthma emergency department visits associated with exposure to oak, birch, and grass pollen in the United States. *GeoHealth*, **3** (1), 11–27. https://doi.org/10.1029/2018gh000153

52. Johnson, M.G., S. Brown, P. Archer, A. Wendelboe, S. Magzamen, and K.K. Bradley, 2016: Identifying heat-related deaths by using medical examiner and vital statistics data: Surveillance analysis and descriptive epidemiology—Oklahoma, 1990–2011. *Environmental Research*, **150**, 30–37. https://doi.org/10.1016/j.envres.2016.05.035

53. Mallen, E., B. Stone, and K. Lanza, 2019: A methodological assessment of extreme heat mortality modeling and heat vulnerability mapping in Dallas, Texas. *Urban Climate*, **30**, 100528. https://doi.org/10.1016/j.uclim.2019.100528

54. Bell, J.E., C.L. Brown, K. Conlon, S. Herring, K.E. Kunkel, J. Lawrimore, G. Luber, C. Schreck, A. Smith, and C. Uejio, 2018: Changes in extreme events and the potential impacts on human health. *Journal of the Air & Waste Management Association*, **68** (4), 265–287. https://doi.org/10.1080/10962247.2017.1401017

55. EPA, 2023: Texas Nonattainment/Maintenance Status for Each County by Year for All Criteria Pollutants. U.S. Environmental Protection Agency, accessed May 21, 2023. https://www3.epa.gov/airquality/greenbook/anayo_tx.html

56. Caminade, C., K.M. McIntyre, and A.E. Jones, 2019: Impact of recent and future climate change on vector-borne diseases. *Annals of the New York Academy of Sciences*, **1436** (1), 157–173. https://doi.org/10.1111/nyas.13950

57. Raghavan, R.K., Z.L. Koestel, G. Boorgula, A. Hroobi, R. Ganta, J. Harrington, Jr., D. Goodin, R.W. Stich, and G. Anderson, 2021: Unexpected winter questing activity of ticks in the central Midwestern United States. *PLoS ONE*, **16** (11), e0259769. https://doi.org/10.1371/journal.pone.0259769

58. Hotez, P.J., 2018: The rise of neglected tropical diseases in the "new Texas". *PLoS Neglected Tropical Diseases*, **12** (1), e0005581. https://doi.org/10.1371/journal.pntd.0005581

59. Gorris, M.E., K.K. Treseder, C.S. Zender, and J.T. Randerson, 2019: Expansion of coccidioidomycosis endemic regions in the United States in response to climate change. *GeoHealth*, **3** (10), 308–327. https://doi.org/10.1029/2019gh000209

60. Peterson, C., V. Chu, J. Lovelace, M. Almekdash, and M. Lacy, 2022: Coccidioidomycosis cases at a regional referral center, West Texas, USA, 2013–2019. *Emerging Infectious Diseases*, **28** (4), 848–851. https://doi.org/10.3201/eid2804.211912

61. Davey Resource Group, 2019: Oklahoma City Metropolitan Area Tree Canopy Assessment. Davey Resource Group. https://tree-canopy-acog.hub.arcgis.com/documents/oklahoma-city-metropolitan-area-tree-canopy-assessment/explore

62. TTF and City of Dallas, 2021: Dallas Urban Forest Master Plan 2021. Texas Trees Foundation and City of Dallas. https://dallascityhall.com/projects/forestry/dch%20documents/city%20of%20dallas%202021%20urban%20forest%20master%20plan.pdf

63. Hopkins, L.P., D.J. January-Bevers, E.K. Caton, and L.A. Campos, 2022: A simple tree planting framework to improve climate, air pollution, health, and urban heat in vulnerable locations using non-traditional partners. *Plants, People, Planet*, **4** (3), 243–257. https://doi.org/10.1002/ppp3.10245

64. Roeland, S., M. Moretti, J.H. Amorim, C. Branquinho, S. Fares, F. Morelli, Ü. Niinemets, E. Paoletti, P. Pinho, G. Sgrigna, V. Stojanovski, A. Tiwary, P. Sicard, and C. Calfapietra, 2019: Towards an integrative approach to evaluate the environmental ecosystem services provided by urban forest. *Journal of Forestry Research*, **30**, 1981–1996. https://doi.org/10.1007/s11676-019-00916-x

65. Lovell, S.T., J. Hayman, H. Hemmelgarn, A.A. Hunter, and J.R. Taylor, 2021: Community orchards for food sovereignty, human health, and climate resilience: Indigenous roots and contemporary applications. *Forests*, **12** (11), 1533. https://doi.org/10.3390/f12111533

66. VanWinkle, T.N. and J. Friedman, 2019: Between drought and disparity: American Indian farmers, resource bureaucracy, and climate vulnerability in the Southern Plains. *Journal of Agriculture, Food Systems, and Community Development*, **9** (B), 53–68. https://doi.org/10.5304/jafscd.2019.09b.022

67. Moda, H.M., W.L. Filho, and A. Minhas, 2019: Impacts of climate change on outdoor workers and their safety: Some research priorities. *International Journal of Environmental Research and Public Health*, **16** (18), 3458. https://doi.org/10.3390/ijerph16183458

68. Benevolenza, M.A. and L. DeRigne, 2019: The impact of climate change and natural disasters on vulnerable populations: A systematic review of literature. *Journal of Human Behavior in the Social Environment*, **29** (2), 266–281. https://doi.org/10.1080/10911359.2018.1527739

69. Newell, R.G. and D. Raimi, 2018: The fiscal impacts of increased U.S. oil and gas development on local governments. *Energy Policy*, **117**, 14–24. https://doi.org/10.1016/j.enpol.2018.02.042

70. Zhang, Y., R. Gautam, S. Pandey, M. Omara, J.D. Maasakkers, P. Sadavarte, D. Lyon, H. Nesser, M.P. Sulprizio, D.J. Varon, R. Zhang, S. Houweling, D. Zavala-Araiza, R.A. Alvarez, A. Lorente, S.P. Hamburg, I. Aben, and D.J. Jacob, 2020: Quantifying methane emissions from the largest oil-producing basin in the United States from space. *Science Advances*, **6** (17), 5120. https://doi.org/10.1126/sciadv.aaz5120

71. ERCOT. 2023: Resource Capacity Trend Charts: Capacity Changes by Fuel Type Charts, April 2023. Electric Reliability Council of Texas. https://www.ercot.com/gridinfo/resource

72. ERCOT. 2023: Monthly Generator Interconnection Status Report (GIS_Report_April_2023). Electric Reliability Council of Texas. https://www.ercot.com/gridinfo/resource

73. BLS, 2023: Quarterly Census of Employment and Wages: Employment and Wages Data Viewer: Third Quarter, 2022: All Industry Levels, One Area. U.S. Bureau of Labor Statistics, accessed May 25, 2023. https://data.bls.gov/cew/apps/data_views/data_views.htm#tab=tables

74. Pollin, R. and B. Callaci, 2019: The economics of just transition: A framework for supporting fossil fuel-dependent workers and communities in the United States. *Labor Studies Journal*, **44** (2), 93–138. https://doi.org/10.1177/0160449x18787051

75. Williams, J.H., R.A. Jones, and M.S. Torn, 2021: Observations on the transition to a net-zero energy system in the United States. *Energy and Climate Change*, **2**, 100050. https://doi.org/10.1016/j.egycc.2021.100050

76. Shoeib, E.A.H., E. Hamin Infield, and H.C. Renski, 2021: Measuring the impacts of wind energy projects on U.S. rural counties' community services and cost of living. *Energy Policy*, **153**, 112279. https://doi.org/10.1016/j.enpol.2021.112279

77. Wimhurst, J.J. and J.S. Greene, 2019: Oklahoma's future wind energy resources and their relationship with the Central Plains low-level jet. *Renewable and Sustainable Energy Reviews*, **115**, 109374. https://doi.org/10.1016/j.rser.2019.109374

78. Bolinger, R.A., V.M. Brown, C.M. Fuhrmann, K.L. Gleason, T.A. Joyner, B.D. Keim, A. Lewis, J.W. Nielsen-Gammon, C.J. Stiles, W. Tollefson, H.E. Attard, and A.M. Bentley, 2022: An assessment of the extremes and impacts of the February 2021 South-Central U.S. Arctic outbreak, and how climate services can help. *Weather and Climate Extremes*, **36**, 100461. https://doi.org/10.1016/j.wace.2022.100461

79. NCEI, 2021: Assessing the U.S. Climate in February 2021. National Oceanic and Atmospheric Administration, National Environmental Satellite, Data, and Information Service, National Centers for Environmental Information. https://www.ncei.noaa.gov/news/national-climate-202102

80. NCEI, 2022: Data Tools: Daily Weather Records. National Oceanic and Atmospheric Administration, National Environmental Satellite, Data, and Information Service, National Centers for Environmental Information. https://www.ncdc.noaa.gov/cdo-web/datatools/records

81. Glazer, Y.R., D.M. Tremaine, J.L. Banner, M. Cook, R.E. Mace, J. Nielsen-Gammon, E. Grubert, K. Kramer, A.M.K. Stoner, B.M. Wyatt, A. Mayer, T. Beach, R. Correll, and M.E. Webber, 2021: Winter storm Uri: A test of Texas' water infrastructure and water resource resilience to extreme winter weather events. *Journal of Extreme Events*, **08** (04), 2150022. https://doi.org/10.1142/s2345737621500226

82. Hellerstedt, J., 2021: February 2021 Winter Storm-Related Deaths–Texas. Texas Department of State Health Services, 8 pp. https://www.dshs.texas.gov/sites/default/files/news/updates/SMOC_FebWinterStorm_MortalitySurvReport_12-30-21.pdf

83. FERC, 2021: FERC, NERC and Regional Entity Staff Report: The February 2021 Cold Weather Outages in Texas and the South Central United States. Federal Energy Regulatory Commission, North American Electric Reliability Corporation. https://www.naesb.org/pdf4/ferc_nerc_regional_entity_staff_report_feb2021_cold_weather_outages_111621.pdf

84. Ghosh, S., A. Bohra, and S. Dutta, 2021: The Texas freeze of February 2021: Event and winterization analysis using cost and pricing data. In: *2021 IEEE Electrical Power and Energy Conference (EPEC)*. Toronto, ON, 22–31 October 2021. https://doi.org/10.1109/epec52095.2021.9621500

85. Carvallo, J.P., F.C. Hsu, Z. Shah, and J. Taneja, 2021: Frozen Out in Texas: Blackouts and Inequity. The Rockefeller Foundation. https://www.rockefellerfoundation.org/case-study/frozen-out-in-texas-blackouts-and-inequity/

86. Busby, J.W., K. Baker, M.D. Bazilian, A.Q. Gilbert, E. Grubert, V. Rai, J.D. Rhods, S. Shidore, C.A. Smith, and M.E. Webber, 2021: Cascading risks: Understanding the 2021 winter blackout in Texas. *Energy Research & Social Science*, **77**, 102106. https://doi.org/10.1016/j.erss.2021.102106

87. Zhang, X., Y. Fu, Z. Han, J.E. Overland, A. Rinke, H. Tang, T. Vihma, and M. Wang, 2022: Extreme cold events from East Asia to North America in winter 2020/21: Comparisons, causes, and future implications. *Advances in Atmospheric Sciences*, **39** (4), 553–565. https://doi.org/10.1007/s00376-021-1229-1

88. Gao, Y., L.R. Leung, J. Lu, and G. Masato, 2015: Persistent cold air outbreaks over North America in a warming climate. *Environmental Research Letters*, **10** (4), 044001. https://doi.org/10.1088/1748-9326/10/4/044001

89. Relating to Preparing for, Preventing, and Responding to Weather Emergencies and Power Outages; Increasing the Amount of Administrative and Civil Penalties. Texas Senate Bill 3, Texas Legislature, 87th Legislature Regular Session, June 8, 2021. https://capitol.texas.gov/billlookup/history.aspx?legsess=87r&bill=sb3

90. NASS, 2023: News Release: Kansas Rank in U.S. Agriculture. U.S. Department of Agriculture, National Agricultural Statistics Service, 2 pp. https://www.nass.usda.gov/statistics_by_state/kansas/publications/economic_releases/rank/2023/ks-rank23.pdf

91. NASS, 2023: Cattle Inventory–January 1, 2023. U.S. Department of Agriculture, National Agricultural Statistics Service. https://usda.library.cornell.edu/concern/publications/h702q636h

92. NASS, 2019: 2017 Census of Agriculture: United States Summary and State Data. AC-17-A-51. U.S. Department of Agriculture, National Agricultural Statistics Service. https://www.nass.usda.gov/publications/agcensus/2017/index.php

93. Settele, J., J. Bishop, and S.G. Potts, 2016: Climate change impacts on pollination. *Nature Plants*, **2** (7), 16092. https://doi.org/10.1038/nplants.2016.92

94. Challinor, A.J., J. Watson, D.B. Lobell, S.M. Howden, D.R. Smith, and N. Chhetri, 2014: A meta-analysis of crop yield under climate change and adaptation. *Nature Climate Change*, **4** (4), 287–291. https://doi.org/10.1038/nclimate2153

95. Allstadt, A.J., S.J. Vavrus, P.J. Heglund, A.M. Pidgeon, W.E. Thogmartin, and V.C. Radeloff, 2015: Spring plant phenology and false springs in the conterminous US during the 21st century. *Environmental Research Letters*, **10** (10), 104008. https://doi.org/10.1088/1748-9326/10/10/104008

96. Chamberlain, C.J., B.I. Cook, I. García de Cortázar-Atauri, and E.M. Wolkovich, 2019: Rethinking false spring risk. *Global Change Biology*, **25** (7), 2209–2220. https://doi.org/10.1111/gcb.14642

97. Tavakol, A., V. Rahmani, and J. Harrington, 2020: Temporal and spatial variations in the frequency of compound hot, dry, and windy events in the central United States. *Scientific Reports*, **10** (1), 15691. https://doi.org/10.1038/s41598-020-72624-0

98. Zhao, H., L. Zhang, M.B. Kirkham, S.M. Welch, J.W. Nielsen-Gammon, G. Bai, J. Luo, D.A. Andresen, C.W. Rice, N. Wan, R.P. Lollato, D. Zheng, P.H. Gowda, and X. Lin, 2022: U.S. winter wheat yield loss attributed to compound hot-dry-windy events. *Nature Communications*, **13** (1), 7233. https://doi.org/10.1038/s41467-022-34947-6

99. Steiner, J.L., D.D. Briske, D.P. Brown, and C.M. Rottler, 2018: Vulnerability of Southern Plains agriculture to climate change. *Climatic Change*, **146** (1), 201–218. https://doi.org/10.1007/s10584-017-1965-5

100. Cho, S.J. and B. McCarl, 2021: Major United States land use as influenced by an altering climate: A spatial econometric approach. *Land*, **10** (5), 546. https://doi.org/10.3390/land10050546

101. Steiner, J.L., D.L. Devlin, S. Perkins, J.P. Aguilar, B. Golden, E.A. Santos, and M. Unruh, 2021: Policy, technology, and management options for water conservation in the Ogallala Aquifer in Kansas, USA. *Water*, **13** (23), 3406. https://doi.org/10.3390/w13233406

102. Drysdale, K.M. and N.P. Hendricks, 2018: Adaptation to an irrigation water restriction imposed through local governance. *Journal of Environmental Economics and Management*, **91**, 150–165. https://doi.org/10.1016/j.jeem.2018.08.002

103. Hegeman, R., 2022: Heat stress blamed for thousands of cattle deaths in Kansas. *The Associated Press*, June 16, 2022. https://apnews.com/article/kansas-cattle-heat-wave-deaths-643f651f1b6118ee6ae4c6833176ce04

104. KDA, 2022: Governor Laura Kelly announces resources, actions to assist cattle producers impacted by heat wave. Kansas Department of Agriculture, Jun 17, 2022. https://agriculture.ks.gov/news-events/news-releases/2022/06/17/governor-laura-kelly-announces-resources-actions-to-assist-cattle-producers-impacted-by-heat-wave

105. Wilmer, H., M.E. Fernández-Giménez, S. Ghajar, P.L. Taylor, C. Souza, and J.D. Derner, 2020: Managing for the middle: Rancher care ethics under uncertainty on western Great Plains rangelands. *Agriculture and Human Values*, **37** (3), 699–718. https://doi.org/10.1007/s10460-019-10003-w

106. Lengnick, L., 2015: *Resilient Agriculture: Cultivating Food Systems for a Changing Climate*. New Society Publishers, 368 pp. https://newsociety.com/books/r/resilient-agriculture-second-edition

107. Smith, A.B. and J.L. Matthews, 2015: Quantifying uncertainty and variable sensitivity within the US billion-dollar weather and climate disaster cost estimates. *Natural Hazards*, **77** (3), 1829–1851. https://doi.org/10.1007/s11069-015-1678-x

108. Marshall, M.I., L.S. Niehm, S.B. Sydnor, and H.L. Schrank, 2015: Predicting small business demise after a natural disaster: An analysis of pre-existing conditions. *Natural Hazards*, **79** (1), 331–354. https://doi.org/10.1007/s11069-015-1845-0

109. Miranda, V.E. and M. Swanstrom, 2020: Surviving disasters: A multi-company case study on disaster recovery plans. *The Journal of Applied Business and Economics*, **22** (6), 87–105. https://doi.org/10.33423/jabe.v22i6.3078

110. Mantripragada, H.C., H. Zhai, and E.S. Rubin, 2019: Boundary Dam or Petra Nova–Which is a better model for CCS energy supply? *International Journal of Greenhouse Gas Control*, **82**, 59–68. https://doi.org/10.1016/j.ijggc.2019.01.004

111. Jones, A.C. and A.J. Lawson, 2021: Carbon Capture and Sequestration (CCS) in the United States. CSR Report R44902. Congressional Research Service. https://sgp.fas.org/crs/misc/R44902.pdf

112. Feder, J., 2021: Geothermal well construction: A step change in oil and gas technologies. *Journal of Petroleum Technology*, **73** (1), 32–35. https://doi.org/10.2118/0121-0032-jpt

113. Clayton, C., 2022: Soil health in central Kansas: Rain still needed, but Kansas soil health tour stresses regenerative AG practices. *DTN Progressive Farmer*, August 3, 2022. https://www.dtnpf.com/agriculture/web/ag/crops/article/2022/08/03/rain-still-needed-kansas-soil-health

114. Gaskill, M., 2021: Paying landowners to store CO_2 in soil a promising climate mitigation tool. *Texas Climate News*. https://texasclimatenews.org/2021/04/15/paying-landowners-to-store-co2-in-soil-a-promising-climate-mitigation-tool/

115. Raw, K., E. Sherry, and K. Rowe, 2022: Sport for social cohesion: Exploring aims and complexities. *Sport Management Review*, **25** (3), 454–475. https://doi.org/10.1080/14413523.2021.1949869

116. Finch, B., 2022: Disaster relief efforts of Houston sport organizations. *Sport, Business and Management: An International Journal*, **12** (3), 253–268. https://doi.org/10.1108/sbm-11-2020-0120

117. Hemmer, L. and D.S. Elliff, 2019: Leaders in action: The experiences of seven Texas superintendents before, during, and after Hurricane Harvey. *Educational Management Administration & Leadership*, **48** (6), 964–985. https://doi.org/10.1177/1741143219873073

118. Orr, M., Y. Inoue, R. Seymour, and G. Dingle, 2022: Impacts of climate change on organized sport: A scoping review. *WIREs Climate Change*, **13** (3), 760. https://doi.org/10.1002/wcc.760

119. Rundell, K.W., 2012: Effect of air pollution on athlete health and performance. *British Journal of Sports Medicine*, **46** (6), 407–412. https://doi.org/10.1136/bjsports-2011-090823

120. Bernard, P., G. Chevance, C. Kingsbury, A. Baillot, A.J. Romain, V. Molinier, T. Gadais, and K.N. Dancause, 2021: Climate change, physical activity and sport: A systematic review. *Sports Medicine*, **51**, 1041–1059. https://doi.org/10.1007/s40279-021-01439-4

121. Ebi, K.L., A. Capon, P. Berry, C. Broderick, R. de Dear, G. Havenith, Y. Honda, R.S. Kovats, W. Ma, A. Malik, N.B. Morris, L. Nybo, S.I. Seneviratne, J. Vanos, and O. Jay, 2021: Hot weather and heat extremes: Health risks. *The Lancet*, **398** (10301), 698–708. https://doi.org/10.1016/s0140-6736(21)01208-3

122. Brocherie, F., O. Girard, and G.P. Millet, 2015: Emerging environmental and weather challenges in outdoor sports. *Climate*, **3** (3), 492–521. https://doi.org/10.3390/cli3030492

123. Cunningham, G.B., P. Wicker, and B.P. McCullough, 2020: Pollution, health, and the moderating role of physical activity opportunities. *International Journal of Environmental Research and Public Health*, **17** (17). https://doi.org/10.3390/ijerph17176272

124. Taylor, W.C., M.F. Floyd, M.C. Whitt-Glover, and J. Brooks, 2007: Environmental justice: A framework for collaboration between the public health and parks and recreation fields to study disparities in physical activity. *Journal of Physical Activity and Health*, **4** (s1), S50–S63. https://doi.org/10.1123/jpah.4.s1.s50

125. Cantu, A., M.A. Graham, A.V. Millard, I. Flores, M.K. Mugleston, I.Y. Reyes, and E.S. Carbajal, 2016: Environmental justice and community-based research in Texas borderland colonias. *Public Health Nursing*, **33** (1), 65–72. https://doi.org/10.1111/phn.12187

126. Lee-Chiong, T.L. and J.T. Stitt, 1995: Heatstroke and other heat-related illnesses: The maladies of summer. *Postgraduate Medicine*, **98** (1), 26–36. https://doi.org/10.1080/00325481.1995.11946015

127. Yeargin, S.W., E. Cahoon, Y. Hosokawa, J.M. Mensch, T.P. Dompier, and Z.Y. Kerr, 2017: Environmental conditions and seasonal variables in American youth football leagues. *Clinical Pediatrics*, **56** (13), 1209–1218. https://doi.org/10.1177/0009922816684603

128. Grundstein, A., E. Cooper, M. Ferrara, and J.A. Knox, 2014: The geography of extreme heat hazards for American football players. *Applied Geography*, **46**, 53–60. https://doi.org/10.1016/j.apgeog.2013.10.007

129. Bergeron, M.F., 2014: Heat stress and thermal strain challenges in running. *Journal of Orthopaedic & Sports Physical Therapy*, **44** (10), 831–838. https://doi.org/10.2519/jospt.2014.5500

130. Bergeron, M.F., C. DiLaura Devore, and S.G. Rice, 2011: Climatic heat stress and exercising children and adolescents. *Pediatrics*, **128** (3), 747. https://doi.org/10.1542/peds.2011-1664

131. Cheng, W., J.O. Spengler, and R.D. Brown, 2020: A comprehensive model for estimating heat vulnerability of young athletes. *International Journal of Environmental Research and Public Health*, **17** (17), 6156. https://doi.org/10.3390/ijerph17176156

132. Vanos, J.K., A.J. Herdt, and M.R. Lochbaum, 2017: Effects of physical activity and shade on the heat balance and thermal perceptions of children in a playground microclimate. *Building and Environment*, **126**, 119–131. https://doi.org/10.1016/j.buildenv.2017.09.026

133. Vanos, J.K., 2015: Children's health and vulnerability in outdoor microclimates: A comprehensive review. *Environment International*, **76**, 1–15. https://doi.org/10.1016/j.envint.2014.11.016

134. Rigolon, A., 2016: A complex landscape of inequity in access to urban parks: A literature review. *Landscape and Urban Planning*, **153**, 160–169. https://doi.org/10.1016/j.landurbplan.2016.05.017

135. Kellison, T. and M. Orr, 2021: Climate vulnerability as a catalyst for early stadium replacement. *International Journal of Sports Marketing and Sponsorship*, **22** (1), 126–141. https://doi.org/10.1108/ijsms-04-2020-0076

136. Murfree, J.R. and A.M. Moorman, 2021: An examination and analysis of Division I football game contracts: Legal implications of game cancellations due to hurricanes. *Journal of Legal Aspects of Sport*, **31** (1), 123–146. https://doi.org/10.18060/24922

137. Orr, M. and Y. Inoue, 2019: Sport versus climate: Introducing the climate vulnerability of sport organizations framework. *Sport Management Review*, **22** (4), 452–463. https://doi.org/10.1016/j.smr.2018.09.007

138. Yasarer, L.M.W. and B.S.M. Sturm, 2016: Potential impacts of climate change on reservoir services and management approaches. *Lake and Reservoir Management*, **32** (1), 13–26. https://doi.org/10.1080/10402381.2015.1107665

139. Lewis, J.M., D.J. Williams, S.J. Harris, and A.R. Trevisan, 2020: Characterization of Peak Streamflow and Stages at Selected Streamgages in Eastern and Northeastern Oklahoma from the May to June 2019 Flood Event—With an Emphasis on Flood Peaks Downstream from Dams and on Tributaries to the Arkansas River. USGS Open-File Report 2020-1090. U.S. Geological Survey, 18 pp. https://doi.org/10.3133/ofr20201090

140. Loveless, B., 2020: KDWPT Update to the Senate Committee on Agriculture and Natural Resources. Kansas Department of Wildlife, Parks, and Tourism, Topeka, KS, 2 pp. http://kslegislature.org/li/b2019_20/committees/ctte_s_agriculture_and_natural_resources_1/documents/testimony/20200115_01.pdf

141. Thomas, D.S.K., O.V. Wilhelmi, T.N. Finnessey, and V. Deheza, 2013: A comprehensive framework for tourism and recreation drought vulnerability reduction. *Environmental Research Letters*, **8** (4), 044004. https://doi.org/10.1088/1748-9326/8/4/044004

142. Osland, M.J., A.R. Hughes, A.R. Armitage, S.B. Scyphers, J. Cebrian, S.H. Swinea, C.C. Shepard, M.S. Allen, L.C. Feher, J.A. Nelson, C.L. O'Brien, Colt R. Sanspree, D.L. Smee, C.M. Snyder, A.P. Stetter, Philip W. Stevens, K.M. Swanson, L.H. Williams, Janell M. Brush, J. Marchionno, and R. Bardou, 2022: The impacts of mangrove range expansion on wetland ecosystem services in the southeastern United States: Current understanding, knowledge gaps, and emerging research needs. *Global Change Biology*, **28** (10), 3163–3187. https://doi.org/10.1111/gcb.16111

143. Dunning, K.H., 2021: Adaptive governance of recreational ecosystem services following a major hurricane. *Ecosystem Services*, **50**, 101324. https://doi.org/10.1016/j.ecoser.2021.101324

144. Dunning, K.H., 2020: Building resilience to natural hazards through coastal governance: A case study of Hurricane Harvey recovery in Gulf of Mexico communities. *Ecological Economics*, **176**, 106759. https://doi.org/10.1016/j.ecolecon.2020.106759

145. Wallace, D.J. and J.B. Anderson, 2013: Unprecedented erosion of the upper Texas coast: Response to accelerated sea-level rise and hurricane impacts. *GSA Bulletin*, **125** (5-6), 728–740. https://doi.org/10.1130/b30725.1

146. Armitage, A.R., W.E. Highfield, S.D. Brody, and P. Louchouarn, 2015: The contribution of mangrove expansion to salt marsh loss on the Texas Gulf Coast. *PLoS ONE*, **10** (5), 0125404. https://doi.org/10.1371/journal.pone.0125404

147. Tolan, J.M., 2007: El Niño-Southern Oscillation impacts translated to the watershed scale: Estuarine salinity patterns along the Texas Gulf Coast, 1982 to 2004. *Estuarine, Coastal and Shelf Science*, **72** (1–2), 247–260. https://doi.org/10.1016/j.ecss.2006.10.018

148. Pathak, A. and A. Fuller, 2021: Vulnerability and Adaptation to Climate Change: An Assessment for the Texas Mid-Coast. National Wildlife Federation, Austin, TX. https://texaslivingwaters.org/wp-content/uploads/2021/05/Mid-Coast-Assessment.pdf

149. Pawluk, M., M. Fujiwara, and F. Martinez-Andrade, 2021: Climate effects on fish diversity in the subtropical bays of Texas. *Estuarine, Coastal and Shelf Science*, **249**, 107121. https://doi.org/10.1016/j.ecss.2020.107121

150. Fujiwara, M., F. Martinez-Andrade, R.J.D. Wells, M. Fisher, M. Pawluk, and M.C. Livernois, 2019: Climate-related factors cause changes in the diversity of fish and invertebrates in subtropical coast of the Gulf of Mexico. *Communications Biology*, **2** (1), 1–9. https://doi.org/10.1038/s42003-019-0650-9

151. BEA, 2021: Outdoor Recreation Satellite Account (ORSA): 2020—Texas. U.S. Department of Commerce, Bureau of Economic Analysis, 2 pp. https://apps.bea.gov/data/special-topics/orsa/summary-sheets/orsa%20-%20texas.pdf

152. Cady, S.M., T.J. O'Connell, S.R. Loss, N.E. Jaffe, and C.A. Davis, 2019: Species-specific and temporal scale-dependent responses of birds to drought. *Global Change Biology*, **25** (8), 2691–2702. https://doi.org/10.1111/gcb.14668

153. Porro, C.M., M.J. Desmond, J.A. Savidge, F. Abadi, K.K. Cruz-McDonnell, J.L. Davis, R.L. Griebel, R.T. Ekstein, and N.H. Rodríguez, 2020: Burrowing Owl (*Athene cunicularia*) nest phenology influenced by drought on nonbreeding grounds. *The Auk*, **137** (2), ukaa008. https://doi.org/10.1093/auk/ukaa008

154. Chen, I.-C., J.K. Hill, R. Ohlemüller, D.B. Roy, and C.D. Thomas, 2011: Rapid range shifts of species associated with high levels of climate warming. *Science*, **333** (6045), 1024–1026. https://doi.org/10.1126/science.1206432

155. Sheridan, J.A. and D. Bickford, 2011: Shrinking body size as an ecological response to climate change. *Nature Climate Change*, **1** (8), 401–406. https://doi.org/10.1038/nclimate1259

156. Knight, S., 2021: A changing world: Ducks are still coming, how they are hunted is evolving. *Tyler Morning Telegraph*, November 4, 2021. https://tylerpaper.com/opinion/columnists/a-changing-world-ducks-are-still-coming-how-they-are-hunted-is-evolving/article_5f1ec2d4-3db0-11ec-a4d0-bb141b0f764d.html

157. Brody, S., R. Blessing, A. Sebastian, and P. Bedient, 2014: Examining the impact of land use/land cover characteristics on flood losses. *Journal of Environmental Planning and Management*, **57** (8), 1252–1265. https://doi.org/10.1080/09640568.2013.802228

158. EPA, 2021: Climate Change and Social Vulnerability in the United States: A Focus on Six Impacts. EPA 430-R-21-003. U.S. Environmental Protection Agency. https://www.epa.gov/cira/social-vulnerability-report

159. Marino, E., 2018: Adaptation privilege and voluntary buyouts: Perspectives on ethnocentrism in sea level rise relocation and retreat policies in the US. *Global Environmental Change*, **49**, 10–13. https://doi.org/10.1016/j.gloenvcha.2018.01.002

160. Martinich, J., J. Neumann, L. Ludwig, and L. Jantarasami, 2013: Risks of sea level rise to disadvantaged communities in the United States. *Mitigation and Adaptation Strategies for Global Change*, **18** (2), 169–185. https://doi.org/10.1007/s11027-011-9356-0

161. Arora, S. and D. Glover, 2017: Power in Practice: Insights from Technography and Actor-Network Theory for Agricultural Sustainability. STEPS Working Paper 100. STEPS Centre, Brighton, UK. https://steps-centre.org/publication/power-practice-insights-technography-actor-network-theory-agricultural-sustainability/

162. Thomas, K., R.D. Hardy, H. Lazrus, M. Mendez, B. Orlove, I. Rivera-Collazo, J.T. Roberts, M. Rockman, B.P. Warner, and R. Winthrop, 2019: Explaining differential vulnerability to climate change: A social science review. *WIREs Climate Change*, **10** (2), e565. https://doi.org/10.1002/wcc.565

163. Kapucu, N., C.V. Hawkins, and F.I. Rivera, 2013: Disaster preparedness and resilience for rural communities. *Risk, Hazards & Crisis in Public Policy*, **4** (4), 215–233. https://doi.org/10.1002/rhc3.12043

164. McDonald, R.I., T. Biswas, C. Sachar, I. Housman, T.M. Boucher, D. Balk, D. Nowak, E. Spotswood, C.K. Stanley, and S. Leyk, 2021: The tree cover and temperature disparity in US urbanized areas: Quantifying the association with income across 5,723 communities. *PLoS ONE*, **16** (4), e0249715. https://doi.org/10.1371/journal.pone.0249715

165. Zhou, W., G. Huang, S.T.A. Pickett, J. Wang, M.L. Cadenasso, T. McPhearson, J.M. Grove, and J. Wang, 2021: Urban tree canopy has greater cooling effects in socially vulnerable communities in the US. *One Earth*, **4** (12), 1764–1775. https://doi.org/10.1016/j.oneear.2021.11.010

166. Goodling, E., 2020: Intersecting hazards, intersectional identities: A baseline Critical Environmental Justice analysis of US homelessness. *Environment and Planning E: Nature and Space*, **3** (3), 833–856. https://doi.org/10.1177/2514848619892433

167. Pellow, D.N., 2021: Struggles for environmental justice in US prisons and jails. *Antipode*, **53** (1), 56–73. https://doi.org/10.1111/anti.12569

168. Skarha, J., M. Peterson, J.D. Rich, and D. Dosa, 2020: An overlooked crisis: Extreme temperature exposures in incarceration settings. *American Journal of Public Health*, **110** (S1), S41–S42. https://doi.org/10.2105/ajph.2019.305453

169. Chakraborty, J., T.W. Collins, and S.E. Grineski, 2019: Exploring the environmental justice implications of Hurricane Harvey flooding in Greater Houston, Texas. *American Journal of Public Health*, **109**, 244–250. https://doi.org/10.2105/ajph.2018.304846

170. Deria, A., P. Ghannad, and Y.-C. Lee, 2020: Evaluating implications of flood vulnerability factors with respect to income levels for building long-term disaster resilience of low-income communities. *International Journal of Disaster Risk Reduction*, **48**, 101608. https://doi.org/10.1016/j.ijdrr.2020.101608

171. Hendricks, M.D. and S. Van Zandt, 2021: Unequal protection revisited: Planning for environmental justice, hazard vulnerability, and critical infrastructure in communities of color. *Environmental Justice*, **14** (2), 87–97. https://doi.org/10.1089/env.2020.0054

172. Johnston, J. and L. Cushing, 2020: Chemical exposures, health, and environmental justice in communities living on the fenceline of industry. *Current Environmental Health Reports*, **7**, 48–57. https://doi.org/10.1007/s40572-020-00263-8

173. Madrigano, J., J.C. Osorio, E. Bautista, R. Chavez, C.F. Chaisson, E. Meza, R.A. Shih, and R. Chari, 2018: Fugitive chemicals and environmental justice: A model for environmental monitoring following climate-related disasters. *Environmental Justice*, **11** (3), 95–100. https://doi.org/10.1089/env.2017.0044

174. Flores, A.B., A. Castor, S.E. Grineski, T.W. Collins, and C. Mullen, 2021: Petrochemical releases disproportionately affected socially vulnerable populations along the Texas Gulf Coast after Hurricane Harvey. *Population and Environment*, **42** (3), 279–301. https://doi.org/10.1007/s11111-020-00362-6

175. Summers, K., A. Lamper, and K. Buck, 2021: National hazards vulnerability and the remediation, restoration and revitalization of contaminated sites—1. Superfund. *Environmental Management*, **67** (6), 1029–1042. https://doi.org/10.1007/s00267-021-01459-w

176. Burleson, D.W., H.S. Rifai, J.K. Proft, C.N. Dawson, and P.B. Bedient, 2015: Vulnerability of an industrial corridor in Texas to storm surge. *Natural Hazards*, **77** (2), 1183–1203. https://doi.org/10.1007/s11069-015-1652-7

177. de Bruijn, K., J. Buurman, M. Mens, R. Dahm, and F. Klijn, 2017: Resilience in practice: Five principles to enable societies to cope with extreme weather events. *Environmental Science & Policy*, **70**, 21–30. https://doi.org/10.1016/j.envsci.2017.02.001

178. Weden, M.M., V. Parks, A.M. Parker, L. Drakeford, and R. Ramchand, 2021: Health disparities in the U.S. Gulf Coast: The interplay of environmental disaster, material loss, and residential segregation. *Environmental Justice*, **14** (2), 110–123. https://doi.org/10.1089/env.2020.0049

179. Hamideh, S. and J. Rongerude, 2018: Social vulnerability and participation in disaster recovery decisions: Public housing in Galveston after Hurricane Ike. *Natural Hazards*, **93**, 1629–1648. https://doi.org/10.1007/s11069-018-3371-3

180. Cordova, S.J., 2022: Federal Indian policy and the fulfillment of the trust responsibility for disaster management in Indian country. In: *Justice, Equity, and Emergency Management*. Jerolleman, A. and W.L. Waugh, Eds. Emerald Publishing Limited, 89–106. https://doi.org/10.1108/s2040-726220220000025005

181. Farrell, J., P.B. Burow, K. McConnell, J. Bayham, K. Whyte, and G. Koss, 2021: Effects of land dispossession and forced migration on Indigenous peoples in North America. *Science*, **374** (6567), 4943. https://doi.org/10.1126/science.abe4943

182. Schramm, P.J., A.L.A. Janabi, L.W. Campbell, J.L. Donatuto, and S.C. Gaughen, 2020: How Indigenous communities are adapting to climate change: Insights from the Climate-Ready Tribes Initiative. *Health Affairs*, **39** (12), 2153–2159. https://doi.org/10.1377/hlthaff.2020.00997

183. Schlosberg, D. and L.B. Collins, 2014: From environmental to climate justice: Climate change and the discourse of environmental justice. *WIREs Climate Change*, **5** (3), 359–374. https://doi.org/10.1002/wcc.275

184. City of El Paso, 2016: Resilient El Paso. City of El Paso, 114 pp. https://www.elpasotexas.gov/assets/Documents/CoEP/Community-Development/Forms-and-Notices/2023-NOFA/City-of-El-Paso-Resilience-Strategy.pdf

185. Norton-Smith, K., K. Lynn, K. Chief, K. Cozzetto, J. Donatuto, M.H. Redsteer, L.E. Kruger, J. Maldonado, C. Viles, and K.P. Whyte, 2016: Climate Change and Indigenous Peoples: A Synthesis of Current Impacts and Experiences. Gen. Tech. Rep. PNW-GTR-944. U.S. Department of Agriculture, Forest Service, Pacific Northwest Research Station, Portland, OR, 136 pp. https://www.fs.usda.gov/treesearch/pubs/53156

186. Bartle, J.R. and D. Leuenberger, 2006: The idea of sustainable development in public administration. *Public Works Management & Policy*, **10** (3), 191–194. https://doi.org/10.1177/1087724X06287507

187. Giner, M.-E. and M. Pavon, 2021: A retrospective analysis of program outcomes and lessons learned on implementing first-time wastewater infrastructure in underserved communities in Texas from 1995 through 2017. *Environmental Challenges*, **5**, 100342. https://doi.org/10.1016/j.envc.2021.100342

188. Guerra Uribe, M., K.M. Faust, and J. Charnitski, 2019: Policy driven water sector and energy dependencies in Texas border colonias. *Sustainable Cities and Society*, **48**, 101568. https://doi.org/10.1016/j.scs.2019.101568

189. Brikowski, T.H., 2008: Doomed reservoirs in Kansas, USA? Climate change and groundwater mining on the Great Plains lead to unsustainable surface water storage. *Journal of Hydrology*, **354** (1), 90–101. https://doi.org/10.1016/j.jhydrol.2008.02.020

190. Nielsen-Gammon, J.W., J.L. Banner, B.I. Cook, D.M. Tremaine, C.I. Wong, R.E. Mace, H. Gao, Z.-L. Yang, M.F. Gonzalez, R. Hoffpauir, T. Gooch, and K. Kloesel, 2020: Unprecedented drought challenges for Texas water resources in a changing climate: What do researchers and stakeholders need to know? *Earth's Future*, **8** (8), e2020EF001552. https://doi.org/10.1029/2020ef001552

191. Dellapenna, T.M., C. Hoelscher, L. Hill, M.E. Al Mukaimi, and A. Knap, 2020: How tropical cyclone flooding caused erosion and dispersal of mercury-contaminated sediment in an urban estuary: The impact of Hurricane Harvey on Buffalo Bayou and the San Jacinto Estuary, Galveston Bay, USA. *Science of The Total Environment*, **748**, 141226. https://doi.org/10.1016/j.scitotenv.2020.141226

192. Lee, C. and G. Foster, 2013: Assessing the potential of reservoir outflow management to reduce sedimentation using continuous turbidity monitoring and reservoir modelling. *Hydrological Processes*, **27** (10), 1426–1439. https://doi.org/10.1002/hyp.9284

193. Mulki, S., C. Rubinstein, and J. Saletta, 2018: Texas' water quality challenge and the need for better communication in an era of increasing water quality contamination events. *Texas Water Journal*, **9** (1), 108–119. https://doi.org/10.21423/twj.v9i1.7059

194. Anderson, F. and N. Al-Thani, 2016: Effect of sea level rise and groundwater withdrawal on seawater intrusion in the Gulf Coast aquifer: Implications for agriculture. *Journal of Geoscience and Environment Protection*, **4** (4), 116–124. https://doi.org/10.4236/gep.2016.44015

195. Chowdhury, A.H., B.R. Scanlon, R.C. Reedy, and S. Young, 2018: Fingerprinting groundwater salinity sources in the Gulf Coast Aquifer System, USA. *Hydrogeology Journal*, **26** (1), 197–213. https://doi.org/10.1007/s10040-017-1619-8

196. Liu, Y., J. Li, J. Fasullo, and D.L. Galloway, 2020: Land subsidence contributions to relative sea level rise at tide gauge Galveston Pier 21, Texas. *Scientific Reports*, **10** (1), 17905. https://doi.org/10.1038/s41598-020-74696-4

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

198. ASCE, 2021: A Comprehensive Assessment of America's Infrastructure: 2021 Report Card for America's Infrastructure. American Society of Civil Engineers. https://infrastructurereportcard.org/

199. Oklahoma DOT, 2020: Oklahoma Long Range Transportation Plan: 2020–2045. Oklahoma Department of Transportation. https://www.oklongrangeplan.org/

200. Texas DOT, 2020: Texas Transportation Plan 2050. Texas Department of Transportation. https://ftp.dot.state.tx.us/pub/txdot/tpp/2050/ttp-2050.pdf

201. Kansas DOT, 2021: Kansas Long Range Transportation Plan: 2020–2045. Kansas Department of Transportation. https://www.ksdot.org/assets/wwwksdotorg/bureaus/burtransplan/documents/kdot_lrtp.pdf

202. Zottarelli, L.K., H.O. Sharif, X. Xu, and T.S. Sunil, 2021: Effects of social vulnerability and heat index on emergency medical service incidents in San Antonio, Texas, in 2018. *Journal of Epidemiology and Community Health*, **75** (3), 271–276. https://doi.org/10.1136/jech-2019-213256

203. Lindley, T., D. Speheger, M. Day, G. Murdoch, B. Smith, N. Nauslar, and D. Daily, 2019: Megafires on the Southern Great Plains. *Journal of Operational Meteorology*, **7** (12), 164. https://doi.org/10.15191/nwajom.2019.0712

204. Donovan, V.M., C.L. Wonkka, D.A. Wedin, and D. Twidwell, 2020: Land-use type as a driver of large wildfire occurrence in the U.S. Great Plains. *Remote Sensing*, **12** (11), 1869. https://doi.org/10.3390/rs12111869

205. Busch, K.C., J.A. Henderson, and K.T. Stevenson, 2019: Broadening epistemologies and methodologies in climate change education research. *Environmental Education Research*, **25** (6), 955–971. https://doi.org/10.1080/13504622.2018.1514588

206. Colston, N.M. and T.A. Ivey, 2015: (Un)doing the Next Generation Science Standards: Climate change education actor-networks in Oklahoma. *Journal of Education Policy*, **30** (6), 773–795. https://doi.org/10.1080/02680939.2015.1011711

207. KSDE, 2013: Kansas Science Standards—The Kansas College and Career Ready Standards for Science (KCCRSS): Disciplinary Core Ideas Arrangement. Kansas State Department of Education, Topeka, KS. https://community.ksde.org/Default.aspx?tabid=5785

208. TEA, 2022: Texas Essential Knowledge and Skills for Science. Texas Education Agency. https://tea.texas.gov/about-tea/laws-and-rules/texas-administrative-code/19-tac-chapter-112

209. Foss, A.W. and Y. Ko, 2019: Barriers and opportunities for climate change education: The case of Dallas-Fort Worth in Texas. *The Journal of Environmental Education*, **50** (3), 145–159. https://doi.org/10.1080/00958964.2019.1604479

210. Cook, J., N. Oreskes, P.T. Doran, W.R.L. Anderegg, B. Verheggen, E.W. Maibach, J.S. Carlton, S. Lewandowsky, A.G. Skuce, S.A. Green, D. Nuccitelli, P. Jacobs, M. Richardson, B. Winkler, R. Painting, and K. Rice, 2016: Consensus on consensus: A synthesis of consensus estimates on human-caused global warming. *Environmental Research Letters*, **11** (4), 048002. https://doi.org/10.1088/1748-9326/11/4/048002

211. Martin, E., R. McPherson, E. Kuster, and A. Bamzai-Dodson, 2020: Managing for a changing climate: A blended interdisciplinary climate course. *Bulletin of the American Meteorological Society*, **101** (12), E2138–E2148. https://doi.org/10.1175/bams-d-19-0242.1

212. Monroe, M.C., R.R. Plate, A. Oxarart, A. Bowers, and W.A. Chaves, 2019: Identifying effective climate change education strategies: A systematic review of the research. *Environmental Education Research*, **25** (6), 791–812. https://doi.org/10.1080/13504622.2017.1360842

213. Solis, M., W. Davies, and A. Randall, 2022: Climate justice pedagogies in green building curriculum. *Curriculum Inquiry*, **52** (2), 235–249. https://doi.org/10.1080/03626784.2022.2041981

214. Lake, P., 2021: Texas reimagines the fight against floods. *Texas Water Journal*, **12** (1), 58–67. https://doi.org/10.21423/twj.v12i1.7133

215. McPherson, R.A., C.A. Fiebrich, K.C. Crawford, J.R. Kilby, D.L. Grimsley, J.E. Martinez, J.B. Basara, B.G. Illston, D.A. Morris, K.A. Kloesel, A.D. Melvin, H. Shrivastava, J.M. Wolfinbarger, J.P. Bostic, D.B. Demko, R.L. Elliott, S.J. Stadler, J.D. Carlson, and A.J. Sutherland, 2007: Statewide monitoring of the mesoscale environment: A technical update on the Oklahoma Mesonet. *Journal of Atmospheric and Oceanic Technology*, **24** (3), 301–321. https://doi.org/10.1175/jtech1976.1

216. Patrignani, A., M. Knapp, C. Redmond, and E. Santos, 2020: Technical overview of the Kansas Mesonet. *Journal of Atmospheric and Oceanic Technology*, **37** (12), 2167–2183. https://doi.org/10.1175/jtech-d-19-0214.1

217. Schroeder, J.L., W.S. Burgett, K.B. Haynie, I. Sonmez, G.D. Skwira, A.L. Doggett, and J.W. Lipe, 2005: The West Texas Mesonet: A technical overview. *Journal of Atmospheric and Oceanic Technology*, **22** (2), 211–222. https://doi.org/10.1175/jtech-1690.1

218. Adeel, Z., A.M. Alarcón, L. Bakkensen, E. Franco, G.M. Garfin, R.A. McPherson, K. Méndez, M.B. Roudaut, H. Saffari, and X. Wen, 2020: Developing a comprehensive methodology for evaluating economic impacts of floods in Canada, Mexico and the United States. *International Journal of Disaster Risk Reduction*, **50**, 101861. https://doi.org/10.1016/j.ijdrr.2020.101861

219. Jenkins-Smith, H., J. Ripberger, C. Silva, N. Carlson, K. Gupta, M. Henderson, and A. Goodin, 2017: The Oklahoma meso-scale integrated socio-geographic network: A technical overview. *Journal of Atmospheric and Oceanic Technology*, **34** (11), 2431–2441. https://doi.org/10.1175/jtech-d-17-0088.1

220. Kindsvater, H.K., N.K. Dulvy, C. Horswill, M.-J. Juan-Jordá, M. Mangel, and J. Matthiopoulos, 2018: Overcoming the data crisis in biodiversity conservation. *Trends in Ecology & Evolution*, **33** (9), 676–688. https://doi.org/10.1016/j.tree.2018.06.004

221. Marston, L.T., A.M. Abdallah, K.J. Bagstad, K. Dickson, P. Glynn, S.G. Larsen, F.S. Melton, K. Onda, J.A. Painter, J. Prairie, B.L. Ruddell, R.R. Rushforth, G.B. Senay, and K. Shaffer, 2022: Water-use data in the United States: Challenges and future directions. *JAWRA Journal of the American Water Resources Association*, **58** (4), 485–495. https://doi.org/10.1111/1752-1688.13004

222. City of Oklahoma City, 2020: ADAPTOKC: Adapting for a Healthy Future. City of Oklahoma, City Planning Department, Oklahoma City, OK. https://www.okc.gov/home/showpublisheddocument/18882/637299972915330000

223. City of Austin, 2018: Climate Resilience Action Plan for City Assets and Operations. City of Austin, Office of Sustainability, Austin, TX. https://www.austintexas.gov/sites/default/files/files/Sustainability/Climate_Resilience_Action_Plan.compressed.pdf

224. City of San Antonio, 2019: SA Climate Ready: A Pathway for Climate Action and Adaptation. City of San Antonio, San Antonio, TX, 92 pp. https://www.sanantonio.gov/portals/0/files/sustainability/saclimateready/sacrreportoctober2019.pdf

225. City of Dallas, 2020: Dallas Comprehensive Environmental and Climate Action Plan. City of Dallas, Office of Environmental Quality and Sustainability. https://www.dallasclimateaction.com/_files/ugd/349b65_e4f9a262cebf41258fd4343d9af0504f.pdf

226. FEMA, 2022: City of Tulsa rises to the top as a leader in risk reduction. *FEMA.gov*. U.S. Department of Homeland Security, Federal Emergency Management Agency. https://www.fema.gov/blog/city-tulsa-rises-top-leader-risk-reduction

227. Kansas Water Office, 2022: The 2022 Kansas Water Plan. Kansas Water Office, Topeka, KS. https://kwo.ks.gov/docs/default-source/water-vision-water-plan/water-plan/finaldraft_kansaswaterplan_080522.pdf?sfvrsn=eefb8114_2

228. Cox, T., M. McCluskey, and K. Arthur, 2012: Incorporating Climate Change into Water Supply Planning and Yield Studies: A Demonstration and Comparison of Practical Methods. State of Oklahoma, Oklahoma Water Resources Board. https://www.owrb.ok.gov/ocwp/pdf/2012update/ocwp_watersmartclimatechangereport.pdf

229. TWDB, 2021: 2022 State Water Plan: Water for Texas. Texas Water Development Board. http://www.twdb.texas.gov/waterplanning/swp/2022/

230. Diringer, S., M. Shimabuku, H. Cooley, M. Gorchels, J. Walker, and S. Leurig, 2020: Scaling Green Stormwater Infrastructure Through Multiple Benefits in Austin, Texas: Distributed Rainwater Capture on Residential Properties in the Waller Creek Watershed. Pacific Institute, Oakland, CA. https://pacinst.org/publication/multiple-benefits-in-austin-texas/

231. Wade, M., R. Peppler, and A. Person, 2021: Community education and perceptions of water reuse: A case study in Norman, Oklahoma. *Journal of Environmental Studies and Sciences*, **11** (2), 266–273. https://doi.org/10.1007/s13412-021-00667-4

232. Beezhold, M.T. and D.W. Baker, 2006: Rain to recreation: Making the case for a stormwater capital recovery fee. *Proceedings of the Water Environment Federation*, **2006** (9), 3814–3825. https://mostcenter.umd.edu/rain-recreation-making-case-stormwater-capital-recovery-fee

233. Jayakaran, A.D., E. Rhodes, and J. Vogel, 2021: Stormwater management at the lot level: Engaging homeowners and business owners to adopt green stormwater infrastructure. In: *Oxford Research Encyclopedia of Environmental Science*. Oxford University Press. https://doi.org/10.1093/acrefore/9780199389414.013.653

234. Smith, D.J. and D. Sutter, 2013: Response and recovery after the Joplin tornado: Lessons applied and lessons learned. *The Independent Review*, **18** (2), 165–188. https://www.independent.org/publications/tir/article.asp?id=953

235. Westfall, N., E. Nelson, and B. Moorhead, 2019: Time and Treasure: Faith-Based Investment in Hurricane Harvey Response. Texas Interfaith Center for Public Policy, Austin, TX, 10 pp. https://texasimpact.org/time-treasure/

236. Hayhoe, K., 2021: *Saving Us: A Climate Scientist's Case for Hope and Healing in a Divided World*. Atria/One Signal Publishers, 320 pp. https://www.simonandschuster.com/books/saving-us/katharine-hayhoe/9781982143831

237. Gottlieb, R.S., ed, 2006: *The Oxford Handbook of Religion and Ecology*. Oxford University Press, USA. https://doi.org/10.1093/oxfordhb/9780195178722.001.0001

238. Haluza-DeLay, R., 2014: Religion and climate change: Varieties in viewpoints and practices. *WIREs Climate Change*, **5** (2), 261–279. https://doi.org/10.1002/wcc.268

239. White, S.S., 2010: Out of the rubble and towards a sustainable future: The "greening" of Greensburg, Kansas. *Sustainability*, **2** (7), 2302–2319. https://doi.org/10.3390/su2072302

240. BNIM Architects, 2008: Greensburg Sustainable Comprehensive Plan. BNIM Architects, Greensburg, KS. https://icma.org/documents/greensburg-sustainable-comprehensive-plan

241. Brundiers, K. and H.C. Eakin, 2018: Leveraging post-disaster windows of opportunities for change towards sustainability: A framework. *Sustainability*, **10** (5), 1390. https://doi.org/10.3390/su10051390

242. Paul, B.K. and D. Che, 2011: Opportunities and challenges in rebuilding tornado-impacted Greensburg, Kansas as "stronger, better, and greener". *GeoJournal*, **76** (1), 93–108. https://doi.org/10.1007/s10708-010-9404-4

243. Sparks, L.H. and S.S. White, 2013: Going green? The impacts of sustainability planning in Greensburg, Kansas, USA. *International Journal of Sustainable Development and Planning*, **8** (3), 288–304. https://doi.org/10.2495/sdp-v8-n3-288-304

244. IPCC, 2018: Summary for policymakers. In: *Global Warming of 1.5°C. An IPCC Special Report on the Impacts of Global Warming of 1.5°C Above Pre-industrial Levels and Related Global Greenhouse Gas Emission Pathways, in the Context of Strengthening the Global Response to the Threat of Climate Change, Sustainable Development, and Efforts to Eradicate Poverty*. Masson-Delmotte, V., P. Zhai, H.-O. Pörtner, D. Roberts, J. Skea, P.R. Shukla, A. Pirani, W. Moufouma-Okia, C. Péan, R. Pidcock, S. Connors, J.B.R. Matthews, Y. Chen, X. Zhou, M.I. Gomis, E. Lonnoy, T. Maycock, M. Tignor, and T. Waterfield, Eds. Cambridge University Press, Cambridge, UK and New York, NY, USA, 3–24. https://doi.org/10.1017/9781009157940.001

245. EIA, 2022: Introduction and Key Concepts: State Energy-Related Carbon Dioxide Emissions Tables. U.S. Department of Energy, U.S. Energy Information Administration, Washington, DC. https://www.eia.gov/environment/emissions/state/

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

247. TPWD, 2022: Private Landowners and Listed Species. Texas Parks and Wildlife Department. https://tpwd.texas.gov/huntwild/wild/wildlife_diversity/nongame/listed-species/landowner-tools.phtml

248. Miller, N., J. Tack, and J. Bergtold, 2021: The impacts of warming temperatures on US sorghum yields and the potential for adaptation. *American Journal of Agricultural Economics*, **103** (5), 1742–1758. https://doi.org/10.1111/ajae.12223

249. Rojas-Downing, M.M., A.P. Nejadhashemi, T. Harrigan, and S.A. Woznicki, 2017: Climate change and livestock: Impacts, adaptation, and mitigation. *Climate Risk Management*, **16**, 145–163. https://doi.org/10.1016/j.crm.2017.02.001

250. Doss-Gollin, J., D.J. Farnham, U. Lall, and V. Modi, 2021: How unprecedented was the February 2021 Texas cold snap? *Environmental Research Letters*, **16** (6), 064056. https://doi.org/10.1088/1748-9326/ac0278

251. Heynen, N., H.A. Perkins, and P. Roy, 2006: The political ecology of uneven urban green space: The impact of political economy on race and ethnicity in producing environmental inequality in Milwaukee. *Urban Affairs Review*, **42** (1), 3–25. https://doi.org/10.1177/1078087406290729

252. Sister, C., J. Wolch, and J. Wilson, 2010: Got green? Addressing environmental justice in park provision. *GeoJournal*, **75** (3), 229–248. https://doi.org/10.1007/s10708-009-9303-8

253. Mullenbach, L.E. and S.A. Wilhelm Stanis, 2022: Climate change adaptation plans: Inclusion of health, equity, and green space. *Journal of Urban Affairs*, 1–16. https://doi.org/10.1080/07352166.2022.2091449

254. Flores, A.B., T.W. Collins, S.E. Grineski, A.L. Griego, C. Mullen, S.M. Nadybal, R. Renteria, R. Rubio, Y. Shaker, and S.A. Trego, 2021: Environmental injustice in the disaster cycle: Hurricane Harvey and the Texas Gulf Coast. *Environmental Justice*, **14** (2), 146–158. https://doi.org/10.1089/env.2020.0039

255. Maldonado, A., T.W. Collins, S.E. Grineski, and J. Chakraborty, 2016: Exposure to flood hazards in Miami and Houston: Are Hispanic immigrants at greater risk than other social groups? *International Journal of Environmental Research and Public Health*, **13** (8), 775. https://doi.org/10.3390/ijerph13080775

256. Prudent, N., A. Houghton, and G. Luber, 2016: Assessing climate change and health vulnerability at the local level: Travis County, Texas. *Disasters*, **40** (4), 740–752. https://doi.org/10.1111/disa.12177

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

258. Collins, T.W., S.E. Grineski, J. Chakraborty, and A.B. Flores, 2019: Environmental injustice and Hurricane Harvey: A household-level study of socially disparate flood exposures in Greater Houston, Texas, USA. *Environmental Research*, **179**, 108772. https://doi.org/10.1016/j.envres.2019.108772

259. Collins, T.W., A.M. Jimenez, and S.E. Grineski, 2013: Hispanic health disparities after a flood disaster: Results of a population-based survey of individuals experiencing home site damage in El Paso (Texas, USA). *Journal of Immigrant and Minority Health*, **15** (2), 415–426. https://doi.org/10.1007/s10903-012-9626-2

260. Li, D., G.D. Newman, B. Wilson, Y. Zhang, and R.D. Brown, 2022: Modeling the relationships between historical redlining, urban heat, and heat-related emergency department visits: An examination of 11 Texas cities. *Environment and Planning B: Urban Analytics and City Science*, **49** (3), 933–952. https://doi.org/10.1177/23998083211039854

261. Atisa, G. and A.E. Racelis, 2022: Analysis of urbanization and climate change effects on community resilience in the Rio Grande Valley, South Texas. *Sustainability*, **14** (15), 9049. https://doi.org/10.3390/su14159049

262. Gutierrez, K.S. and C.E. LePrevost, 2016: Climate justice in rural southeastern United States: A review of climate change impacts and effects on human health. *International Journal of Environmental Research and Public Health*, **13** (2), 189. https://doi.org/10.3390/ijerph13020189

263. OWRB, 2012: Oklahoma Comprehensive Water Plan: Executive Report. Oklahoma Water Resources Board. https://www.owrb.ok.gov/ocwp/pdf/2012update/ocwp%20executive%20rpt%20final.pdf

264. Oklahoma Education, 2020: Oklahoma Academic Standards for Science. Oklahoma Education, 175 pp. https://sde.ok.gov/sites/ok.gov.sde/files/Oklahoma%20Academic%20Standards%20for%20Science.pdf

265. Puglisi, A. and J. Buitendag, 2022: A faith-based environmental approach for people and the planet: Some inter-religious perspectives on our Earth-embeddedness. *HTS Theological Studies*, **78** (2), 1–7. https://doi.org/10.4102/hts.v78i2.7582

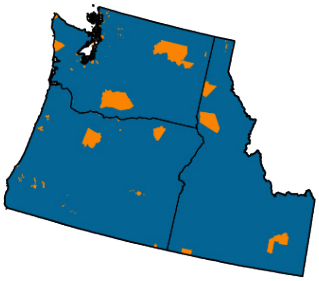
266. Jenkins, W., E. Berry, and L.B. Kreider, 2018: Religion and climate change. *Annual Review of Environment and Resources*, **43** (1), 85–108. https://doi.org/10.1146/annurev-environ-102017-025855

267. GCOOS, 2015: GCOOS Build-Out Plan—A Sustained, Integrated Ocean Observing System for the Gulf of Mexico: Infrastructure for Decision-Making. Gulf of Mexico Coastal Ocean Observing System. https://gcoos.org/wp-content/uploads/2020/04/BuildOutPlan-V2-updatedlogo-fin.pdf

268. Bender III, L.C., N.L. Guinasso Jr., J.N. Walpert, L.L. Lee III, R.D. Martin, R.D. Hetland, S.K. Baum, and M.K. Howard, 2007: Development, operation, and results from the Texas Automated Buoy System. *Gulf of Mexico Science*, **25** (1). https://doi.org/10.18785/goms.2501.04

Fifth National Climate Assessment: Chapter 27

Northwest



Chapter 27. Northwest

Authors and Contributors

Federal Coordinating Lead Author

Li Erikson, US Geological Survey, Pacific Coastal and Marine Science Center

Chapter Lead Author

Michael Chang, Cascadia Consulting Group

Chapter Authors

Kathleen Araújo, Boise State University, CAES Energy Policy Institute
Erica N. Asinas, University of Washington, Climate Impacts Group
Samantha Chisholm Hatfield, Oregon State University
Lisa G. Crozier, NOAA Fisheries, Northwest Fisheries Science Center
Erica Fleishman, Oregon State University
Ciarra S. Greene, Sapóoq'is Wíit'as Consulting
Eric E. Grossman, US Geological Survey, Pacific Coastal and Marine Science Center
Charles Luce, USDA Forest Service
Jayash Paudel, University of Oklahoma
Kirti Rajagopalan, Washington State University, Department of Biological Systems Engineering
Elise Rasmussen, Washington State Department of Health
Crystal Raymond, University of Washington, Climate Impacts Group
Julian J. Reyes, US Department of Agriculture
Vivek Shandas, Portland State University

Technical Contributors

Blane L. Bellerud, NOAA Fisheries, West Coast Region
Su J. Kim, NOAA Fisheries, Northwest Fisheries Science Center
Angela Pietschmann, Cascadia Consulting Group

Review Editor

Kathryn McConnell, Brown University

Cover Art

Claire Seaman

Recommended Citation

Chang, M., L. Erikson, K. Araújo, E.N. Asinas, S. Chisholm Hatfield, L.G. Crozier, E. Fleishman, C.S. Greene, E.E. Grossman, C. Luce, J. Paudel, K. Rajagopalan, E. Rasmussen, C. Raymond, J.J. Reyes, and V. Shandas, 2023: Ch. 27. Northwest. In: *Fifth National Climate Assessment*. Crimmins, A.R., C.W. Avery, D.R. Easterling, K.E. Kunkel, B.C. Stewart, and T.K. Maycock, Eds. U.S. Global Change Research Program, Washington, DC, USA. https://doi.org/10.7930/NCA5.2023.CH27

Table of Contents

Introduction 5

Key Message 27.1
Frontline Communities Are Overburdened, and Prioritizing Social Equity Advances Regional Resilience 8

Low-Income Urban Communities of Color 8
Rural and Natural Resource–Dependent Communities 10
Tribes and Indigenous Communities 10
Climate Action and Social Equity 10

Key Message 27.2
Ecosystems Are Transitioning in Response to Extreme Events and Human Activity 11

Ecological Effects of Climate Trends and Extreme Events 11
Terrestrial Ecosystems 13
Aquatic Ecosystems 13
Coastal and Marine Ecosystems 14
Box 27.1. Snake River Sockeye Salmon 16
Ability of Ecosystems and Species to Adapt to Climate Change 16

Key Message 27.3
Impacts to Regional Economies Have Cascading Effects on Livelihoods and Well-Being 17

Agricultural Industries and Livelihoods 17
Forest Industries and Livelihoods 18
Commercial Fisheries and Livelihoods 19
Tourism, Recreation, and Customer Service Industries 19
Box 27.2. Tribal Agricultural Economies Are Adapting to Climate Change 20
Just Transition and Community Livelihoods 20

Key Message 27.4
Infrastructure Systems Are Stressed by Climate Change but Can Enable Mitigation and Adaptation 21

Water Infrastructure 21
Energy Infrastructure 22
Box 27.3. Washington State's Electric Utility Wildland Fire Prevention Task Force 23
Transportation Infrastructure 24
Housing and Land Use 25

Key Message 27.5
Climate Change Amplifies Health Inequities 26
Physical Health Impacts of Climate Change 26
Mental Health Impacts and Climate Change 29
Community Health and Well-Being Impacts 29
Tribal Well-Being Impacts 29
Climate Action Can Benefit Human Health and Address Inequities 29

Key Message 27.6
Climate Change Affects Heritage and Sense of Place 30
Sense of Stability and Security 30
Environmental Amenities and Sense of Place 32
Tribal Cultures and Connection to the Land 33
Maintaining a Sense of Place and Heritage for the Northwest 34

Traceable Accounts 35
Process Description 35
Key Message 27.1 36
Key Message 27.2 38
Key Message 27.3 39
Key Message 27.4 40
Key Message 27.5 41
Key Message 27.6 42

References 44

Introduction

The Northwest—Washington, Oregon, and Idaho—encompasses diverse communities, economies, and ecosystems, with almost 14 million residents.[1] From western coastal regions to forested mountains to arid shrub-steppe, the Northwest is home to numerous culturally and economically important native plants and animals. Northwest ecosystems provide housing, recreation, food, and income that support the collective health and well-being of the region's communities and economies. The 43 Federally Recognized Tribes in the Northwest also rely on the region's ecosystems to sustain their livelihoods. Climate change has already affected all areas in the Northwest and will continue transforming the region in consequential ways. Northwest communities are employing a variety of strategies to adapt to and prepare for climate change; however, there are limits to the long-term effectiveness of adaptation actions without comparable investments to mitigate climate change (KM 31.1).[2,3]

Climate change observations in the Northwest are consistent with projections from previous National Climate Assessments.[4,5,6] Annual average air temperatures in the region have risen by almost 2°F since 1900. Washington and Idaho have warmed by nearly 2°F, and Oregon has warmed by 2.5°F. Relative to 1900–2020, the annual number of extremely hot days and warm nights in the Northwest has been above the long-term average over the past decade, and the annual number of extremely cold nights over the same period has been below the long-term average.[7,8] By the 2080s, annual average temperatures in the Northwest are projected to increase by an average of 4.7°F under a low scenario (SSP1-2.6) and by an average of 10.0°F under a very high scenario (SSP5-8.5) relative to the period 1950–1999.[9] Future warming in the region is expected to exacerbate regional heatwave intensities (KM 27.5).[8,10]

Warmer winter temperatures have led to declines in mountain snowpack, particularly in areas with warm maritime climates.[11,12,13,14] A greater proportion of winter precipitation is projected to fall as rain rather than snow.[15] Warmer winter temperatures are expected to increase snow-line elevation, contributing to snow-dominated watersheds transitioning to mixed rain-and-snow watersheds and mixed rain-and-snow watersheds transitioning to rain-dominated watersheds.[16,17] Summer precipitation is projected to decline under all scenarios, although it will be variable,[9] contributing to more frequent, longer, and more severe regional drought conditions that increase wildfire risk and decrease water availability (KMs 27.2, 27.3).

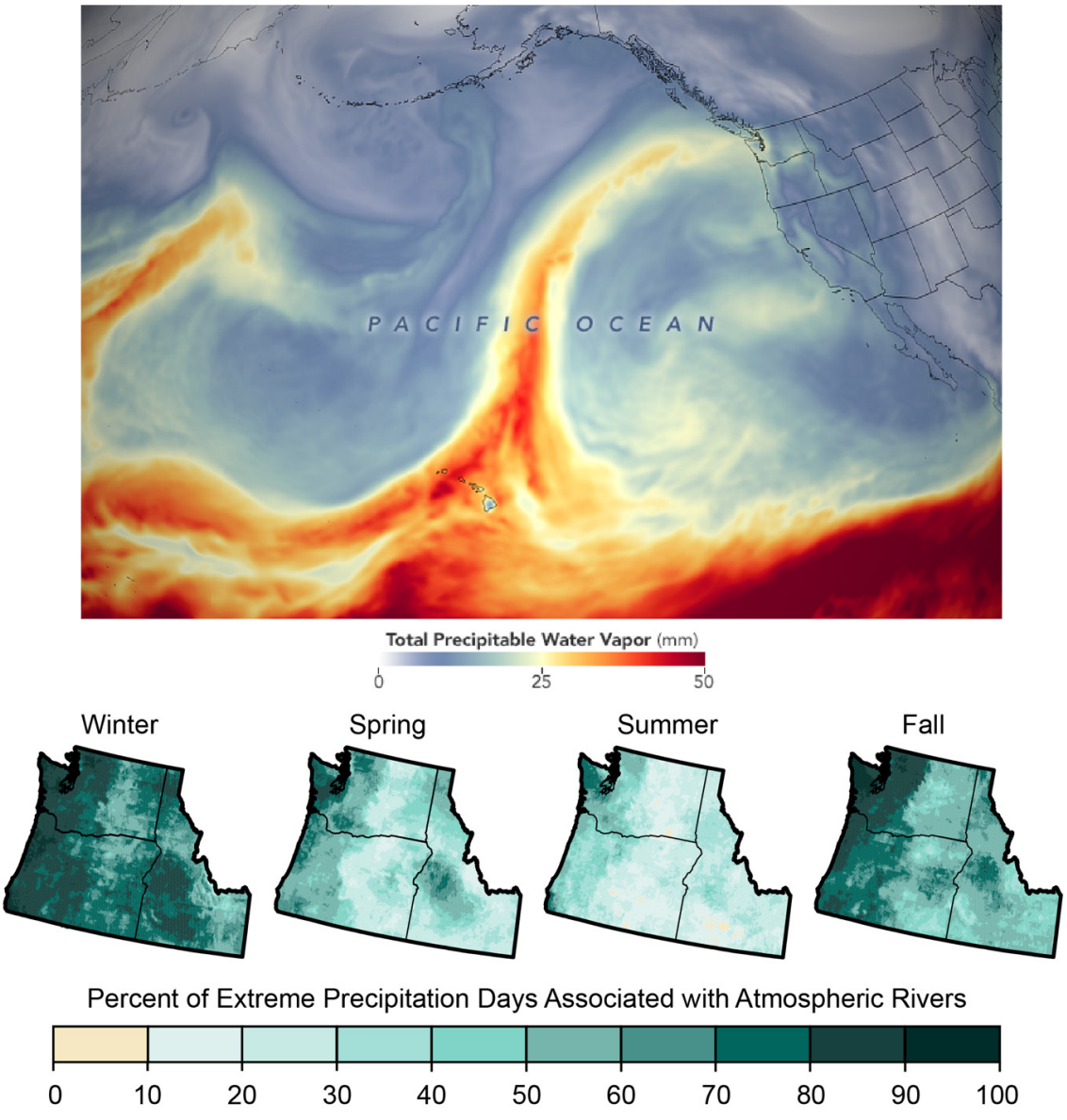
Interannual variability in precipitation is projected to persist, and observed lower streamflows in summer are expected to decrease even further due to reduced snow storage, increased evapotranspiration, and longer lags between summer precipitation events.[18,19,20] Increasingly low precipitation in drought years has driven extremely low streamflows.[20] Some currently permanent streams will transition to ephemeral streams, affecting aquatic species and regional water supply (KMs 27.2, 27.4).

Decreased snow accumulation and increasing melt are raising the elevation of the snow line, or the point at which annual accumulation and melt of snow are equal, which is causing Northwest glaciers to recede,[21,22] affecting recreation industries and regional water systems (KMs 27.3, 27.4, 27.6). Over the long term, streamflow reductions are expected in basins historically fed by glaciers.[23] Debris flows and landslides are expected to become more frequent as glacial recessions leave more bare land exposed to direct precipitation and the steep sideslopes of glaciated valleys are left unbuttressed by ice.[24]

The frequency and intensity of extreme precipitation events are projected to increase across the region.[7,8,25] Long, narrow bands of atmospheric water vapor transport, commonly known as atmospheric rivers (ARs), are associated with extreme precipitation in the western United States, where they contribute an average of 30%–45% of total winter precipitation (Figure 27.1).[26,27,28] ARs can cause severe damages,[29] such as the widespread damage resulting from ARs witnessed in western Washington in November 2021 (KM 27.4). A greater number of strong AR events and fewer moderate and weak events are projected to occur,[30]

although the changes in the frequency of landfalling ARs vary across climate models.[31,32] While the average contribution of ARs to annual precipitation in coastal areas is 50% or greater,[33] ARs are projected to reach farther inland.[34,35,36,37,38] Understanding how climate change affects ARs is critical to estimating how the region's water supply will change (KM 27.4).

Atmospheric Rivers and Extreme Precipitation in the Northwest



Extreme precipitation days are closely associated with atmospheric rivers, which are projected to be more frequent and intense and to reach farther inland.

Figure 27.1. (**top**) Satellite imagery shows the total precipitable water vapor on February 6, 2020. Red areas indicate more precipitable water vapor, which appears in a narrow band known as an atmospheric river (AR) directed toward the Northwest. (**bottom**) ARs are closely associated with extreme precipitation events and vary across meteorological seasons, as seen by the percentage of extreme precipitation events during 1981–2016 associated with ARs: winter (December–February), spring (March–May), summer (June–August), and fall (September–November). Fall and winter months have a higher percentage of extreme precipitation days associated with ARs, particularly in coastal regions and regions west of the Cascades. (top) Satellite image: Joshua Stevens, NASA Earth Observatory; (bottom) adapted with permission from Slinskey et al. 2020.[27] ©American Meteorological Society.

Seasonal coastal upwelling causes nearshore sea surface temperatures off the Washington and Oregon coasts to be cooler than offshore surface temperatures, tracking temperature trends in the slower-warming deep water.[39] Nonetheless, annual average coastal sea surface temperatures in the Northwest have warmed approximately 1.2°F since 1900, and the northern California Current is projected to warm by an additional 4.6°–7.3°F by the end of the century under a very high scenario (RCP8.5), affecting marine species in a variety of ways (KM 27.2).[39,40,41,42] Human-caused carbon emissions have already driven ocean acidification of surface and subsurface waters off Oregon and Washington.[43] Synergies among ocean acidification, hypoxia, and human-caused nutrient inputs negatively affect many species, with cascading effects on food webs and human communities (KMs 27.2, 27.6).[44,45,46]

Two recent periods of widespread and persistent high sea surface temperatures in 2014–2016 and in 2019, known as marine heatwaves (and informally as the "Blob" and "Blob 2.0"), temporarily increased onshore temperatures by up to 11°F above regional averages,[47] resulting in short-term shifts in species distributions and mortality of many seabirds[48] and marine mammals (KMs 10.1, 27.2).[49] These heatwaves increased the toxicity of harmful algal blooms to marine mammals and humans who consume crabs and other shellfish (KM 27.6).[50,51,52,53,54]

Sea level is projected to increase across the Northwest under all scenarios (App. 3.3).[55] Net sea level changes vary by location in response to rising sea levels and vertical land motion, which is the long-term change in land surface elevation from processes such as tectonic forces (Table 27.1).[56] Sea levels are further affected by climate cycles, such as El Niño, which can raise sea levels up to another 7.9 inches for several months. Relative to the 1991–2009 average, relative sea levels in the Northwest are projected to rise 0.6 to 1.0 feet by 2050 for the Intermediate and High scenarios, respectively (Table 27.1),[55] placing physical structures and communities at risk (KMs 27.1, 27.4).[57] In Puget Sound, where most land is subsiding, sea levels are expected to rise 0.9 to 1.6 feet by 2050 and 3.2 to 10.2 feet by 2150 under a very high scenario (RCP8.5), relative to the reference period. On Washington's outer coast, sea level rise is anticipated to range from 0.1 to 0.8 feet by 2050 in Neah Bay, where land is rising, and 0.5 to 1.2 feet by 2050 in Tahola, where land is subsiding, under a very high scenario (RCP8.5).[58]

Table 27.1 Sea Level Rise Projections for the Northwest

Sea level rise is projected to increase across the Northwest under all sea level rise scenarios. This table illustrates the variability of sea level rise projections for 2050, 2100, and 2150 across the Northwest under the Intermediate and High sea level scenarios[55] and for specific locations under comparable scenarios (50% likelihood of exceedance and 1% likelihood of exceedance, respectively) for downscaled sea level rise projections for Washington State under a very high scenario (RCP8.5).[58] The changes are increases in feet, relative to the 1991–2009 average. See Appendix 3 for associated information on scenarios.

Location	2050	2100	2150
Northwest Region	0.60–1.03	2.64–5.98	5.40–10.86
Tacoma, WA	0.9–1.6	2.5–5.3	4.2–10.7
Neah Bay, WA	0.1–0.8	1.0–3.8	1.8–8.4
Tahola, WA	0.5–1.2	1.7–4.5	3.0–9.5

Key Message 27.1

Frontline Communities Are Overburdened, and Prioritizing Social Equity Advances Regional Resilience

Ongoing systemic oppression disproportionately exposes frontline communities in the Northwest—including low-income urban communities of color; rural and natural resource–dependent communities; and Tribes and Indigenous communities—to the consequences of extreme heat, flooding, and wildfire smoke and other climate hazards (*very high confidence*). Frontline communities often have fewer resources to cope with and adapt to climate change but have been leaders in developing climate solutions within and outside their communities (*high confidence*). Actions to limit and adapt to climate change that prioritize climate justice and redirect investments to frontline communities can advance regional resilience (*medium confidence*).

In the Northwest, a history of disenfranchisement and systemic neglect of specific populations has influenced their geographic and occupational exposure to climate-related hazards.[59,60] Long-lasting effects of settler colonialism, racially restrictive covenants, and exclusionary laws have pushed Indigenous communities, communities of color, and low-income communities into areas that are more vulnerable to climate change.[59,61,62]

Additionally, economic, political, and social systems play critical roles in distributing the costs and benefits of climate action (KM 20.3), limiting frontline communities' socioeconomic mobility and, thus, their capacity to adapt. As a result, these communities not only experience disproportionate climate burden but also have the fewest resources with which to respond and adapt to climate change.[59]

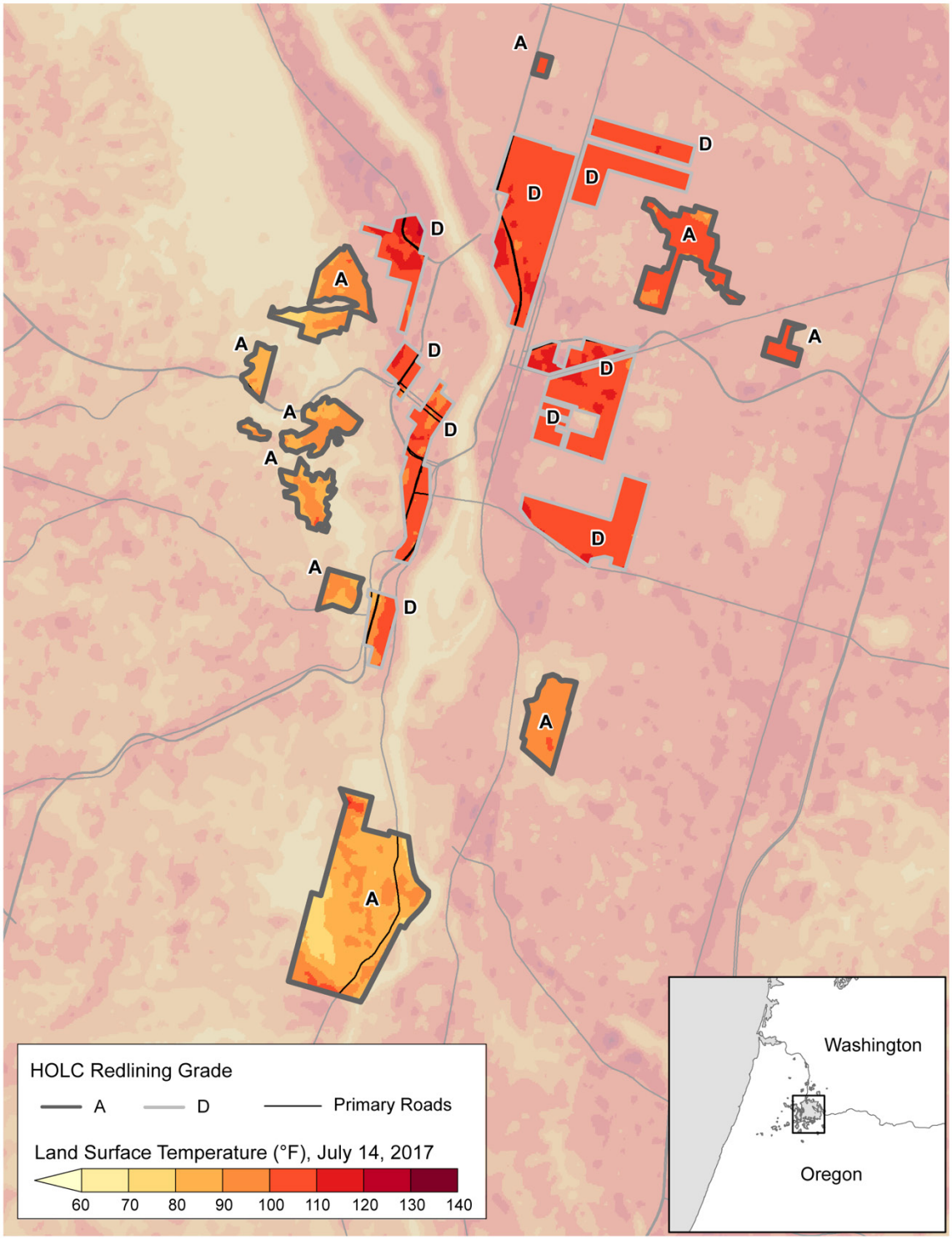
While many types of frontline communities exist—such as unhoused individuals, young children, older adults, and people with preexisting health conditions—this section highlights three communities: low-income urban communities of color, rural and natural resource–dependent communities, and Tribes and Indigenous communities.

Low-Income Urban Communities of Color

Redlining, restrictive housing covenants, and other historical policies have reinforced racial and economic discrimination and exacerbated inequitable exposure to contemporary climate impacts (KM 20.3).[63] Formerly redlined communities in Portland, Tacoma, Seattle, and Spokane are still economically and racially segregated and continue to be deprived of equitable access to environmental amenities that protect against the consequences of climate change.[64,65,66] Formerly redlined areas can be up to 13°F warmer than the city's average surface temperature (KM 27.4), intensifying some impacts for residents such as heat exhaustion (Figure 27.2).[67,68] Incidences of heat-related illness and death are on the rise and are expected to increase as the climate changes.[69] Extreme heat poses the most consequential health risks for older adults, low-income households, outdoor laborers such as agricultural workers and construction workers, people who are unhoused, and others who have limited access to adaptive resources such as affordable cooling options (KM 27.5).

Previously redlined communities also have reduced diversity of plant and animal species due to land-use decisions that facilitated industrialization, reduced tree cover, and increased the severity of the urban heat island effect.[68,70,71] Furthermore, the same factors contributing to urban heat islands—a higher proportion of water-impervious surfaces and lack of green spaces—also increase the chances of urban flooding during extreme precipitation events.[72,73]

Redlining and Extreme Heat in Portland, Oregon



Economically and racially segregated urban communities are inequitably exposed to climate change impacts, including extreme heat.

Figure 27.2. The map shows satellite-derived land surface temperature (in °F) for July 14, 2017. Areas in Portland, Oregon, that were historically redlined—that is, areas that received Home Owners' Loan Corporation (HOLC) grades of D, or "hazardous"—experience more intense heat island effects than areas that received HOLC grades of A or B. Residents are disproportionately exposed to extreme heat in these areas, where surface temperatures are up to 13°F warmer than the city's average surface temperatures.[68] Figure credit: Portland State University and NOAA NCEI.

Rural and Natural Resource–Dependent Communities

Many rural communities depend on natural resources and therefore are particularly vulnerable to climate change (KM 27.3).[74] Workers in natural resource and outdoor-based industries will experience heightened exposure to heatwaves and wildfire smoke,[75,76] and outdoor construction workers face higher rates of traumatic injuries when exposed to extreme heat.[77] Washington and Oregon have high numbers of agricultural workers, especially Latino migrant workers, many of whom live in areas with low community resilience to climate-related hazards.

Structural inequities limit low-income, migrant, and agricultural workers' access to clean air and drinking water, adequate living conditions, healthcare, and other social services, compromising their ability to adapt to climate-related risks.[78] As natural resource economies adapt, shifts in the seasonal availability of work and the diversification of local economies yield both positive and negative outcomes, including new economic opportunities, improved equitable occupational health and safety policies, and job security for outdoor workers and rural communities.[79,80,81] Weather- and climate-service providers supply these communities with tools and resources—such as communication materials or user-friendly models—to help them be more resilient.[82,83,84] Effective climate services that are inclusive of diverse perspectives and communities that also contextualize extreme weather events within long-term climate changes can reduce maladaptation and improve community resilience to climate change.[3,74,85,86,87]

Tribes and Indigenous Communities

Tribes and Indigenous communities experience disproportionate climate impacts and systemic barriers that limit their ability to adapt to climate change (KM 16.1).[88,89] Due to historical policies of land allotment, many landscapes have heterogeneous management across Tribal and non-Tribal jurisdictions, which can amplify wildfire or flooding risk to Tribal structures and limit the adaptation options for Tribal members. These policies complicate the ability of Tribes to access structures and spiritual locations during or after climate-related events.[90,91] For example, some coastal Tribes, such as the Quinault Indian Nation, are adapting to coastal flooding by reacquiring fractionated land to relocate housing and key facilities.[92] Even when Tribes manage contiguous areas of lands, limited access to funding, among other challenges, hinders planned or community-led relocation efforts (KM 9.3).[92,93]

Climate change also affects cultural and traditional foods and other resources, leaving Tribes without traditional sustenance and medicines for religious or ceremonial purposes (KM 27.6).[94,95] Climate change can shift resources outside usual and accustomed areas into adjacent non-Tribal jurisdictions or cause phenological shifts that affect cultural harvesting practices.[95] For example, shifts are expected in huckleberry habitat and the timing of huckleberry flowering and fruit ripening, affecting Tribes who rely on huckleberries for cultural and economic uses.[96]

Climate Action and Social Equity

Climate solutions designed without input from frontline communities can result in maladaptation, increasing vulnerability and cost burden.[97,98] For example, measures to lessen the impacts of extreme heat, like green infrastructure, have increased real estate values in cities such as Portland and Seattle, a phenomenon known as green gentrification.[59,99,100] As utilities transfer the costs related to extreme events and the transition to renewable energy directly to consumers, utility bills are expected to become unaffordable for low-income households.[101] Inequitable adaptation exacerbates displacement risks for low-income urban populations and can lead to cascading development pressures in rural areas (KM 27.6).[102,103,104] The rising cost of living, alongside socioeconomic disparities, limits temporary relief and long-term recovery options for those who are affected by climate-intensified extreme weather events, such as the 2021 heat dome event.

In response to grassroots advocacy and community-led efforts, state and local climate policies in the Northwest are increasingly recognizing the importance of climate justice. These policies are prioritizing strategies such as subsidizing adaptation, redistributing benefits, and reducing harm to frontline communities.[105,106] Despite facing disproportionate risks from climate change impacts, frontline communities have emerged as leaders in climate action, elevating policies that center social equity and confer resilience to communities across the region.[97]

Key Message 27.2

Ecosystems Are Transitioning in Response to Extreme Events and Human Activity

Ecosystems are expected to change as the climate continues to change and as the magnitude and frequency of extreme events increases (*very high confidence*). Some historical and ongoing human activities reduce ecosystem resilience and the adaptive capacity of species (*very high confidence*). These human activities are expected to exacerbate many effects of climate change (*very high confidence*). Human efforts to enable ecological adaptation founded in ecological theory are expected to improve ecosystem functions and services and reduce exposure to climate-related hazards (*medium confidence*).

Ecological Effects of Climate Trends and Extreme Events

Long-term changes in climate and the frequency and magnitude of extreme events, such as droughts, floods, and heatwaves, affect species and ecological processes (Figure 27.3).[107,108,109,110] High temperature records set in the Northwest from 2015 through 2021 were associated with many short-term or long-term ecological transformations, such as mortality or physiological damage to numerous native species of plants and animals, changes in water availability, and wildfire dynamics. Ecological effects and responses to climate change are not uniform, even among closely related species.[111,112]

Impacts of Climate-Related Extreme Events on Northwest Ecosystems

Long-term climate changes and extreme events threaten Northwest ecosystems.

Figure 27.3. (**top**) Flooding on November 16, 2021, in the Nooksack River is shown. Flooding is expected to become more frequent and severe as a result of more intense rainfall and rain-on-snow events. (**middle left**) Non-native invasives such as the European green crab (*Carcinus maenas*) disrupt food webs as their distribution expands with warming coastal waters. (**middle center**) Postfire debris flows are expected to become more common with increased wildfire and precipitation intensity. (**middle right**) Large areas across the Northwest—such as in Idaho—are prone to increased risk of wildfires. (**bottom left**) Aspen is sensitive to high air temperature, leading to more dying aspen groves. (**bottom center**) Increases in the distribution and density of non-native invasive grasses, such as cheatgrass (*Bromus tectorum*), exacerbate wildfire risk. (**bottom right**) Seedlings are more sensitive than mature trees to heat stress and drought. Satellite image: (top) Lauren Dauphin and Joshua Stevens, NASA Earth Observatory. Photo credits: (middle left) ©Emily Grason; (middle center, middle right, bottom left) ©Charlie Luce; (bottom center) ©Erica Fleishman; and (bottom right) Colorado State Forest Service.

Terrestrial Ecosystems

People in the Northwest rely on forests for diverse goods, services, and cultural purposes (KMs 7.2, 27.2). Warming temperatures and decreased summer precipitation over the past four decades have contributed to increases in the size and maximum elevation of wildfires in Northwest forests, and those trends are expected to continue.[113,114,115] Because concurrent heat and drought are becoming more common,[116] the volume of stressed or dead vegetation is increasing, which is increasing fuel load and wildfire risk. Across the western United States, many previously burned forests are reburning.[117] Some low-elevation and dry areas are converting from forest to shrubland after wildfires, and these transitions are expected to continue in the Northwest.[118,119]

In arid woodlands and shrublands throughout the Northwest, the distribution and abundance of non-native and highly flammable cheatgrass (*Bromus tectorum*) continue to increase before and after wildfires.[120,121] Cheatgrass establishment is associated with relatively high precipitation during autumn and spring[120] and with ground disturbance from wildfire, livestock grazing, and other types of land uses.[121,122] Changes in human activities such as recreation, development, transportation routing, and energy transmission will also continue to affect wildfire frequency (KM 27.4).[104] The length of the wildfire season and the potential for human-caused ignitions in all Northwest ecosystems are expected to increase as drought frequency, duration, and intensity increase.[123]

Climate change can affect the distribution and population dynamics of native and non-native species. When some non-native species become effective competitors with native and other non-native species, they are considered to be invasive in natural and human-dominated systems, including forests used for timber harvest or recreation. Some of these invasive species are expected to become more prevalent in response to projected increases in temperature, especially minimum winter temperature, and increases in the frequency, duration, and severity of drought across the Northwest.[117,124]

Additionally, some insects in the Northwest that harm or kill conifers are native herbivores that are prone to outbreaks. For example, densities of native mountain pine beetles (*Dendroctonus ponderosae*) generally are low, but outbreaks can result in 60% stand-level mortality over vast forest areas.[125] The Douglas-fir beetle (*Dendroctonus pseudotsugae*), another insect native to the Northwest, can damage both stressed and healthy Douglas firs (*Pseudotsuga menziesii*). The effects of outbreaks on trees generally are greatest during hot, dry summers when trees may be water-stressed.[126] Additionally, warm winters may decrease beetle mortality, increasing the likelihood of an eruption.[126,127]

Aquatic Ecosystems

Hydrological and thermal changes will prompt shifts in species composition of native and non-native fishes, especially where their habitats have been impaired by land use, including stream modifications and water withdrawals.[128,129,130,131] For example, rising temperatures, disease spread, and competition threaten the native bull trout (*Salvelinus confluentus*) and cutthroat trout (*Oncorhynchus clarkii*).[132] Non-native invasive species such as smallmouth bass (*Micropterus dolomieu*), which thrive in warmer waters, continue to expand in the Columbia River basin, competing with and consuming native salmonids.[133,134] Increased intensity of precipitation and occurrence of rain-on-snow events will increase flood severity and frequency, endangering salmon eggs and juveniles.[135,136,137,138,139]

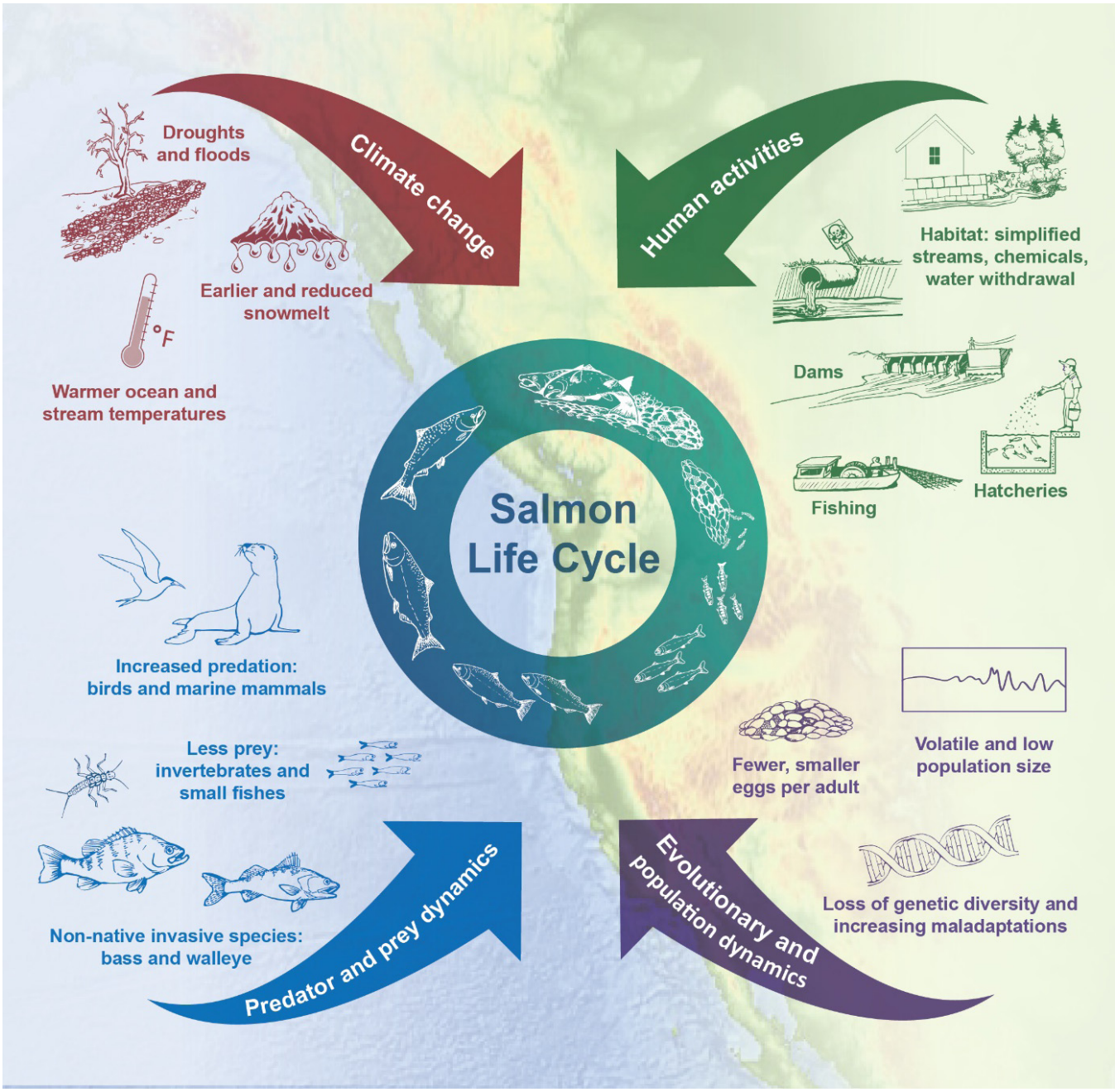
Increases in wildfire size and intensity are expected to lead to local extinctions of resident fishes,[140] warmer stream temperatures,[141] and increased sediment transport, turbidity, and fine sediments in streambeds.[142,143] Habitat connectivity can ameliorate local extinctions following wildfire and postfire debris flows, although local extinction can be permanent if habitat patches are small and are isolated by temperature or road culverts.[144]

Coastal and Marine Ecosystems

The 2014–2016 marine heatwave had numerous effects in the highly productive California Current marine ecosystem,[145,146,147] including the first documented domoic acid poisoning of sea lions, with detectable levels of domoic acid in dolphins, whales, and seals off the Washington coast.[148] These toxins are now detectable year-round in sea lions, not just during algal blooms.[149] Changes in the ecosystem during the heatwave also caused mass mortality of seabirds, such as Cassin's auklets (*Ptychoramphus aleuticus*)[48] and common murres (*Uria aalge*)[150] and led to extensive closures of crab and shellfish fisheries.[54] Many salmon populations also contracted sharply after the heatwave.[151] Preliminary evidence indicates that, following extreme heat in June 2021, numerous shellfish species became thermally stressed or died.[152] The frequency and intensity of marine heatwaves are expected to increase.[153] These marine heatwaves are expected to have broad-ranging impacts on marine ecosystems[154] and increase the incidence of human–wildlife conflict, such as entanglement of whales in fishing gear.[155] While the impacts of future marine heatwaves on species will vary—some species will decline, others will increase, and others will shift their distributions—current regulations and practices may not adequately respond to these impacts, potentially leading to disruptions in fisheries (KM 27.3).[145]

Salmon abundance, age at maturation, and size at maturity are widely correlated with climate trends (Figure 27.4).[156,157,158,159] Idaho's Snake River spring and summer Chinook and sockeye salmon are at particularly high risk across multiple future temperature scenarios (Box 27.1).[160,161,162,163,164,165] Increasing temperatures are expected to increase the duration and spatial extent of enabling conditions for harmful algal blooms,[166,167] increasing threats to marine mammals, fish, and shellfish. Population instability increases volatility in fisheries and the extinction risk for species that are already at low abundance.[168,169]

Interacting Stressors Affecting Salmon Resilience



Stressors stemming from interactions between human activities and natural systems affect freshwater and marine ecosystems and reduce salmon resilience to climate change.

Figure 27.4. Human activities and climate change alter the physical environment in concert, often amplifying their impacts through cumulative effects over the salmon life cycle. They also directly and indirectly alter freshwater and marine systems. Natural systems respond to changes in their environment through both evolutionary and ecological processes. The sum of these many different processes has led to declines in many populations of salmon over decades and reduced their ability to cope with future climate change. Figure credit: NOAA Fisheries.

Box 27.1. Snake River Sockeye Salmon

Snake River sockeye salmon, an important species for the region, is highly vulnerable to climate change.[161,170,171,172] Application of conservation genetics and interagency and Tribal cooperation[173,174] have sustained this culturally and ecologically unique population.

Over 150 years, a variety of human activities have affected Idaho sockeye. For example, overfishing, construction of dams that blocked migration for periods of time, and stocking of non-native fish populations altered aquatic ecological processes in complex ways.[175] Numerous factors contributed to sockeye declines until almost no fish returned from the ocean in the 1990s. All 16 adults known to have returned during that decade were captured and taken into a breeding program.[176,177] Subsequently, a collaboration among federal, state, and Tribal biologists increased reproduction of the captive fish, allowing the release of smolts and some adults to the wild to spawn. In 2014, a peak of 1,579 sockeye salmon returned to Idaho's Sawtooth Mountains.[151]

In July 2015, a record-breaking heatwave combined with low snowpack from the previous winter led to high water temperatures that killed nearly all naturally migrating adults, highlighting the vulnerability of this life stage in sockeye salmon.[161,178,179] To protect genetic diversity in hot years and maximize reproductive capacity, adults have been collected at dams and transported upriver nearly 500 miles. By the 2040s, temperatures in the free-flowing Salmon River, which travels 425 miles in central and eastern Idaho, could rise several degrees more than larger rivers downstream under SRES A1B and B1 scenarios (similar to intermediate and high scenarios). The Salmon River could lose nearly half its streamflow during the adult migration window, threatening this endangered species.[161] Extensive water withdrawals and habitat modifications in the Salmon River basin[171,180,181] exacerbate these conditions. Nevertheless, the quality of juvenile rearing habitat[182] and marine survival[174] are relatively high in this population, and reintroduction programs are widely supported.[183] Additional actions to restore cool, clean water throughout the basin would support the population's natural adaptation to climate change.[181,184,185]

Ability of Ecosystems and Species to Adapt to Climate Change

Historic and contemporary land use interacts with climate change to affect species' adaptive capacity—their genetic, physical, and behavioral ability to respond to environmental change.[186,187] Many different strategies to adapt and build resilience within Northwest ecosystems include ecological protection and management, assisted migration, market-based mechanisms, and conservation of genetic diversity.[188,189,190]

Protection and restoration of natural water bodies and processes that maintain water availability and quality can offset some effects of land use, including the growing demand for irrigation that reduces streamflow and freshwater habitat quality.[16] Similarly, modification of natural or built flood-control structures can reduce adverse downstream effects of changes in hydrology, sedimentation, and shoreline erosion and improve water quality and capacity for groundwater drainage in agricultural systems.[191] These efforts can lead to cascading benefits for habitats, supporting salmonids, other fishes, shellfish, and shorebirds.[192,193]

Restoration of floodplains that provide habitat for salmon[194] also benefits humans by reducing the current and future exposure of agriculture and infrastructure to flooding from the combined effects of higher sea levels, storm surge, and stream runoff.[195,196] As several dams and other barriers to historical spawning areas have been removed in recent decades, fishes have rapidly recolonized newly accessible habitat in some cases.[197,198,199,200]

Reintroduction of fire and thinning of non-fire-resistant vegetation reduce wildfire severity and risk in some Northwest forests and woodlands, especially dry forest types where vegetation has accumulated due to past fire exclusion policies.[201,202] These forest management practices also have the potential to reduce drought-related mortality.[203] Burning and forest thinning may not decrease wildfire severity and risks in wet or cold forest types[204,205] but can increase plant and animal diversity.

Wetlands offer some protection against extreme weather events.[206] Wetland mitigation banks create or enhance wetlands in a given location as compensation for loss or degradation of other wetlands. The number of these banks has increased across the region,[207] but long-term evaluations of created wetlands[208] or the effectiveness of wetland mitigation banks[209] are uncommon. Market-based approaches, such as temporary water-right leases or permanent transfers, have the potential to support ecosystem functions, such as instream flow augmentation for fish health, with payments to users of competing resources.[210] However, market and political bottlenecks affect the efficacy of these approaches.[211]

The ability of species to adapt to climate change is varied, and the likelihood of adaptation depends in part on the amount of genetic variation in a population or species, which is often related to the number of individuals and their relatedness.[188] Evolutionary responses to recent climate change have generally been less than what might be expected, and these constraints are not fully understood.[212,213] The feasibility of quantifying abundance, relatedness, and genetic variation varies among populations and species, and these measures have not been estimated for many populations and species.

Key Message 27.3

Impacts to Regional Economies Have Cascading Effects on Livelihoods and Well-Being

Climate change impacts to the Northwest's natural resource- and outdoor-dependent economies will be variable, given the diversity of industries, land cover, and climatic zones (*very high confidence*). Impacts to these industries will have cascading effects on community livelihoods and well-being (*high confidence*). While some industries and resource-dependent communities are resilient to climate-related stresses, economic responses to climate change can benefit affected industries, workers, and livelihoods (*medium confidence*).

Agricultural Industries and Livelihoods

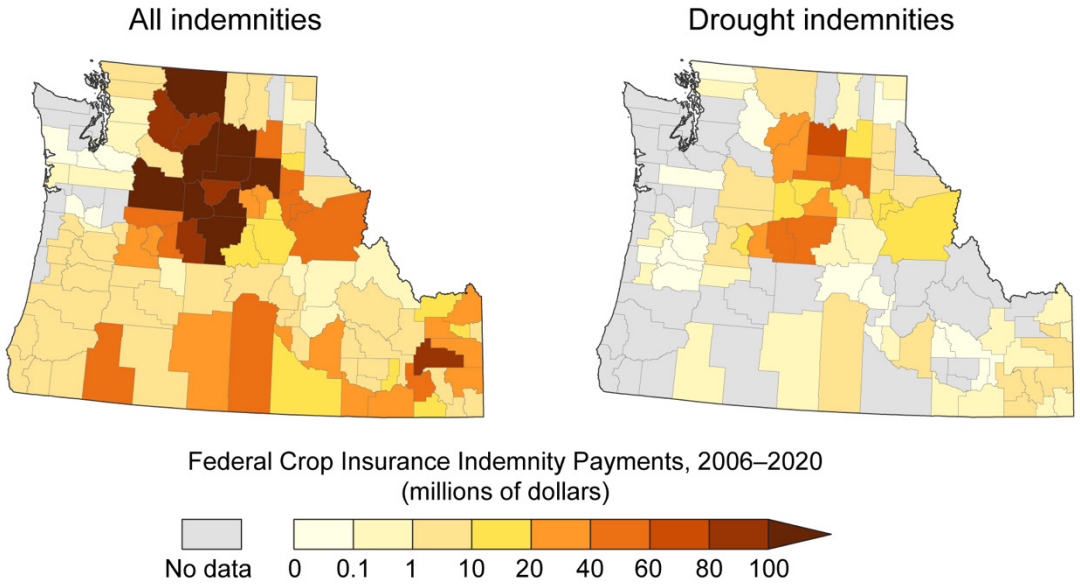
The Northwest encompasses 138.8 million acres of public and private cropland, grassland, pasture, rangeland, and forests,[214] and agricultural production totaled $6.28 billion in 2021 (in 2021 dollars).[215] The agricultural economy includes farms and ranches that have been in operation for multiple generations and is dependent on a seasonal migrant workforce, mostly from Mexico and Central America (KM 27.1).

Climate change affects crop production quantity and quality, and multiple competing effects depend on crop and region, causing increases and decreases in projected yields (Box 27.2; KM 11.1).[216] Chill accumulation—exposure to cold temperatures during dormancy—is key for fruit set and fruit quality in perennial crops and is expected to decrease in the southern parts of the Northwest and increase in the northern parts.[217] Increased exposure to extreme temperatures can induce cosmetic effects (e.g., sunburn in apples) that make crops increasingly unmarketable.[218] Pest pressures are expected to increase due to climate change; however, preliminary research indicates that the efficacy of non-chemical control of pests can also increase, providing opportunities for reduced pesticide use and environmental benefits.[217] Warmer autumns have been linked to potential increased risk of honeybee (*Apis mellifera*) colony failure in the following spring even in the absence of other stressors,[219,220] thereby affecting the specialty crop industry that relies on managed honeybees. While increasing temperatures in some regions may present new economic opportunities, such as winegrape growing in Puget Sound,[221] other climate-related impacts such as wildfire smoke may impede these emerging industries.[222]

Drought conditions have also affected the region's agricultural lands and rangelands. Across the region, the 2021 drought resulted in reduced access to irrigation water and yield loss for several crops.[223] Significant yield declines between 2020 and 2021 in winter wheat, spring wheat, and barley were also attributed to drought.[224] Droughts have also decreased forage availability and productivity, affecting livestock operations and management of habitat for other species.[225] Market approaches such as temporary leasing of water can alleviate drought impacts on agricultural productivity and the regional economy to a certain extent.[226] Similarly, grass banks, which allow landowners to lease forage space for ranchers in exchange for implementation of conservation projects by ranchers, can allow ranchers to better manage forage shortages caused by drought and are gaining popularity in the western United States.[227,228]

Increasing trends in crop insurance loss payments—an indicator associated with economic disruption of agricultural production due to extreme events and impacts—reflect the region's warming temperatures and declining snowpack (Figure 27.5).[229,230] Agricultural producer perceptions of climate risk affect the efficacy of place-based adaptation and resilience efforts, and operations that adapt to extreme weather and changing climate conditions may see improved productivity and resilience (KMs 6.1, 27.1).[3,82,83,87,231]

Agricultural Losses Through Crop Insurance Indemnity Payments



Increasing trends in crop insurance loss payments reflect the economic disruption of agricultural production due to extreme events including droughts.

Figure 27.5. These county-level maps compare all crop insurance indemnity payments from the US Department of Agriculture Risk Management Agency (**left**) with those specifically due to drought, from 2006 through 2020 (**right**). All indemnity payments reflect both biophysical and socioeconomic impacts from weather- and climate-driven events, including major droughts, on important commodities such as wheat and potatoes. Figure credit: USDA. See figure metadata for additional contributors.

Forest Industries and Livelihoods

Northwest forests provide multiple ecosystem and economic services. Rising temperatures and increased frequency of ecological disturbances may affect forest structure and growth (KM 27.2),[232] leading to reductions in the quantity and quality of forest products and commercially important timber species.[233,234,235,236] For example, these impacts could lead to the increase in density and distribution of ponderosa pine at higher elevations in the Blue Mountains ecoregion and the expansion of western Cascade

Range Douglas fir into higher elevations, affecting timber supply and carbon sequestration potential.[234,237,238] Dry coniferous forests and woodlands in lower to middle elevations—such as those on the east side of the Cascade Range, the Palouse Prairie–forest ecotone in Idaho, and drier areas of the Rocky Mountains—will experience large increases in wildfire frequency, extent, and severity, threatening forest and timber management initiatives.[117,239,240]

Climate impacts to forest industries will affect the livelihoods of communities dependent on timber and non-timber forest products.[234,237] While rural timber-based economies face additional economic risks from wildfires and drought, they also have local knowledge and insight to effectively reduce some of these risks (KM 27.1).[241] Despite this, climate impacts to forest product industries can lead to economic depression within some communities, resulting in migration away from these communities (KM 27.6).[241] However, localized species shifts could induce industries and private landowners to make new financially beneficial adaptation choices.[235,242] Other emerging opportunities, such as cross-laminated timber, can support local timber economies while providing sustainable and less carbon-intensive alternatives for construction.[243]

Reforestation and afforestation are expected to benefit ecosystem functions, such as increasing water quality, long-term carbon storage capacity, and viability of some native species (KM 7.2).[244] Tribal forest enterprises use harvest and conservation techniques reliant on Indigenous value systems to support improved forest management.[245] For example, the Confederated Tribes of the Colville Reservation are employing innovative drone technologies to conduct forest inventories, enabling them to improve their forest and timber management efforts, air and water quality, wildlife habitat, preservation of cultural areas and practices, and carbon sequestration potential.[246]

Commercial Fisheries and Livelihoods

Climate change has affected fisheries in the Northwest (KMs 27.2, 10.2). Marine heatwaves and harmful algal blooms have led to climate-induced fishery losses on the West Coast, accounting for a $641.1 million (in 2022 dollars) reduction in commercial fishing revenue.[247] Climate change can also intensify stressors such as decreasing catch and landing rates and accelerating the graying of the fleet phenomenon—the increasing average age of commercial fishers.[248,249] Fishery losses and closures can affect fishing-adjacent industries, such as hospitality, and the cultural identity of residents who directly or indirectly rely on fishing.[250]

Tribes account for over half of federal fishery loss requests.[247] Further population declines, especially of Pacific salmon, will have additional consequences for Tribal communities reliant on fish for subsistence, ceremonies, and health.[95,251] Ocean acidification, hypoxia events, and algal blooms are also hurting Tribal Dungeness crab fisheries.[252] It is not always feasible for Tribes to secure loans and equipment and to thrive in competitive market systems. However, many Tribes are utilizing Indigenous approaches and Tribal–federal partnerships to increase the resilience of their commercial and subsistence fisheries.[253]

Tourism, Recreation, and Customer Service Industries

The outdoor tourism and recreation industry in the Northwest supports $51.9 billion (in 2022 dollars) in annual expenditures and employs more than 588,000 individuals.[254] The economic impacts of climate change on the recreation industry will vary.[79] The snow season is projected to decrease by nearly half by the end of the century in parts of the Cascade Range.[255] Snow-based recreational industries such as skiing have already lost revenue due to the decrease in snow days, and future impacts to snowpack are expected to further harm snow-based recreational industries.[256,257] In contrast, earlier spring snowmelt and increasing temperatures can increase access to hiking trails and campgrounds, thereby extending these seasons. However, a regional shift from a snow- to a rain-dominated system (KM 27.6)[16,258] may present new operational and maintenance challenges from increased flooding and erosion.[259] Recently burned areas

typically are closed as a safety precaution, and poor air quality from wildfire smoke can deter outdoor activities and recreation.[79,260]

Higher temperatures may increase the demand for water-based and warm-weather activities such as boating, cycling, and fishing (KM 27.6).[79,261] For example, economic gains for cycling activities in Washington are expected to increase due to the declining numbers of cold days.[262] However, climate change can reduce the quality and aesthetics of recreational sites, affecting user preference and leading to reduced visitation rates.[79]

Changes in recreation management may produce inequitable outcomes. Rising costs to access recreation sites and limited ability to travel to alternative destinations will disproportionately affect low-income visitors. Increased cost of living in high-amenity areas such as ski resort towns will also stress workers and adjacent communities (KM 27.6).[263] Outdoor activities such as skiing and hiking can improve overall health and thereby reduce healthcare costs; however, decreased access to such activities can lead to increased risk of chronic diseases, mental health impacts, and loss of cultural heritage and connection to place (KM 27.6).[264]

Box 27.2. Tribal Agricultural Economies Are Adapting to Climate Change

Northwest Tribal economies are diverse, and many are affected by climate change. Tribes are utilizing innovative approaches that braid Indigenous and Western sciences together to respond to these challenges.

Climate change is affecting Tribal agriculture.[265] The Nez Perce Tribe is currently working with non-Tribal managers to pilot regenerative agricultural practices that integrate Traditional Ecological Knowledge to improve economic, ecological, and cultural resilience.[266] The Yakama Nation is reacquiring agricultural lands to promote food sovereignty and to train the next generation's Tribal members in sustainable and regenerative farming.[267,268]

Just Transition and Community Livelihoods

As local economies in the Northwest shift to low-carbon industries and climate-adaptive practices, historically overburdened workers will face higher exposure to climate-related hazards as well as risks of being excluded from economic shifts to a green economy (KM 27.1).[76,97,269] Local governments, Tribes, labor unions, and community groups across the region are evaluating and adopting policies and programs that support a just transition (KM 20.3).[97] Efforts toward a just transition in the Northwest region include investments in low-carbon sectors, local economic diversification plans, training and skills development for workers in resource-dependent and fossil fuel–dependent industries, financial assistance for impacted communities, and worker protections.[270,271] Despite progress in specific sectors, efforts that account for historically overburdened workers can reduce potential livelihood disruptions caused by economic shifts associated with decarbonization.[97,272]

Key Message 27.4

Infrastructure Systems Are Stressed by Climate Change but Can Enable Mitigation and Adaptation

Recent extreme events have stressed water systems and housing, transportation, and energy infrastructure across the Northwest (*very high confidence*). Extreme precipitation, droughts, and heatwaves will intensify due to climate change and continue to threaten these interrelated systems (*very high confidence*). Given the complexity of and interdependencies among infrastructure systems, an impact or a response within one sector can cascade to other sectors (*very high confidence*). Cross-sectoral planning, which can include redesigning aging infrastructure and incorporating climate considerations into land-use decisions, can increase resilience to future climate variability and extremes (*high confidence*).

Infrastructure systems are threatened by extreme events such as drought, wildfire, heatwaves, floods, and landslides (KM 12.2).[273] Climate change has revealed vulnerabilities in infrastructure planning and design, which are typically based on historical conditions and do not account for recent increases in the frequency or severity of extreme events. Isolated communities and those without alternatives if infrastructure fails are among the most vulnerable. Designing resilient infrastructure requires accounting for interdependencies among the built environment's physical and social elements.[274,275,276]

Water Infrastructure

Droughts in the last decade in the Northwest demonstrated water supply vulnerabilities, such as depletion of reservoirs across central and eastern Oregon and southern Idaho.[277,278] Some water sources, infrastructure, and operations that treat and convey water were resilient during these droughts. However, some water providers were forced to access alternative sources, institute mandatory or voluntary conservation measures, or otherwise modify their operations. Small rural water providers are vulnerable because they usually depend on a single water source or sources with limited capacity and because operators generally have limited resources for planning, upgrades, and emergency response (KM 27.1). Wildfires in 2020 and 2021 damaged physical elements of the water delivery and treatment systems, disrupted electricity systems, and increased the amount of sediment in waterways and reservoirs.[142,279] These vulnerabilities will increase as droughts and wildfires become more frequent and severe.

About 30% of Northwest households use septic systems to treat their wastewater.[280] Sea level rise, high temperatures, extreme precipitation, and high streamflows reduce the function of septic systems.[281,282] For example, saturated soils impede wastewater treatment in drainfields.[283] Failures of wastewater storage and treatment will negatively affect human health and increase nitrogen loads in waterways.[284]

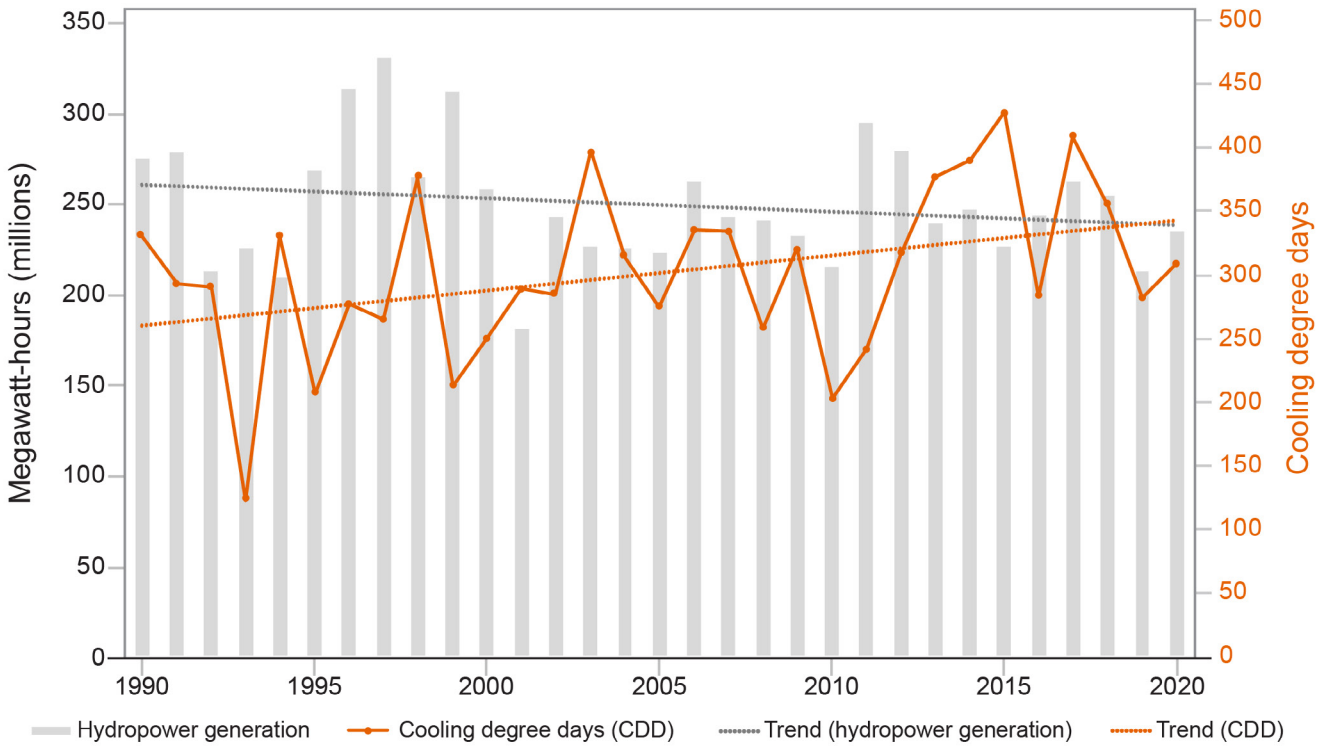
Emerging data and technologies can make drinking water and stormwater systems more resilient to climate change. For example, projections of changes in storm duration, intensity, and frequency[285] provide information needed to upgrade stormwater systems to reduce stresses from extreme precipitation.[286,287] Water utilities can reduce water losses during delivery and alleviate stress to the system during hotter summers and more severe droughts by upgrading distribution lines and minimizing water losses during treatment.[288] Water-efficient appliances, sprinklers with soil moisture sensors, drought resilient plants, and conservation education and incentives can also reduce water demand.[288]

Energy Infrastructure

Climate change impacts nearly every aspect of the energy system, with interdependencies and cascading effects in other critical sectors (KMs 5.1, 12.2, 31.1; Focus on Compound Events). For instance, less snow, earlier snowmelt, and more frequent and intense droughts will alter the seasonal capacity of hydropower, a primary source of regional energy, to meet electricity demand.[278,289,290,291] Earlier snowmelt is also increasing the need for water storage in Idaho reservoirs.[11] Removal of dams may support salmon recovery but can reduce resilience in the regional power system (Box 27.1).[292]

Increasing temperatures and heatwaves are shifting the seasonal timing and spatial footprint of electricity demand.[291,293] Cooling degree days, a metric associated with energy demand for cooling, are increasing across the Northwest, and the region's population increases will also affect the electricity demand, potentially leading to energy shortfalls (Figure 27.6).[294] Population growth and droughts are expected to amplify competing claims to the water supply by irrigators, Tribes, power plants, and other water rights holders,[295,296] highlighting the interdependencies of energy, water, and agricultural systems. Strategies such as demand-side management (voluntarily shifts in power loads) and ongoing additions of solar power, such as that being pursued by the Nez Perce Tribe,[297] can increase the resilience of energy infrastructure.

Annual Cooling Degree Days Relative to Annual Hydropower Generation



Hydropower generation is currently meeting the number of cooling degree days but might not continue to do so as temperatures and heatwaves increase in the future.

Figure 27.6. Cooling degree days—the annual cumulative number of days on which the average temperature is greater than 65°F—are typically used to measure cooling energy demand. During 1990–2020, the annual number of cooling degree days (orange lines) increased, whereas annual hydropower generation (in millions of megawatt-hours, gray bars) decreased slightly. Hydropower generation may not meet projected future cooling demand, especially during summer. Figure credit: Boise State University and Cascadia Consulting Group.

Electricity transmission and distribution grids are both a source of wildfire risk and are also at risk from wildfire, particularly in hot, dry, and windy conditions. Electric utilities and land management agencies are evaluating potential actions that they can take to reduce future wildfire risk and impacts on electricity systems (Box 27.3). Some Northwest electric utilities are exercising public safety power shutoffs or "fast trip" programs that trigger outages when faults are detected.[298] Such shutoffs can reduce the likelihood of ignitions from the electric grid when complemented by other risk-mitigation measures but can also negatively affect local economies and human health (Focus on Western Wildfires). Risks to electric grid infrastructure from wildfires may also be higher in remote areas, as monitoring capacity is less robust.

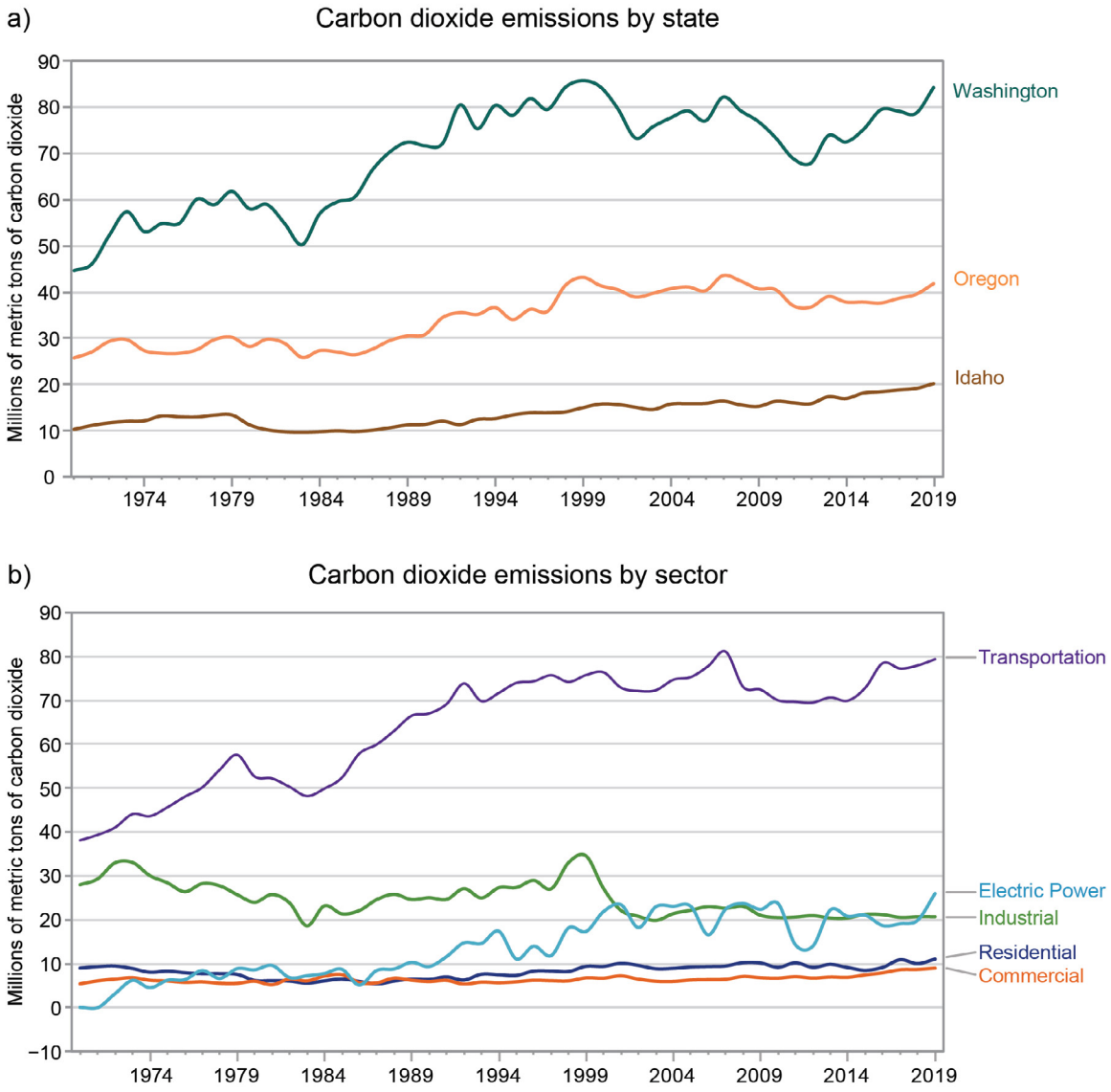
Box 27.3. Washington State's Electric Utility Wildland Fire Prevention Task Force

Many states, including those in the Northwest, are taking new action on climate-related challenges for critical energy infrastructure. For example, in response to western wildfires in 2019 ignited by electricity transmission lines or that temporarily reduced electric services, the Washington State Legislature convened the Electric Utilities Wildland Fire Prevention Task Force[299] with the intent of increasing electricity infrastructure resilience through improved coordination across agencies and information sources. The task force advised the Washington State Department of Natural Resources on vegetation management, communication protocols, and investigation protocols related to wildfire risk and electricity reliability. The three outcomes of the task force's work were a model agreement for managing vegetation outside rights-of-way, protocols for coordinated investigation of wildfires that interact with utilities, and coordination of annual information exchanges among land managers, utility operators, and wildfire experts.

Carbon emissions have been increasing on an absolute basis in the Northwest (Figure 27.7). The shift to low-carbon energy systems can be complex, and there are varied trade-offs and co-benefits between technological innovations that can enhance the viability of clean energy sources and increase the resilience of both infrastructure systems and the communities and industries dependent on them (KM 5.3).[300,301]

Transitions to low-carbon energy may be perceived as requiring substantial time to accomplish, yet research has shown that considerable low-carbon transitions can occur in less than 15 years.[302] Considering these conditions, states, local governments, and utilities have begun to develop low-carbon and decarbonization plans and pathways. Oregon passed legislation to eliminate carbon emissions from the power grid by 2040, and Washington passed legislation to reduce carbon emissions by 95% from 1990 levels by 2050. In Idaho, cities such as Boise and utilities such as Idaho Power have carbon reduction plans.[105,303] Agencies and utilities are utilizing diverse strategies including energy conservation and efficiency investments; design approaches such as buildings with southern-facing windows to reduce cooling needs; harnessing renewable gas from farms and municipal landfills; and exploring and utilizing alternative energy sources while investing in decarbonization technologies.[300,304,305,306]

Carbon Dioxide Emissions from Fossil Fuels by State and Sector



Carbon dioxide emissions from fossil fuel consumption vary widely by sector and state.

Figure 27.7. These graphs show carbon dioxide (CO_2) emissions (in millions of metric tons) from fossil fuel consumption by state (**top**) and sector (**bottom**). Carbon dioxide emissions from fossil fuel consumption are greatest in Washington, followed by Oregon and Idaho. Transportation emits more CO_2 than other sectors across Idaho, Oregon, and Washington. Figure credit: Boise State University and Cascadia Consulting Group.

Transportation Infrastructure

Atmospheric rivers in 2021 illustrated existing understanding of how landslides and flooding can disrupt transportation routes.[307,308] The disruption of transportation routes can lead to injury or death due to a lack of evacuation routes and cutoff from critical emergency services, healthcare, and other goods and services.[29,309] In extreme cases, the loss of transportation routes and social services may displace households and reduce regional labor supply.[310] Much of the Northwest's transportation infrastructure, such as railroads, bridges, and highways, is aging and thereby increasing vulnerability to climate-related hazards. For example, the average age of all surveyed bridges in Oregon is 46 years old, and the typical design life is

75 years.[311] Some state transportation agencies, such as Washington State Department of Transportation and Oregon Department of Transportation, have assessed climate risks to their routes and highways and various adaptation options (KM 13.1).[312,313]

Transportation is the largest source of greenhouse gas emissions in the Northwest (Figure 27.7), and utilities and transportation agencies across the region are exploring electrification options to reduce emissions. However, efforts to electrify the transportation sector will increase electricity demand and place additional stress on the regional energy system (KM 13.1).[314,315,316] Electric vehicles' energy efficiency and electricity sources will affect the potential magnitude of reduction in transportation-related emissions (KM 13.4).[314,316]

Housing and Land Use

The majority of the land in urban areas is devoted to residential housing, which provides shelter to people during extreme events but can also exacerbate exposure to harmful impacts. The specific location of urban housing structures can directly affect the severity of local climate impacts. Urban areas are warmer than their surrounding landscapes, a phenomenon known as the urban heat island effect, and some urban neighborhoods can experience temperatures upwards of 13°F warmer than other areas of the same city (KMs 27.1, 12.2). Residential density in urban areas is increasing more in historically lower-income neighborhoods, reducing the availability of green space and increasing the extent of impervious surfaces, thereby worsening heat island effects.[68,100] Urban trees and other vegetation could provide shade, but there are trade-offs between mitigating heat islands and conserving water.[317] Creating incentives or requirements for water-efficient landscaping (xeriscaping) while also providing shade and stormwater absorption could help reduce adverse impacts from extreme heat and storms.

Similarly, the location of housing beyond urban centers also interacts with the impacts from climate change. For example, housing in the wildland–urban interface (WUI)—or locations where wildland vegetation and houses meet—has increased over the past several decades and increases the risk of wildfire impacts on housing structures (KM 27.6).[102,318]

Furthermore, the quality of materials and types of amenities in both urban and rural housing design and construction affect exposure to some impacts, such as wildfire smoke. Households with access to HVAC and air filtration systems can improve indoor air quality and reduce wildfire smoke exposure;[319,320] however, they may be insufficient to mitigate anticipated increases in the number of wildfire smoke days and associated high concentrations of fine particulate matter and other pollutants.[321,322]

Climate change will also affect digital infrastructure, such as internet infrastructure systems. For example, fiber conduits and nodes in the greater Seattle area are at risk of inundation from sea level rise by the 2030s,[323] jeopardizing telecommuting strategies that some jurisdictions are using to reduce vehicle-miles traveled by employees and associated transportation-related emissions.

Because land-use laws determine how human activity is distributed in space and how infrastructure is built, they affect mitigation of and adaptation to climate change.[324] While each state has a different set of land-use policies, state-level land-use planning guidelines can limit or expand opportunities for local land-use plans to respond to climate change (KMs 6.2, 12.3). Nevertheless, land-use laws and policies can facilitate adaptation in multiple ways, including protection (protecting existing structures from climate-related hazards via engineered structures), accommodation (continued use in hazardous locations, like flood zones, by improving design or development standards such as raising foundations or creating natural floodplains), or retreat (restricting new development in hazardous locations).[324,325,326,327]

Key Message 27.5

Climate Change Amplifies Health Inequities

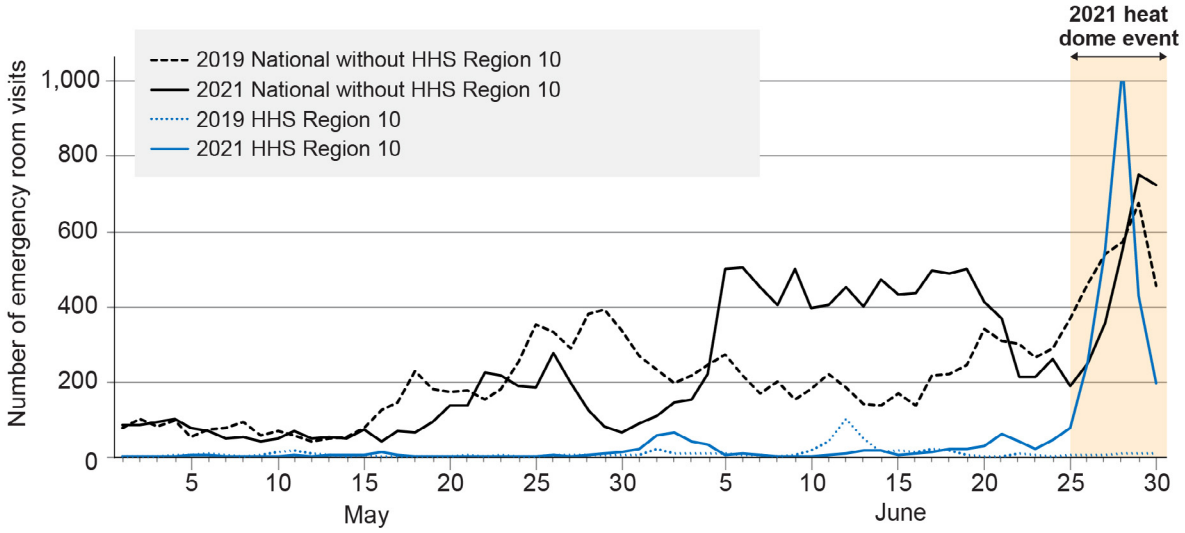
The Northwest's climate has historically been temperate and relatively mild, but shifting weather patterns associated with climate change are adversely affecting physical, mental, and community health (*very high confidence*). The incidence of illnesses and death during extreme heat events and wildfire smoke days is increasing, and climate change is stressing health systems (*high confidence*). Climate-related health risks disproportionately affect certain individuals and groups (*very high confidence*). Climate resilience efforts can be leveraged to improve health, especially among the most vulnerable populations (*high confidence*).

Multiple public health challenges have been associated with climate change. Those whose livelihoods are dependent on the weather—like outdoor day laborers and wildland firefighters—and people with preexisting health conditions and limited coping capacities face some of the gravest challenges (KM 15.1). COVID-19 has overextended the public health sector since 2020 and strained traditional approaches to reducing public health impacts from climate-induced disasters (such as cooling or warming shelters), because convening groups in large areas has been prohibited or limited (Focus on COVID-19 and Climate Change).

Physical Health Impacts of Climate Change

Climate change amplifies health risks, especially for those with underlying health conditions, and leads to physical health impacts such as premature mortality from heatwaves, compromised respiratory health due to wildfire smoke, infectious and vector-borne diseases, exposure to mold and environmental health hazards, diseases in some foods and natural resources such as shellfish toxins (KMs 27.2, 27.6), and exposure to toxicants (KM 15.1). Heatwaves and extreme heat, which are increasing in frequency and intensity, kill more people annually than any other natural hazard.[328,329] Increasing frequency of wildfires will increase the number of poor air quality days.[75] Together, heat and wildfire smoke have caused thousands of deaths in the Northwest since 2018. The greatest number of deaths occurred in summer 2021 (Figure 27.8)[330] when almost a thousand people perished during an extraordinary heatwave that was partially attributed to climate change.[331,332] Although it is unknown whether events such as the 2021 heat dome are an anomaly or will become increasingly frequent in the Northwest,[333] future heat-related morbidity and mortality across the Northwest are expected to increase across all scenarios.[69,334] Many of these deaths were preventable and happened because communities were maladapted to the level of heat, which disproportionately affected women, people of color, and people with chronic illnesses and placed additional strain on the Northwest's healthcare system.[69,330]

Heat-Related Emergency Room Visits for Health and Human Services (HHS) Region 10

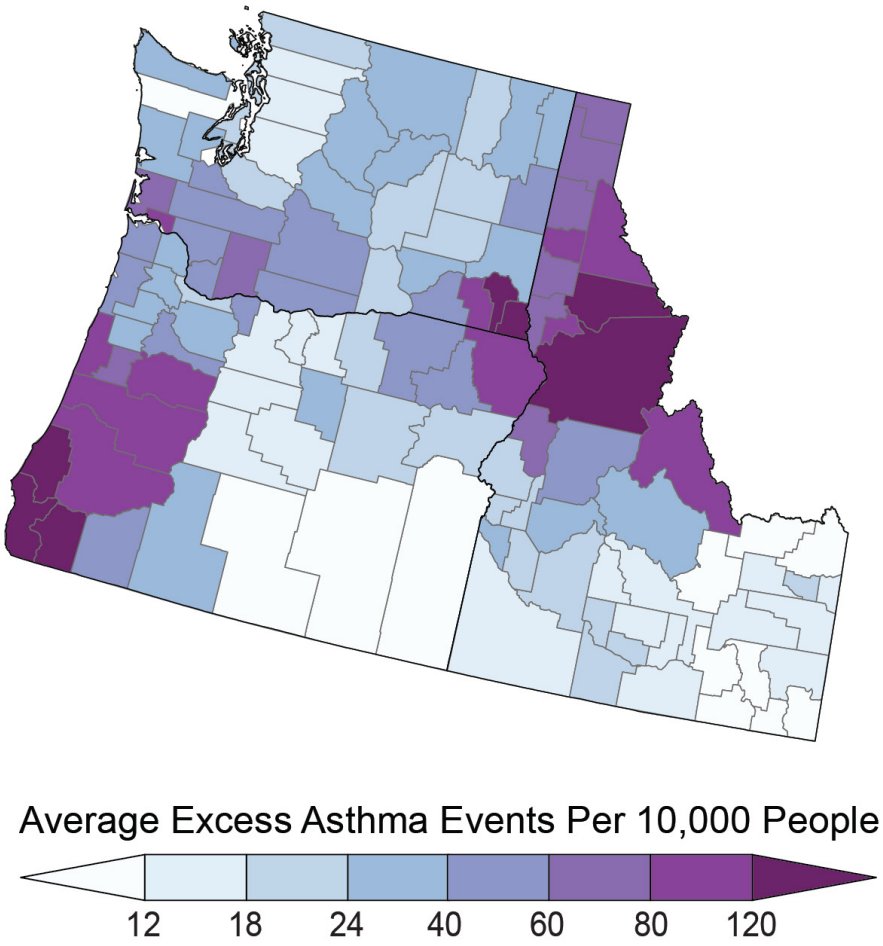


Heatwaves, such as the heat dome event in the summer of 2021, place strains on healthcare systems.

Figure 27.8. The graph shows the number of heat-related emergency department visits for US Department of Health and Human Services (HHS) Region 10 (which includes Alaska, Oregon, Idaho, and Washington), relative to the rest of the country, from May 1–June 30 in 2019 and 2021. There was a sharp increase in emergency department visits for heat-related illness during the 2021 heat dome event in HHS Region 10, relative to the heat-related emergency department visits for the region in 2019. HHS Region 10 also experienced relatively more heat-related emergency department visits during the 2021 heat dome event compared to the rest of the country over the same time period. Adapted from Schramm et al. 2021.[335]

Wildfire smoke can be severe in the region, particularly in highly populated areas, Idaho, and eastern Washington and Oregon.[321,336] In the western US, smoke events from 2004 through 2009 were associated with a 7.2% increase in respiratory hospital admissions among adults over 65, compared to the previous decade. In Washington, smoke-related mortality increased during the 2020 wildfire season, when the ambient total particulate matter concentration changed from near zero to 100 micrograms per cubic meter ($\mu g/m^3$) over the course of a summer.[322] Increased particulate matter ($PM_{2.5}$) due to wildfire smoke in the West has been associated with a predisposition to COVID-19 and higher COVID-19 case rates and mortality.[337] Future wildfire seasons—and increases in $PM_{2.5}$ associated with those wildfire seasons—is projected to increase excess asthma incidences by the 2050s under a very high scenario (RCP8.5; Figure 27.9); Washington, Oregon, and Idaho are expected to see an increase of 25.7, 41.9, and 29.4 wildfire smoke–related emergency department visits per 10,000 persons, respectively.[336] The anticipated financial burden of healthcare costs associated with wildfire smoke exposure is expected to significantly increase across the Northwest.[336,338,339]

Projected Asthma Burden per Wildfire Season in 2050



Excess asthma burden associated with wildfire smoke is expected to disproportionately affect the Northwest.

Figure 27.9. Northern Idaho, coastal Oregon, and southwest Washington are expected to face some of the highest wildfire smoke–related asthma burden in the Northwest. Excess asthma incidences related to wildfire smoke are expected to increase across the Northwest. The figure shows the average expected total number of excess asthma events per 10,000 people per wildfire season by the 2050s under a very high scenario (RCP8.5). Adapted from Stowell et al. 2022[336] [CC BY 4.0].

Additional health-related impacts are associated with heatwaves and wildfire smoke.[340] Lower birth weight and premature birth are attributed to these events,[341,342] although empirical evidence from the Northwest is still emerging. Similarly, evidence of an association between repeated long-term exposure to wildfire smoke and cancer incidence is emerging.[343]

People with access to air-conditioners or air purifiers, along with the financial capacity to operate these systems, will fare better than those whose homes are poorly insulated and allow for a greater concentration of ambient pollutants to enter indoor spaces. Young children and older adults are particularly vulnerable, as are those who live in trailer parks, recreational vehicles, or historically disinvested urban areas. Discriminatory policies such as redlining also contribute to greater exposure to heat and other climate-induced events, such as urban flooding (KM 27.1).

Mental Health Impacts and Climate Change

Each extreme event has its own set of observed mental health consequences, including some overlapping disorders such as post-traumatic stress, anxiety, depression, and suicide.[344,345] Negative mental health outcomes have been observed before and after a climate-related extreme event.[346] For example, wildfire smoke can limit outdoor activities, reducing individuals' ability to exercise, recreate, and relieve stress, leading to additional mental health consequences (KM 27.6). Mental health consequences of climate change may resolve quickly; however, long-term impacts can be delayed and, in the case of post-traumatic stress, can even affect future generations.[347,348]

Idaho, Oregon, and Washington have a higher prevalence of mental illness relative to the rest of the country.[349] The mental health impacts of climate change will continue to be uneven. Youth concerned about climate change, Tribal communities losing cultural resources at a rapid pace, and houseless individuals who experience increased exposures to climate change have a higher prevalence of climate-related mental illnesses compared to other populations.[345,350,351,352]

Community Health and Well-Being Impacts

Climate change impacts community health and well-being in many ways. Increased temperatures are associated with an increase in violence and self-harm, including suicide.[344,353] The magnitude and duration of droughts in the Northwest are projected to increase and potentially disrupt agricultural production and exacerbate food insecurity,[354] which can cause psychological distress.[355] Extreme events will continue to disrupt medical care and services, and injury and illness from such events are expected to exceed the capacity of the healthcare system. Strengthening community and social cohesion can improve community health outcomes and increase preparedness for disasters and extreme events.[356,357]

Tribal Well-Being Impacts

Climate change is disrupting Tribal communities' access to traditional foods, compounding legacy effects of settler colonialism that have led to increased consumption of processed foods, which is associated with higher rates of diabetes, heart disease, and obesity for Tribal communities.[358,359,360] Algal blooms have contaminated shellfish to the point that they cannot be consumed during traditional seasons (KM 27.2). Increasing temperatures have created more favorable conditions for transmission of parasitic and invasive species among food sources such as deer and fish.[361,362] The continued effects of climate change on the phenology of important species and access to cultural resources are expected to disrupt multiple cultural and ceremonial activities, compounding mental, cultural, and physical well-being issues for Tribes.[265,352,363] Impacts to these cultural resources and sites disrupt intergenerational teachings, an important component of Indigenous health and a method to address intergenerational trauma (KM 27.6).[364]

Climate Action Can Benefit Human Health and Address Inequities

Historically, the intersection of climate change and health has been unclear, leading to insufficient capacity and resources for health agencies to properly respond and prioritize climate change actions.[365] However, because of the health consequences of recent extreme events, public health responses to climate change have become an essential part of climate adaptation, and health resilience frameworks, such as the CDC's Building Resilience Against Climate Effects (BRACE) or Oregon's Climate Equity Blueprint, are becoming more common.[366] Many strategies—such as setting universal climate and health goals and providing adequate resources to communities and populations to reach these goals—offer promise for avoiding negative public health outcomes due to climate change and can advance regional resilience (KM 27.1).[367] For example, investments to increase electric vehicle adoption and active transportation (e.g., walking, biking) are expected to lead to greenhouse gas emissions reductions, improvements in air quality, and reductions in fatal traffic accidents.[368] Investments in cooling options—such as shade coverage from trees, cross-ven-

tilation in apartment units, and air-conditioning capacity—can support communities, particularly formerly redlined communities, in adapting to extreme heat events (KM 27.1).[369]

Key Message 27.6

Climate Change Affects Heritage and Sense of Place

Climate change has disrupted sense of place in the Northwest, affecting noneconomic values such as proximity and access to nature and residents' feelings of security and stability (*high confidence*). Place-based communities, including Tribes, face additional challenges from climate change because of cultural and economic relationships with their locale (*very high confidence*). Leveraging local or Indigenous Knowledge and value systems can spur climate action to ensure that local heritage and sense of place persist for future generations (*medium confidence*).

The heritage of the Northwest is intertwined with the diversity of landscapes, economies, and quality of life (Figure 27.10). Climate change affects all these core characteristics of the Northwest, with impacts on the quality of life and sense of place—the attachment or relationship that people feel to their locations and environment—for all communities and the ability to share the familiar parts of where one lives with others and across generations.[370] While there are differences among cultures' relationships, there are deep commonalities. Supporting the continued emotional and cultural well-being of residents across the region will require a mutual appreciation from multiple perspectives across diverse communities.

Sense of Stability and Security

Climate change can negatively affect peoples' sense of security and stability due to disruptions to supply chains and food systems, which underpin economies and communities (KM 18.2; Focus on Risks to Supply Chains).[371,372] For example, a forest products industry requires regular inputs of timber and cannot thrive on supplies that increasingly come in pulses or waves due to drought, wildfires, and insect infestations.[373] Climate change impacts to natural resource economies will affect residents' financial security and livelihoods (KM 27.3) and will have cascading impacts across regional to international economic systems (KM 19.2).

Heritage, Sense of Place, and Amenities at Risk

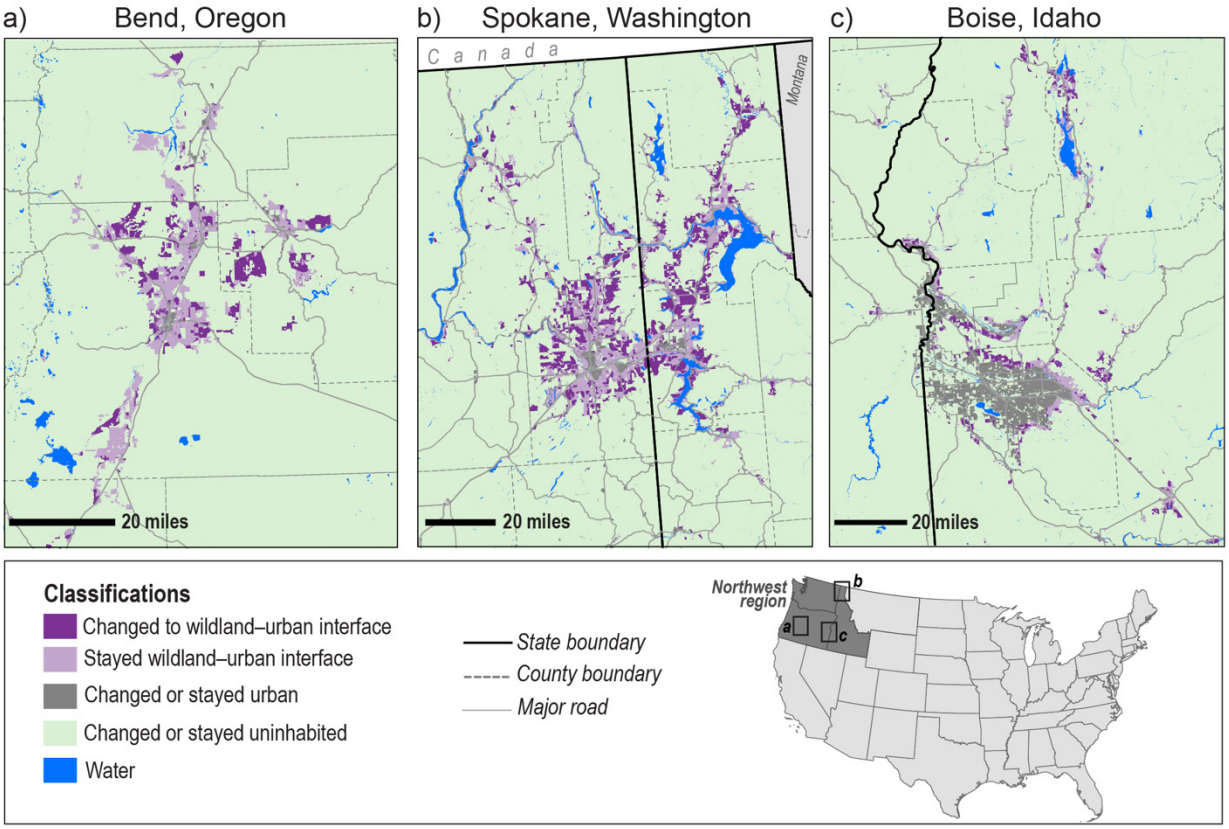
The heritage of the Northwest is intertwined with the diversity of landscapes, economies, and quality of life.

Figure 27.10. These photos illustrate different heritages, cultural traditions, and amenities at risk from climate change. (**top left**) Coastal change is threatening beaches and shellfish habitat for the Swinomish Tribe, threatening cultural activities like the Swinomish Clam Bake. (**top right**) Fire retardant drops protect vulnerable homes in the wildland–urban interface. (**center left**) Culturally important foods, such as camas, will be affected by climate change. (**center right**) Climate change is affecting salmon, potentially affecting the ability of some Tribes to roast and smoke salmon. (**bottom left**) Wildfire smoke days are increasing, affecting school recreation opportunities. (**bottom right**) Warmer winters, such as the winter of 2015, will lead to less winter snow, affecting ski resorts such as Mount Baker Ski Resort, Washington, which had no snow on February 15, 2015, during the height of ski season. Photo credits: (top left) ©Richard A. Walker; (top right) National Interagency Fire Center; (center left and bottom left) ©Charles Luce; (center right) ©Samantha Chisholm Hatfield; (bottom right) ©Duncan Howat.

Many in the Northwest have moved from city centers to an expanding wildland–urban interface (WUI) (Figure 27.11),[102,103,104] increasing community exposure to wildfires and floods.[374] Homes dependent on shallow wells are at risk from more frequent and intense drought conditions (KM 27.4).[375] Increases in the frequency

of algal blooms or outbreaks of forest diseases and pests reduce the value of homes with water frontage or surrounded by forest (KM 19.3).[376,377,378] The decline of home values, aggregated across communities, can lead to local economic and community instability by reducing the desire or ability to rebuild after fires and floods.[379,380] Although insured households may be able to rebuild, climate risks can increase insurance costs and decrease insurance availability, affecting which residents and businesses thrive in the future.[381]

Growth in Wildland–Urban Interface (1990–2020)



The growth of homes in the wildland–urban interface puts an increasing number of people at risk of wildfire and flooding.

Figure 27.11. The maps show growth in the wildland–urban interface (WUI; dark purple) areas, which are associated with increased wildfire and flooding risks, between 1990 and 2020 near Bend, Oregon (**a**); Spokane, Washington (**b**); and Boise, Idaho (**c**). Bend and Spokane have experienced fast rates of development and population growth that have led to new areas being developed as WUI. Figure credit: USDA Forest Service, NOAA NCEI, and CISESS NC.

Environmental Amenities and Sense of Place

Northwest residents value the region for its environmental amenities like good air and water quality and proximity to recreational opportunities.[263,382] Climate change has already started and will continue to disrupt many kinds of outdoor recreational activities.[79,383] Multiple recreational seasons have simultaneously shortened and shifted. Skiing and snowmobiling seasons have started later and become shorter over much of the region, especially in the Cascades,[13,384] affecting winter recreation businesses (KM 27.3). Loss of spring snowmelt will shift opportunities for rafting, kayaking, and canoeing into rainy winter months, when rapidly fluctuating flow conditions are less safe. Water-based recreation demand is expected to increase in spring

and summer months; however, reduced water quality and harmful algal blooms are expected to restrict these recreation opportunities.[79]

Many previously forested trails and camping areas have already lost forest cover due to wildfires and drought.[385] As the frequency of disturbances increases, so will the number of dead and downed trees,[386] closing roads, trails, and campgrounds and potentially causing injuries or death for recreationists.[387] Greater flooding risk in winter months will pose risks to recreational facilities and users.[388] More frequent smoke and extreme heat events will increase risks to outdoor summer recreationists, especially for high-exertion activities.[389] State health agencies, such as the Idaho Department of Health and Welfare, have developed recreation guidelines for K–12 and adult fitness activities and sports in response to increasing wildfire smoke days and decreased air quality.[390]

Climate change will also affect recreational and subsistence hunting, gathering, and fishing activities. Although some game species may benefit from increased shrub cover and reduced winter mortality, increasing populations can lead to other challenges, affecting managed resources and increasing pathogen spread.[391,392] Algal blooms and increased toxin levels will lead to shellfish harvest closures, sometimes lasting entire seasons. While these impacts will affect recreational hunters and fishers, impacts will be greater for households and communities that are nutritionally dependent on these resources, such as Tribal communities and households reliant on subsistence diets.[393]

Amenity migration, or movement of people to areas with higher environmental quality or increased access to amenities, will be affected by climate change in various ways.[394,395] For example, people moving to the WUI to be closer to environmental amenities will experience increased risks of wildfires and, in some cases, landslides (Figure 27.11). Additionally, there are compounding challenges for communities that are receiving an influx of amenity migrants, especially rural and low-income communities where established residents provide the labor force but may become priced out by increasing costs of housing and other necessities.[396,397] Interacting stresses between socioeconomic and development impacts associated with migration and climate change will affect communities in high-amenity areas in the Northwest, such as ski communities in the Cascade Range or island communities in the San Juan Islands.[398]

Tribal Cultures and Connection to the Land

Climate change has affected Tribal harvesting, hunting, and ceremonial practices.[399] Climate change will impact Pacific salmon (KM 27.2) and other cultural resources such as Pacific lamprey, deer, elk, bear, berries, eel, flounder, sturgeon, shellfish, and seaweeds.[400] Plant die-offs and range shifts can disrupt and impede Tribal access to traditional foods, thereby affecting Tribes' and Indigenous Peoples' sense of place and connections (KM 27.5).[363] Extreme weather events and extreme heat and cold can prevent Tribal members, especially elders, from participating in Tribal ceremonies. Access to ceremonial sites can also be disrupted or damaged by flooding, landslides, and wildfires, exacerbating degradation associated with other land-use decisions (KM 27.1).

Indigenous Knowledges can be utilized to increase resilience to climate change for Tribes.[251] Tribal landscape management is one method for maintaining connections to landscapes and preserving ceremonial sites, medicinal plants, and gravesite locations for future generations.[401,402,403] However, federal, state, and local jurisdictions have prevented some Tribes from utilizing Indigenous management techniques such as prescribed burning, which can remove underbrush to reduce fire risk and establish wildlife corridors (KM 27.2), thereby limiting Tribes' ability to exercise their sovereignty and to maintain a sense of place for future generations.[404,405,406,407,408] Western adaptation options of replacement, fortification, or relocation (KM 27.4) may not be possible or appropriate, as some sites (e.g., gravesites and ceremonial sites) do not have one-to-one exchange equivalents. Despite these limitations, federal–Tribal partnerships can increase landscape resilience to future climate change risks.[409,410]

Maintaining a Sense of Place and Heritage for the Northwest

Climate change poses an existential threat to the ability of Northwest communities to maintain their sense of place and heritage for future generations. Many cultures rely on nature-based experiences to transfer knowledge and form cultural identity. For example, the Swinomish Tribe holds cultural clam bakes, where community elders transfer Traditional Knowledges about the natural world that are vital to maintain their cultural well-being and heritage.[399] However, recent shoreline changes and projected beach loss threaten access to these culturally important shellfish harvest areas, reducing opportunities to hold cultural clam bakes.[411]

Communities across the Northwest pride themselves on their environmental values and actions, such as promoting conservation or voluntarily employing sustainable practices. Leveraging these community values can lead to innovative climate adaptation and mitigation policies at the local level,[412,413] furthering regional climate mitigation and adaptation goals (KM 27.4) to ensure that the heritage and the communities of the Northwest persist for future generations.

Traceable Accounts

Process Description

The Northwest chapter focuses on advances in regional climate science and understanding of the social and economic impacts of climate change. Therefore, the author team reflects the breadth and depth of scholarship and experiences about climate science, impacts, and responses. The author team was recruited from a list of nominated authors, regional experts from past assessments and conferences, and recommendations from authors or author candidates. The author team includes: 1) a diversity of expertise in the areas of physical climate science, social sciences, economics, public health, ecosystem services, adaptation, and mitigation; 2) a diversity of geographies and institutions that represent each state in the Northwest; 3) a range of experiences and career stages that includes university researchers, practitioners, and state government employees; and 4) a diversity across multiple demographic characteristics, including gender, race, and ethnicity.

Initial Key Message themes were developed via consensus, and these Key Messages were confirmed at the Northwest's regional engagement workshop on February 1, 2022. Specific content within the Key Messages was further refined based on comments from the regional engagement workshop and public comments on the Zero Order Draft. Authors were assigned to Key Message–specific teams based on their expertise and were charged with developing the text, citations, Traceable Accounts, and Key Messages. Key Message narratives were developed to ensure that content built off prior National Climate Assessments (NCAs) and was not repetitive of previous NCAs (Table 27.2). Author meetings were generally held biweekly throughout development of the Fifth National Climate Assessment (NCA5) for discussions and deliberations and to ensure that deadlines were met. Additionally, the smaller Key Message teams met frequently to refine their Key Messages, text, figures, and Traceable Accounts.

Table 27.2. How NCA5 Northwest Chapter Built on Prior NCAs

NCA5 Key Message	How NCA5 Built on NCA3[5] and NCA4[4]
27.1 Frontline Communities	Since NCA4, much more research has been published on the distributional burden of climate change on various communities across the Northwest. NCA5 expands on the literature base to focus on the different dimensions of how climate change inequitably impacts various groups. Additionally, NCA5 focuses on some of the emerging information on how different frontline groups are advancing climate action within their communities and states.
27.2 Ecosystem Changes	More research has been published since both NCA3 and NCA4 on the ecological impacts of climate change. NCA5 builds on this work by focusing on ecological responses across the Northwest to extreme events and the interaction between climate change and human activity (e.g., land use). Additionally, NCA5 builds on how different types of adaptation responses, such as restoration, can build ecological resilience.
27.3 Economics and Well-Being	Since NCA3 and NCA4, there has been more scholarship on the economic impacts of climate change. NCA5 dives deeper into some economic impacts previously discussed, including impacts to the natural resource economy. NCA5 also provides a synthesis of new research on the recreational impacts of climate change and economic opportunities in a low-carbon future.
27.4 Infrastructure and Resilience	NCA5 builds on NCA3 and NCA4 by focusing on different types of infrastructure systems and their responses to climate change. NCA5 also highlights the trade-offs of climate action across systems, such as the trade-off between transportation electrification and energy resilience. Additionally, NCA5 focuses on how infrastructure systems and the built environment are the largest contributors of greenhouse gas emissions and provides a narrative on climate mitigation and decarbonization in the region.
27.5 Health Inequities	Since NCA4, more extreme events, such as large wildfires, more wildfire smoke days, and extreme heatwaves, have led to health consequences. NCA5 builds on NCA4, which delved into a variety of impacts, by focusing primarily on heat and smoke impacts to public health. Additionally, NCA5 adds emerging research on the mental and community health impacts of climate change.
27.6 Heritage and Sense of Place	Since NCA4, there has been more research that establishes how regional sense of place is changing due to climate change. NCA5 provides more in-depth coverage on many of the topics covered in NCA4, such as sense of security from extreme events, how different amenities are changing, and how different iconic parts of the Northwest are being affected. Additionally, NCA5 provides additional discussion of climate-related migration and how that affects a community's identity and sense of place.

Key Message 27.1

Frontline Communities Are Overburdened, and Prioritizing Social Equity Advances Regional Resilience

Description of Evidence Base

Recent studies and reports have built on decades of research that have provided strong evidence that the prevalence of people of color in a community continues to be the most significant predictor for where environmental hazards are sited throughout the Northwest, due to racialized and racist policies.[59,60,62,63,64,65,66,97] A wealth of evidence, including peer-reviewed research, gray literature, and government reports and resources, links racial and socioeconomic demographics across the Northwest with disproportionate exposure and vulnerability of frontline communities to a variety of climate

hazards and extreme events, including wildfire, wildfire smoke and impaired air quality, extreme heat, and flooding.[59,61,62,67,68,70,71,74,75,76,77,89,92,93,95,414]

Additionally, NCA5 listening sessions and community-led research provided evidence on the lived experiences of frontline communities with climate impacts and how these communities are implementing community-informed climate resilience priorities. The literature supports the diversity of approaches that frontline communities are utilizing to increase their resilience to climate change, including for urban communities of color,[59,97] rural and natural resource–dependent communities,[79,80,81] and Tribal and Indigenous communities.[93,265] Peer-reviewed literature and gray literature document that while frontline communities are inherently resilient to both climate change and other forms of oppression, policies and other structural barriers continue to prevent frontline communities from enacting community-led adaptation strategies.[78,90,91,92,93]

Major Uncertainties and Research Gaps

While the priorities and needs of frontline communities are increasingly being considered in state and local government policies, plans, and budgets in the Northwest, such efforts are in early stages of implementation. While these efforts are resulting in some benefits to frontline communities in the near term, long-term outcomes are yet to be seen. Advancing climate justice and social equity in the region is dependent on institutions' ability to transform and meet the needs of frontline communities.

While community-led research and plans provide documentation of frontline communities' priorities, it is critical to note that these sources probably do not represent the full range of perspectives, values, and experiences of the diverse communities in the Northwest. Assessment authors understand that communities are not monoliths and that many adaptation and resilience strategies are culturally, temporally, and geographically specific; therefore, the information in this assessment cannot be used to make blanket statements about all communities experiencing environmental and climate injustices in the region.

Description of Confidence and Likelihood

Based on the breadth of available research and literature, authors concluded that there is *very high confidence* that frontline communities are experiencing disproportionately high exposure to climate-related hazards, although there is variation across the types of frontline communities.

Additionally, because of the wealth of community-led documentation, government reports, and preliminary peer-reviewed research, authors concluded that there is *high confidence* that frontline communities generally have fewer resources to adapt and respond to climate change but are leading efforts to increase resilience to climate change and extreme events.

While there is a growing body of evidence suggesting that the priorities, values, and needs of frontline communities are increasingly being considered in state and local policies and plans, these efforts are still in early stages of implementation and long-term outcomes remain to be seen. In addition, existing efforts are not yet sufficient to meet the scale and speed of justice-centered climate action required to secure a safe and livable future for frontline communities. Therefore, authors of this Key Message have *medium confidence* that the extent of these efforts will deliver long-term resilience benefits and climate justice to the region.

Key Message 27.2

Ecosystems Are Transitioning in Response to Extreme Events and Human Activity

Description of Evidence Base

Strong evidence supports the projection that ecosystems will change as climate changes. Numerous assessments project extensive changes in species distributions as climate changes. Additionally, extreme events (e.g., droughts, floods, and heatwaves), which are becoming more frequent and intense, may be equally relevant to the physical condition and population dynamics of species,[107,109] especially those with short generation times.[110] Multiple peer-reviewed publications and government reports document the extensive impacts of extreme events on Northwest ecosystems, especially in the past two decades. Given projections of future climate, it is expected that wildfire will continue to affect forest systems,[113,114,115,116,117,118,119,120,121,123] changes in hydrology and temperature will affect aquatic ecosystems,[128,129,130,131,132,133,134,138,139] and ocean acidification and marine heatwaves will affect coastal and marine systems.[42,48,54,145,146,147,148,149,150,151,152,154,155,159,415]

In addition, robust peer-reviewed evidence documents how these ecosystem-level changes will have myriad effects on native species, including game species,[391,392] trees,[232,234,237,238,244] marine taxa,[148,149,150] and the region's iconic salmonids[48,159,160,161,162,163,164,165,415]

Extensive evidence within the peer-reviewed literature also demonstrates the widespread impact of human land uses on the extent to which species can adapt to environmental change, including climate change.[104,118,119,120,121,122,144] For example, fine-grained variation in land cover, including land cover types associated with human activities, affects the resilience of species or ecological processes to climate variability and change[189] and the extent to which land uses function as stressors. Historical and recent fragmentation of a species' habitat and barriers to movement affect its capacity to adapt to both human-caused and natural forms of environmental change.[129,130,144,186,187]

There is extensive evidence that conservation of genetic diversity and ecological protection and restoration can benefit ecosystem processes and increase species' adaptive capacity.[120,121,122,192,193,194,195,196] For example, restoration via removal of impassable dams and structures across the Northwest has restored some natural ecological and hydrological processes that allow anadromous fishes to access historical habitat.[194,197,198,199,200] However, evidence of the effectiveness of other types of ecological management, such as vegetation removal to mitigate wildfire risk and market-based ecosystem management tools, is limited, especially in the long term.[204,205,206,208,209]

Major Uncertainties and Research Gaps

Relations between climate and population dynamics of most species are complex, so there is uncertainty in projections even for well-studied species. Moreover, distributions, abundances, or other species-level metrics more closely reflect interactions among climate variables, and interactions among species, rather than single climate variables.[111,112]

Evolutionary responses to climate are also complex.[212,213] The likelihood of adaptation depends in part on the amount of genetic variation in a population or species, which is often related to the number of individuals and their relatedness.[188] The feasibility of quantifying abundance, relatedness, and genetic variation differs among populations and species, and these measures have not been estimated for a majority of populations and species. Furthermore, empirical estimates of opposing selection pressures in different environments are difficult to obtain. Similarly, phenotypic plasticity, its heritability, and potential response to selection have not been estimated in most taxa. Accordingly, the adaptive capacity of most taxa is highly uncertain.

Also, data on which biological and physical attributes affect viability most strongly are not available for most species.

The extent to which restoration efforts can increase genetic variation and ecosystem function and productivity is uncertain, especially given the extensive anthropogenic modification of ecosystem structure, composition, and function. Because ecosystems rarely can be restored to a historical state, restoration actions tend to focus on increasing ecosystems' capacity to support diverse and valued functions and services and enhanced genetic and species variation. Information needs include improved understanding of habitat quality, stress tolerance, and adaptation capacity of diverse species. There are substantial gaps in understanding of the complex interactions within and among species, communities, and biogeochemical processes, all of which are being modified by climate change and land use.

Description of Confidence and Likelihood

The enormous body of evidence on ecological sensitivity to climate yields *very high confidence* in projections of change, despite uncertainty in how individual and interacting ecological components will respond. Similarly, although adaptive capacity is difficult to quantify, there is *very high confidence* that such capacity has been reduced by decreases in abundance and genetic diversity of many native species. There is *very high confidence* that human activities and land uses interact with ecological responses to climate change, and in many cases exacerbate these effects.

Climate change impacts could be ameliorated by changes in human actions. However, restoration to previous ecological states often is unlikely. For example, certain non-native invasive species are unlikely to be eradicated, and land modifications rarely can be completely reversed. Furthermore, climate change will modify some species and ecosystem characteristics regardless of human actions. Although the scientific community has medium to low confidence that ecosystem restoration efforts can increase genetic variation in many native species, there is high to medium confidence that reconnecting and improving the quality of species' habitats can increase the feasibility of species persistence. The likelihood of ecological recovery is location- and context-specific and depends on factors including the severity of ecological stressors; the location, timing, design, and scope of restoration actions; and the potential to restore abiotic and biotic processes, land cover, and flows of energy and genes. Thus, the authors have *medium confidence* that human-led adaptation efforts can reduce exposure to climate-related hazards.

Key Message 27.3

Impacts to Regional Economies Have Cascading Effects on Livelihoods and Well-Being

Description of Evidence Base

Over the past several decades, multiple peer-reviewed studies have established how climate change affects diverse annual and perennial cropping systems,[216,217,218,219,220,221,222,223] fishery systems,[225,247,248,249,250,253] forestry systems,[233,234,236,237,242,244] and the tourism industry.[16,79,256,257,258,261]

Despite these varying climate impacts, there is emerging science, including peer-reviewed sciences, that indicates that the Northwest continues to maintain economic resilience to climate change due to the region's inherent diversification. For example, federal crop insurance for the Northwest shows multiple weather- and climate-related causes of crop loss (e.g., drought, heat, freeze, frost, excess moisture), demonstrating the diversity of risks agricultural producers experience.[230] However, new and emerging opportuni-

ties in these important economic sectors are also beginning to be noted.[82,83,87,231,243,244,245] The effectiveness and extent of these new adaptation and mitigation opportunities is still unclear.

Emerging case studies, gray literature, and frameworks, such as the just transition framework, are being implemented across the Northwest to transition to a low-carbon economy.[97,246,303,416,417] There are frameworks and evidence that associate economic resilience with prioritizing worker protections and marginalized labor populations.[270,272] However, such publications in the Northwest region are still relatively new and limited in extent.

Major Uncertainties and Research Gaps

Recent events such as the 2021 heat dome have highlighted the significant impacts of extreme weather. Regional industries are investing in research that can increase understanding of risk factors associated with extreme weather and assess whether the risks are high enough to warrant additional infrastructure investments and management alternatives to limit damage. Much of the existing literature on climate change impacts on the region is based on limited climate ensembles rather than large ensembles, which are key to understanding extreme weather probabilities and impacts. New efforts addressing this gap are starting to be initiated, especially those addressing the regional agricultural industry.

The potential for new adaptation and mitigation opportunities is still unclear. Additional region-specific information is necessary to obtain a better picture of the potential. The region is still in its early phases of implementing low-carbon economy transition plans and strategies. There are still many gaps associated with the efficacy of implementing these plans. Evaluation of the recently launched efforts should provide valuable information for future streamlining of these efforts.

Description of Confidence and Likelihood

Because of the wealth of peer-reviewed research published across multiple decades, we have *very high confidence* that climate change is affecting—oftentimes in negative ways—natural resource– and outdoor-dependent economies, although the ways they are affected will be variable depending on the location and industry or commodity. Based on robust peer-reviewed literature and a growing number of publications specific to the Northwest, there is *high confidence* that climate change effects on these industries will have cascading impacts on the livelihoods of resource-dependent communities. Because of an emerging evidence base in the peer-reviewed literature—and a nascent evidence base specific to the Northwest region—the authors have *medium confidence* that the region's natural resource industries are effectively responding to climate change and that a transition to a low-carbon economy can impart economic resilience, especially for those disproportionately impacted, such as workers in fossil fuel–dependent industries and outdoor laborers.

Key Message 27.4

Infrastructure Systems Are Stressed by Climate Change but Can Enable Mitigation and Adaptation

Description of Evidence Base

There is considerable evidence that climate change and extreme events have negatively affected built infrastructure, especially older infrastructure, in the Northwest.[100,142,273,278,279,291,307,308,311,318,323] Evidence varies among sectors, and multiple studies document effects of drought on water infrastructure and supply,[277] effects of wildfires on virtually all types of infrastructure,[142,277,418] and effects of extreme precipitation and flooding on water and transportation infrastructure.[29,281,282,283,323]

Multiple studies highlight the interdependencies of systems.[274,275,276,291,294,310,314,315,316] Within the Northwest, infrastructure system dependencies can spark conflicts about trade-offs among uses and between adaptation to and mitigation of climate change. These trade-offs have been documented in peer-reviewed publications and government reports and plans.[293,295,296,314,315,316,419] Furthermore, some studies suggest that climate adaptation and mitigation actions across infrastructure systems can lead to cascading consequences in other sectors, such as public health, water conservation, and land use (Focus on Western Wildfires).[277,278]

Despite these conflicts and trade-offs, emerging case studies document approaches to manage trade-offs in use of water, transportation, and electricity infrastructure. There are examples of new technology and data products to support adaptation[285,286,300,304,305,306] and case studies of collaborative efforts to address these complex systems and their responses to climate change.[105,303,418]

Major Uncertainties and Research Gaps

Trade-offs among uses of infrastructure and efforts to increase infrastructure resilience create substantial uncertainties in the social and environmental effects of those actions. For example, electrification of mass transit and vehicles can reduce emissions of greenhouse gases but strain energy supplies, affecting adoption of electric vehicles across communities. Similarly, provision of air-conditioning and air filtration, especially in regions where they are currently rare, can alleviate the public health consequences of extreme heat but strain energy supplies. Potential consequences of decreasing wildfire exposure may come at the expense of those medically dependent on electricity.

Description of Confidence and Likelihood

The available research, peer-reviewed literature, and case studies indicate that there is *very high confidence* that climate change, climate hazards, and climate-related extreme events have stressed the Northwest's built infrastructure, and that there is *very high confidence* that climate change will continue to stress these systems. Additionally, there is broad agreement that these infrastructure systems are complex and interrelated and, therefore, that climate-related impacts or responses to extreme events will present trade-offs and lead to conflicts over use. Within the Northwest, documentation of these conflicts and trade-offs varies among sectors and locations. Nevertheless, the literature continues to highlight trade-offs among systems. Therefore, there is *very high confidence* that climate-related disruptions and efforts to adapt to and mitigate the effects of climate change on a given infrastructure system may stress other infrastructure systems. Multiple case studies highlighted how practitioners are managing these conflicts and trade-offs via collaborative planning, engineering, and design. Given the breadth of case studies across sectors, there is *high confidence* that cross-sectoral and multisystem planning will increase the resilience of built infrastructure systems to future climate change.

Key Message 27.5

Climate Change Amplifies Health Inequities

Description of Evidence Base

An extensive peer-reviewed literature base documents the physical and mental health impacts of extreme events and climate change,[69,75,321,322,330,334,335,336,337,340,341,345] and a smaller but growing evidence base documents the community health impacts of climate change.[344,353,355] The Northwest has experienced more extreme heat events, wildfires, and wildfire smoke days in the past decade, and research has documented mortality and morbidity directly associated with these hazards and impacts.[69,328,329,330,334] The evidence connecting extreme heat, for example, to poor mental health outcomes such as anxiety, psychological fatigue, and suicide is still emerging, although researchers and clinicians are developing promising methodologies and approaches to address climate-related mental health needs.[345]

Multiple lines of evidence document the inequitable distribution of climate-related health risks among Northwest communities.[265,322,337,345,350,351,352,358,359,360,363,364] There are some gaps specific to the Northwest region on climate change impacts to community health (e.g., domestic violence). However, both national and international peer-reviewed articles document these associations. Multiple case studies and gray literature and an emerging peer-reviewed literature base document how health professionals and communities are responding to increasing public and community health challenges induced or exacerbated by climate change.[356,357,364,367]

Major Uncertainties and Research Gaps

Reports and published studies have focused on community impacts following extreme events, or other traumatic events felt at the community level, that may reduce social cohesion. More research is needed to better understand the regional extent of mental health challenges from climate change and to inform protocols to better prepare health professionals for climate-related community health impacts. There are also opportunities to decolonize public health methods and improve the integration of local and Indigenous knowledge systems and methodologies to better inform public health research.

There is still uncertainty about the extent that climate change will place additional stress on healthcare services in the Northwest. Preliminary research based on previous extreme weather events highlighted medication and medical equipment supply chain challenges, yet the demand for healthcare is expected to increase due to extreme events. However, compounding stresses that lead to shortage of healthcare workers, other public health challenges (e.g., COVID-19), and acute climate-related extreme events are beginning to illuminate potential gaps in the healthcare system.

There is still uncertainty in associating community health impacts, such as domestic violence, with climate change and its subsequent impacts on the healthcare system.

Description of Confidence and Likelihood

Given the breadth of literature documenting climate change impacts on physical, mental, and community health, the authors have *very high confidence* that climate change is adversely affecting public and community health outcomes in the Northwest. The authors have *high confidence* that mortality and illnesses related to extreme heat events and poor air quality is increasing and further stressing the public health sector. This confidence assignment is based on research that illuminates the association between morbidity and mortality during and after extreme heat events, such as the 2021 heat dome, and the increasing number of wildfire smoke days across the region. The authors also have *very high confidence* that climate change and extreme events worsen existing health disparities, unequally distributing the health burden on groups such as older adults, communities of color, Tribal communities, and low-income communities. On the basis of emerging research and case studies, the authors have *high confidence* that climate adaptation and mitigation efforts can lead to health co-benefits.

Key Message 27.6

Climate Change Affects Heritage and Sense of Place

Description of Evidence Base

In the Northwest, a growing evidence base of scientific literature, gray literature, and community knowledges continues to elucidate the interactions between climate change and the regional amenities and lifestyles that make the Northwest an attractive place to live, work, and visit. For example, multiple peer-reviewed publications document the ways in which climate impacts have disrupted key industries

that are critical to supply chains and economic and community stability[249,371,372,373] and local infrastructure (KM 27.4).[375] Additionally, multiple peer-reviewed publications document the interactions between climate change and land use, such as growth of the wildland–urban interface[102,103,104] and the increasing community exposure to climate-related events such as wildfires and flooding.[103,374,381] Multiple publications document these cumulative risks to safety, amenity access, and sense of place across the Northwest.[376,377,378,379,380,388]

The literature has documented how places with more or higher-quality environmental amenities (e.g., recreation, proximity to outdoors, good air and water quality, less traffic congestion) drives migration to more rural and exurban areas.[263,382] A wealth of gray literature and some peer-reviewed research document how climate change affects amenities, including recreation across all seasons[79,384] and environmental quality.[390] There are multiple peer-reviewed publications that document how impacts to these amenities can lead to regional emigration, migration, and displacement, especially as a result of climate-related extremes.[394,395,396,397,398]

There are multiple lines of research that detail climate-related impacts to place-based communities. For example, climate change will affect Tribes' cultural and subsistence resources,[92,251,265,363,364,399,400] which can have adverse impacts on Tribal sense of place and Tribal health and well-being (KM 27.5).[93,95,363,393,401] Other communities that have generational ties to specific rural or exurban areas—such as industry-specific workers and communities of color—will experience indirect and cascading amenity impacts from climate change that can drive migration either from or into specific regions.[394,396,398]

There are multiple examples of how leveraging community knowledges can result in successful adaptation outcomes; however, the bulk of this research is specific to Tribal communities.[251,399,402,403,404,408,409,411] There is emerging research that documents how other types of local knowledge and community values can drive climate action.[412,413]

Major Uncertainties and Research Gaps

Generally, the social science research within the Northwest is still developing and strengthening understanding of the connections between climate change and regional sense of place and heritage. Therefore, there are still many uncertainties and research gaps. This includes understanding social and economic responses to extreme events or repeated exposures to climate hazards, how these responses drive intra-regional migration, and how amenity migration can lead to cascading effects of displacement of other place-based communities (e.g., communities that strongly identify with specific industries, such as timber or fishing). There is also uncertainty in motivators for climate action by institutions. While some research is available on the social and political dimensions of climate action, including many case studies, the evidence base is nascent.

Description of Confidence and Likelihood

Research on climate change impacts to regional amenities, heritage, and sense of place varies by place, amenity, culture, and place. However, a common theme across the evidence base is that climate change is disrupting these regional values and cultures. Accordingly, the authors have *high confidence* that climate change is affecting regional amenities, heritage, and sense of place. Additionally, the authors have *very high confidence* that climate change is affecting place-based communities, such as Tribes and natural resource–based communities, given the breadth of regional and national research on these disproportionate impacts. Extensive scholarship highlights how integrating local and Indigenous Knowledges can support community resilience to climate change. However, there is limited research on how local heritage and values, such as environmental or sustainability values, can lead to climate adaptation and mitigation actions. Therefore, the authors have *medium confidence* that regional heritage and values can spur climate action to ensure the persistence of heritages, cultures, and amenities across the Northwest.

References

1. U.S. Census Bureau, 2021: 2020 Census Apportionment Results. U.S. Department of Commerce, U.S. Census Bureau. https://www.census.gov/data/tables/2020/dec/2020-apportionment-data.html

2. Kates, R.W., W.R. Travis, and T.J. Wilbanks, 2012: Transformational adaptation when incremental adaptations to climate change are insufficient. *Proceedings of the National Academy of Sciences of the United States of America*, **109** (19), 7156–7161. https://doi.org/10.1073/pnas.1115521109

3. Wilson, R.S., A. Herziger, M. Hamilton, and J.S. Brooks, 2020: From incremental to transformative adaptation in individual responses to climate-exacerbated hazards. *Nature Climate Change*, **10** (3), 200–208. https://doi.org/10.1038/s41558-020-0691-6

4. May, K., C. Luce, J. Casola, M. Chang, J. Cuhaciyan, M. Dalton, S. Lowe, G. Morishima, P. Mote, A. Petersen, G. Roesch-McNally, and E. York, 2018: Ch. 24. Northwest. In: *Impacts, Risks, and Adaptation in the United States: Fourth National Climate Assessment, Volume II*. Reidmiller, D.R., C.W. Avery, D. Easterling, K. Kunkel, K.L.M. Lewis, T.K. Maycock, and B.C. Stewart, Eds. U.S. Global Change Research Program, Washington, DC, USA, 1036–1100. https://doi.org/10.7930/nca4.2018.ch24

5. Mote, P., A.K. Snover, S. Capalbo, S.D. Eigenbrode, P. Glick, J. Littell, R. Raymondi, and S. Reeder, 2014: Ch. 21. Northwest. In: *Climate Change Impacts in the United States: The Third National Climate Assessment*. Melillo, J.M., T.C. Richmond, and G.W. Yohe, Eds. U.S. Global Change Research Program, Washington, DC, 487–513. https://doi.org/10.7930/j04q7rwx

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

7. Frankson, R., K.E. Kunkel, S.M. Champion, D.R. Easterling, L.E. Stevens, K. Bumbaco, N. Bond, J. Casola, and W. Sweet, 2022: Washington State Climate Summary 2022. NOAA Technical Report NESDIS 150-WA. National Oceanic and Atmospheric Administration, National Environmental Satellite, Data, and Information Service, Silver Spring, MD. 5 pp. https://statesummaries.ncics.org/chapter/wa/

8. Runkle, J., K.E. Kunkel, R. Frankson, S.M. Champion, L.E. Stevens, and J. Abatzoglou, 2022: Idaho State Climate Summary 2022. NOAA Technical Report NESDIS 150-ID. National Oceanic and Atmospheric Administration, National Environmental Satellite, Data, and Information Service, Silver Spring, MD, 4 pp. https://statesummaries.ncics.org/chapter/id/

9. Rogers, M. and G.S. Mauger, 2021: Pacific Northwest Climate Projection Tool. University of Washington, Climate Impacts Group. https://cig.uw.edu/resources/analysis-tools/pacific-northwest-climate-projection-tool/

10. Salathé Jr., E.P., A. Beggs, C. McJunkin, and S. Sandhu, 2023: The relative warming rates of heat events and median days in the Pacific Northwest from observations and a regional climate model. *Journal of Climate*, **36** (8), 2471–2481. https://doi.org/10.1175/jcli-d-22-0313.1

11. Humes, K., R. Walters, J. Ryu, R. Mahler, and C. Woodruff, 2021: Water report. In: *Idaho Climate-Economy Impacts Assessment*. James A. & Louise McClure Center for Public Policy Research, University of Idaho. https://www.uidaho.edu/president/direct-reports/mcclure-center/iceia/water

12. Ikeda, K., R. Rasmussen, C. Liu, A. Newman, F. Chen, M. Barlage, E. Gutmann, J. Dudhia, A. Dai, C. Luce, and K. Musselman, 2021: Snowfall and snowpack in the western U.S. as captured by convection permitting climate simulations: Current climate and pseudo global warming future climate. *Climate Dynamics*, **57** (7), 2191–2215. https://doi.org/10.1007/s00382-021-05805-w

13. Lute, A.C. and C.H. Luce, 2017: Are model transferability and complexity antithetical? Insights from validation of a variable-complexity empirical snow model in space and time. *Water Resources Research*, **53** (11), 8825–8850. https://doi.org/10.1002/2017wr020752

14. Mote, P.W., S. Li, D.P. Lettenmaier, M. Xiao, and R. Engel, 2018: Dramatic declines in snowpack in the western US. *Npj Climate and Atmospheric Science*, **1** (1), 1–6. https://doi.org/10.1038/s41612-018-0012-1

15. Nolin, A.W. and C. Daly, 2006: Mapping "at risk" snow in the Pacific Northwest. *Journal of Hydrometeorology*, **7** (5), 1164–1171. https://doi.org/10.1175/jhm543.1

16. Clifton, C.F., K.T. Day, C.H. Luce, G.E. Grant, M. Safeeq, J.E. Halofsky, and B.P. Staab, 2018: Effects of climate change on hydrology and water resources in the Blue Mountains, Oregon, USA. *Climate Services*, **10**, 9–19. https://doi.org/10.1016/j.cliser.2018.03.001

17. Wagner, A.M., K.E. Bennett, G.E. Liston, C.A. Hiemstra, and D. Cooley, 2021: Multiple indicators of extreme changes in snow-dominated streamflow regimes, Yakima River Basin region, USA. *Water*, **13**, 2608. https://doi.org/10.3390/w13192608

18. Chang, H., I.-W. Jung, M. Steele, and M. Gannett, 2012: Spatial patterns of March and September streamflow trends in Pacific Northwest streams, 1958–2008. *Geographical Analysis*, **44** (3), 177–201. https://doi.org/10.1111/j.1538-4632.2012.00847.x

19. Dalton, M., and E. Fleishman, Ed. 2021: *Fifth Oregon Climate Assessment*. Oregon State University, Oregon Climate Change Research Institute, Corvallis, OR. https://ir.library.oregonstate.edu/concern/technical_reports/pz50h457p

20. Kormos, P.R., C.H. Luce, S.J. Wenger, and W.R. Berghuijs, 2016: Trends and sensitivities of low streamflow extremes to discharge timing and magnitude in Pacific Northwest mountain streams. *Water Resources Research*, **52** (7), 4990–5007. https://doi.org/10.1002/2015wr018125

21. Fountain, A.G., C. Gray, B. Glenn, B. Menounos, J. Pflug, and J.L. Riedel, 2022: Glaciers of the Olympic Mountains, Washington—The past and future 100 years. *Journal of Geophysical Research: Earth Surface*, **127** (4), e2022JF006670. https://doi.org/10.1029/2022jf006670

22. Frans, C., E. Istanbulluoglu, D.P. Lettenmaier, A.G. Fountain, and J. Riedel, 2018: Glacier recession and the response of summer streamflow in the Pacific Northwest United States, 1960–2099. *Water Resources Research*, **54** (9), 6202–6225. https://doi.org/10.1029/2017wr021764

23. Lee, S.-Y., A.F. Hamlet, and E.E. Grossman, 2016: Impacts of climate change on regulated streamflow, hydrologic extremes, hydropower production, and sediment discharge in the Skagit River Basin. *Northwest Science*, **90** (1), 23–43. https://doi.org/10.3955/046.090.0104

24. Lancaster, S.T., A.W. Nolin, E.A. Copeland, and G.E. Grant, 2012: Periglacial debris-flow initiation and susceptibility and glacier recession from imagery, airborne LiDAR, and ground-based mapping. *Geosphere*, **8** (2), 417–430. https://doi.org/10.1130/ges00713.1

25. Lorente-Plazas, R., T.P. Mitchell, G. Mauger, and E.P. Salathé, 2018: Local enhancement of extreme precipitation during atmospheric rivers as simulated in a regional climate model. *Journal of Hydrometeorology*, **19** (9), 1429–1446. https://doi.org/10.1175/jhm-d-17-0246.1

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

27. Slinskey, E.A., P.C. Loikith, D.E. Waliser, B. Guan, and A. Martin, 2020: A climatology of atmospheric rivers and associated precipitation for the seven U.S. National Climate Assessment regions. *Journal of Hydrometeorology*, **21** (11), 2439–2456. https://doi.org/10.1175/jhm-d-20-0039.1

28. Xiong, Y. and X. Ren, 2021: Influences of atmospheric rivers on North Pacific winter precipitation: Climatology and dependence on ENSO condition. *Journal of Climate*, **34** (1), 277–292. https://doi.org/10.1175/jcli-d-20-0301.1

29. Corringham, T.W., F.M. Ralph, A. Gershunov, D.R. Cayan, and C.A. Talbot, 2019: Atmospheric rivers drive flood damages in the western United States. *Science Advances*, **5** (12). https://doi.org/10.1126/sciadv.aax4631

30. Hughes, M., D. Swales, J.D. Scott, M. Alexander, K. Mahoney, R.R. McCrary, R. Cifelli, and M. Bukovsky, 2022: Changes in extreme integrated water vapor transport on the U.S. west coast in NA-CORDEX, and relationship to mountain and inland precipitation. *Climate Dynamics*, **59** (3), 973–995. https://doi.org/10.1007/s00382-022-06168-6

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

32. Shields, C.A. and J.T. Kiehl, 2016: Atmospheric river landfall-latitude changes in future climate simulations. *Geophysical Research Letters*, **43** (16), 8775–8782. https://doi.org/10.1002/2016gl070470

33. Rutz, J.J., W.J. Steenburgh, and F.M. Ralph, 2014: Climatological characteristics of atmospheric rivers and their inland penetration over the western United States. *Monthly Weather Review*, **142** (2), 905–921. https://doi.org/10.1175/mwr-d-13-00168.1

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

35. Gao, Y., J. Lu, L.R. Leung, Q. Yang, S. Hagos, and Y. Qian, 2015: Dynamical and thermodynamical modulations on future changes of landfalling atmospheric rivers over western North America. *Geophysical Research Letters*, **42** (17), 7179–7186. https://doi.org/10.1002/2015gl065435

36. Mahoney, K., D. Swales, M.J. Mueller, M. Alexander, M. Hughes, and K. Malloy, 2018: An examination of an inland-penetrating atmospheric river flood event under potential future thermodynamic conditions. *Journal of Climate*, **31** (16), 6281–6297. https://doi.org/10.1175/jcli-d-18-0118.1

37. Warner, M.D. and C.F. Mass, 2017: Changes in the climatology, structure, and seasonality of northeast Pacific atmospheric rivers in CMIP5 climate simulations. *Journal of Hydrometeorology*, **18** (8), 2131–2141. https://doi.org/10.1175/jhm-d-16-0200.1

38. Massoud, E.C., V. Espinoza, B. Guan, and D.E. Waliser, 2019: Global climate model ensemble approaches for future projections of atmospheric rivers. *Earth's Future*, **7** (10), 1136–1151. https://doi.org/10.1029/2019EF001249

39. Howard, E.M., H. Frenzel, F. Kessouri, L. Renault, D. Bianchi, J.C. McWilliams, and C. Deutsch, 2020: Attributing causes of future climate change in the California Current System with multimodel downscaling. *Global Biogeochemical Cycles*, **34** (11), e2020GB006646. https://doi.org/10.1029/2020gb006646

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

41. Siedlecki, S.A., D. Pilcher, E.M. Howard, C. Deutsch, P. MacCready, E.L. Norton, H. Frenzel, J. Newton, R.A. Feely, S.R. Alin, and T. Klinger, 2021: Coastal processes modify projections of some climate-driven stressors in the California Current System. *Biogeosciences*, **18** (9), 2871–2890. https://doi.org/10.5194/bg-18-2871-2021

42. Sunday, J.M., E. Howard, S. Siedlecki, D.J. Pilcher, C. Deutsch, P. MacCready, J. Newton, and T. Klinger, 2022: Biological sensitivities to high-resolution climate change projections in the California Current Marine Ecosystem. *Global Change Biology*, **28** (19), 5726–5740. https://doi.org/10.1111/gcb.16317

43. Feely, R.A., S.R. Alin, B. Carter, N. Bednaršek, B. Hales, F. Chan, T.M. Hill, B. Gaylord, E. Sanford, R.H. Byrne, C.L. Sabine, D. Greeley, and L. Juranek, 2016: Chemical and biological impacts of ocean acidification along the west coast of North America. *Estuarine, Coastal and Shelf Science*, **183** (Part A), 260–270. https://doi.org/10.1016/j.ecss.2016.08.043

44. Doney, S.C., D.S. Busch, S.R. Cooley, and K.J. Kroeker, 2020: The impacts of ocean acidification on marine ecosystems and reliant human communities. *Annual Review of Environment and Resources*, **45**, 83–112. https://doi.org/10.1146/annurev-environ-012320-083019

45. Feely, R.A., R.R. Okazaki, W.-J. Cai, N. Bednaršek, S.R. Alin, R.H. Byrne, and A. Fassbender, 2018: The combined effects of acidification and hypoxia on pH and aragonite saturation in the coastal waters of the California Current Ecosystem and the northern Gulf of Mexico. *Continental Shelf Research*, **152**, 50–60. https://doi.org/10.1016/j.csr.2017.11.002

46. Pelletier, G., L. Bianucci, W. Long, T. Khangaonkar, T. Mohamedali, A. Ahmed, and C. Figueroa-Kaminsky, 2017: Salish Sea Model: Ocean Acidification Module and the Response to Regional Anthropogenic Nutrient Sources. Publication No. 17-03-009. State of Washington, Department of Ecology. https://apps.ecology.wa.gov/publications/documents/1703009.pdf

47. Gentemann, C.L., M.R. Fewings, and M. García-Reyes, 2017: Satellite sea surface temperatures along the West Coast of the United States during the 2014–2016 northeast Pacific marine heat wave. *Geophysical Research Letters*, **44** (1), 312–319. https://doi.org/10.1002/2016gl071039

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

49. NMFS, 2022: 2019-2022 Gray Whale Unusual Mortality Event along the West Coast and Alaska. National Oceanic and Atmospheric Administration, National Marine Fisheries Service. https://www.fisheries.noaa.gov/national/marine-life-distress/2019-2022-gray-whale-unusual-mortality-event-along-west-coast-and

50. Amaya, D.J., A.J. Miller, S.-P. Xie, and Y. Kosaka, 2020: Physical drivers of the summer 2019 North Pacific marine heatwave. *Nature Communications*, **11** (1), 1903. https://doi.org/10.1038/s41467-020-15820-w

51. Bond, N.A., M.F. Cronin, H. Freeland, and N. Mantua, 2015: Causes and impacts of the 2014 warm anomaly in the NE Pacific. *Geophysical Research Letters*, **42** (9), 3414–3420. https://doi.org/10.1002/2015gl063306

52. Oliver, E.C.J., J.A. Benthuysen, S. Darmaraki, M.G. Donat, A.J. Hobday, N.J. Holbrook, R.W. Schlegel, and A. Sen Gupta, 2021: Marine heatwaves. *Annual Review of Marine Science*, **13** (1), 313–342. https://doi.org/10.1146/annurev-marine-032720-095144

53. Peterson, W.T., J.L. Fisher, P.T. Strub, X. Du, C. Risien, J. Peterson, and C.T. Shaw, 2017: The pelagic ecosystem in the Northern California Current off Oregon during the 2014–2016 warm anomalies within the context of the past 20 years. *Journal of Geophysical Research: Oceans*, **122** (9), 7267–7290. https://doi.org/10.1002/2017jc012952

54. Trainer, V.L., S.K. Moore, G. Hallegraeff, R.M. Kudela, A. Clement, J.I. Mardones, and W.P. Cochlan, 2020: Pelagic harmful algal blooms and climate change: Lessons from nature's experiments with extremes. *Harmful Algae*, **91**, 101591. https://doi.org/10.1016/j.hal.2019.03.009

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

56. Newton, T.J., R. Weldon, I.M. Miller, D. Schmidt, G. Mauger, H. Morgan, and E. Grossman, 2021: An assessment of vertical land movement to support coastal hazards planning in Washington state. *Water*, **13** (3). https://doi.org/10.3390/w13030281

57. Taherkhani, M., S. Vitousek, P.L. Barnard, N. Frazer, T.R. Anderson, and C.H. Fletcher, 2020: Sea-level rise exponentially increases coastal flood frequency. *Scientific Reports*, **10** (1), 6466. https://doi.org/10.1038/s41598-020-62188-4

58. Miller, I.M., H. Morgan, G. Mauger, T. Newton, R. Weldon, D. Schmidt, M. Welch, and E. Grossman, 2018: Projected Sea Level Rise for Washington State—A 2018 Assessment. University of Washington, 24 pp. https://cig.uw.edu/projects/projected-sea-level-rise-for-washington-state-a-2018-assessment/

59. UW Climate Impacts Group, 2018: *An Unfair Share: Exploring the Disproportionate Risks from Climate Change Facing Washington State Communities*. University of Washington, Seattle, WA. https://cig.uw.edu/projects/an-unfair-share/

60. Voelkel, J., D. Hellman, R. Sakuma, and V. Shandas, 2018: Assessing vulnerability to urban heat: A study of disproportionate heat exposure and access to refuge by socio-demographic status in Portland, Oregon. *International Journal of Environmental Research and Public Health*, **15** (4), 640. https://doi.org/10.3390/ijerph15040640

61. Farrell, J., P.B. Burow, K. McConnell, J. Bayham, K. Whyte, and G. Koss, 2021: Effects of land dispossession and forced migration on Indigenous peoples in North America. *Science*, **374** (6567), 4943. https://doi.org/10.1126/science.abe4943

62. Lane, H.M., R. Morello-Frosch, J.D. Marshall, and J.S. Apte, 2022: Historical redlining is associated with present-day air pollution disparities in U.S. cities. *Environmental Science & Technology Letters*, **9** (4), 345–350. https://doi.org/10.1021/acs.estlett.1c01012

63. Alvarez, C.H., 2023: Structural racism as an environmental justice issue: A multilevel analysis of the state racism index and environmental health risk from air toxics. *Journal of Racial and Ethnic Health Disparities*, **10** (1), 244–258. https://doi.org/10.1007/s40615-021-01215-0

64. Colon, J., 2016: The Disproportionate Impacts of Climate Change on Communities of Color in Washington State. Front and Centered, 6 pp. https://frontandcentered.org/the-disproportionate-impacts-of-climate-change-on-communities-of-color-in-washington-state/

65. Digital Scholarship Lab and the National Community Reinvestment Coalition, 2020: Not even past: Social vulnerability and the legacy of redlining. In: *American Panorama.* Nelson, R. and E. Ayers, Eds. The Digital Scholarship Lab and the National Community Reinvestment Coalition. https://dsl.richmond.edu/socialvulnerability/

66. Priske, M., 2020: Environmental Racism and Economic Health Injustice: Exploring the LatinX Community in Eugene, Oregon. ArcGIS. https://storymaps.arcgis.com/stories/d519ab45cfc646438b8e91e846d674af

67. Bencivengo, A., E. Clark, M. Davies, E. Kushkowski, A. Loukides, F. Marten, A. Miller, L.I. Parker, H. Wise, and S. Witte, 2017: Vulnerability and Climate Change Adaptation Planning: Heat and Floods in Portland, Oregon. Reed College, Environmental Studies Department Junior Seminar, 62 pp. https://www.reed.edu/es/assets/es_300_2017_vulnerability-and-climate-change-adaptation-planning.pdf

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

69. Arnold, L., M.D. Scheuerell , and T. Busch Isaksen 2022: Mortality associated with extreme heat in Washington state: The historical and projected public health burden. *Atmosphere*, **13** (9), 1392. https://doi.org/10.3390/atmos13091392

70. Earth Economics, 2020: Urban Heat Island Analysis. Earth Economics, Tacoma, WA, 2 pp. https://cms.cityoftacoma.org/enviro/urbanforestry/tacomawa_heatislandanalysis.pdf

71. Schell, C.J., K. Dyson, T.L. Fuentes, S.D. Roches, N.C. Harris, D.S. Miller, C.A. Woelfle-Erskine, and M.R. Lambert, 2020: The ecological and evolutionary consequences of systemic racism in urban environments. *Science*, **369** (6510), 4497. https://doi.org/10.1126/science.aay4497

72. He, B.-J., J. Zhu, D.-X. Zhao, Z.-H. Gou, J.-D. Qi, and J. Wang, 2019: Co-benefits approach: Opportunities for implementing sponge city and urban heat island mitigation. *Land Use Policy*, **86**, 147–157. https://doi.org/10.1016/j.landusepol.2019.05.003

73. Richards, D.R. and P.J. Edwards, 2018: Using water management infrastructure to address both flood risk and the urban heat island. *International Journal of Water Resources Development*, **34** (4), 490–498. https://doi.org/10.1080/07900627.2017.1357538

74. Fischer, A.P., 2019: Pathways of adaptation to external stressors in coastal natural-resource-dependent communities: Implications for climate change. *World Development*, **108**, 235–248. https://doi.org/10.1016/j.worlddev.2017.12.007

75. Childs, M.L., J. Li, J. Wen, S. Heft-Neal, A. Driscoll, S. Wang, C.F. Gould, M. Qiu, J. Burney, and M. Burke, 2022: Daily local-level estimates of ambient wildfire smoke/$PM_{2.5}$ for the contiguous US. *Environmental Science & Technology*, **56** (19), 13607–13621. https://doi.org/10.1021/acs.est.2c02934

76. Tigchelaar, M., D.S. Battisti, and J.T. Spector, 2020: Work adaptations insufficient to address growing heat risk for U.S. agricultural workers. *Environmental Research Letters*, **15** (9), 094035. https://doi.org/10.1088/1748-9326/ab86f4

77. Calkins, M.M., D. Bonauto, A. Hajat, M. Lieblich, N. Seixas, L. Sheppard, and J.T. Spector, 2019: A case-crossover study of heat exposure and injury risk among outdoor construction workers in Washington State. *Scandinavian Journal of Work, Environment & Health*, **45** (6), 588–599. https://doi.org/10.5271/sjweh.3814

78. Oregon Health Authority, 2020: Climate and Health in Oregon 2020 Report. Oregon Health Authority, Public Health Division. https://www.oregon.gov/oha/ph/healthyenvironments/climatechange/documents/2020/climate%20and%20health%20in%20oregon%202020%20-%20full%20report.pdf

79. Miller, A.B., P.L. Winter, J.J. Sánchez, D.L. Peterson, and J.W. Smith, 2022: Climate change and recreation in the western United States: Effects and opportunities for adaptation. *Journal of Forestry*, **120** (4), 453–472. https://doi.org/10.1093/jofore/fvab072

80. Petersen-Rockney, M., P. Baur, A. Guzman, S.F. Bender, A. Calo, F. Castillo, K. De Master, A. Dumont, K. Esquivel, C. Kremen, J. LaChance, M. Mooshammer, J. Ory, M.J. Price, Y. Socolar, P. Stanley, A. Iles, and T. Bowles, 2021: Narrow and brittle or broad and nimble? Comparing adaptive capacity in simplifying and diversifying farming systems. *Frontiers in Sustainable Food Systems*, **5**, 564900. https://doi.org/10.3389/fsufs.2021.564900

81. Weiler, A.M., 2022: Farmworkers, climate change, and "converging crises". *Gastronomica*, **22** (1), 44–49. https://doi.org/10.1525/gfc.2022.22.1.44

82. Lavoie, A.L., K. Dentzman, and C.B. Wardropper, 2021: Using diffusion of innovations theory to understand agricultural producer perspectives on cover cropping in the inland Pacific Northwest, USA. *Renewable Agriculture and Food Systems*, **36** (4), 384–395. https://doi.org/10.1017/s1742170520000423

83. Roesch-McNally, G., A. Garrett, and M. Fery, 2020: Assessing perceptions of climate risk and adaptation among small farmers in Oregon's Willamette Valley. *Renewable Agriculture and Food Systems*, **35** (6), 626–630. https://doi.org/10.1017/s1742170519000267

84. Wardropper, C.B., J.P. Angerer, M. Burnham, M.E. Fernández-Giménez, V.S. Jansen, J.W. Karl, K. Lee, and K. Wollstein, 2021: Improving rangeland climate services for ranchers and pastoralists with social science. *Current Opinion in Environmental Sustainability*, **52**, 82–91. https://doi.org/10.1016/j.cosust.2021.07.001

85. Boag, A.E., J. Hartter, L.C. Hamilton, N.D. Christoffersen, F.R. Stevens, M.W. Palace, and M.J. Ducey, 2018: Climate change beliefs and forest management in eastern Oregon: Implications for individual adaptive capacity. *Ecology and Society*, **23** (4). https://doi.org/10.5751/es-10355-230401

86. Haltinner, K. and D. Sarathchandra, 2021: Considering attitudinal uncertainty in the climate change skepticism continuum. *Global Environmental Change*, **68**, 102243. https://doi.org/10.1016/j.gloenvcha.2021.102243

87. Maas, A., C. Wardropper, G. Roesch-McNally, and J. Abatzoglou, 2020: A (mis)alignment of farmer experience and perceptions of climate change in the U.S. inland pacific northwest. *Climatic Change*, **162** (3), 1011–1029. https://doi.org/10.1007/s10584-020-02713-6

88. Hand, J.P., 2008: Global climate change: A serious threat to Native American lands and culture. *Environmental Law Reporter-News & Analysis*, **38**, 10329. https://heinonline.org/HOL/LandingPage?handle=hein.journals/elrna38&div=28&id=&page=

89. Vinyeta, K. and K. Lynn, 2013: Exploring the Role of Traditional Ecological Knowledge in Climate Change Initiatives. Gen. Tech. Rep. PNW-GTR-879. U.S. Department of Agriculture, Forest Service, Pacific Northwest Research Station, Portland, OR, 37 pp. https://doi.org/10.2737/pnw-gtr-879

90. Burkett, M., R.R.M. Verchick, and D. Flores, 2017: Reaching Higher Ground: Avenues to Secure and Manage New Land for Communities Displaced by Climate Change. Research Paper No. 2017-07. Loyola University New Orleans College of Law, Center for Progressive Reform. https://ssrn.com/abstract=3034040

91. Ford, J.K. and E. Giles, 2015: Climate change adaptation in Indian country: Tribal regulation of reservation lands and natural resources. *William Mitchell Law Review*, **41** (2), 519–551. http://open.mitchellhamline.edu/wmlr/vol41/iss2/3/

92. Watkinson-Schutten, M., 2022: Decolonizing climate adaptation by reacquiring fractionated tribal lands. In: *The Oxford Handbook of Indigenous Sociology*. Walter, M., T. Kukutai, A.A. Gonzales, and R. Henry, Eds. Oxford University Press. https://doi.org/10.1093/oxfordhb/9780197528778.013.42

93. Maldonado, J., D. Antrobus, C. Comardelle, S.R. Cox, L. Laukea, C. Jones, P. Keys, H. Mullen, M. Neale, and D. Sambo Dorough, 2021: Ch. 10. Protection-in-place & community-led relocation. In: *Status of Tribes and Climate Change Report*. Marks-Marino, D., Ed. Institute for Tribal Environmental Professionals, 241–259. http://nau.edu/stacc2021

94. Jantarasami, L.C., R. Novak, R. Delgado, E. Marino, S. McNeeley, C. Narducci, J. Raymond-Yakoubian, L. Singletary, and K.P. Whyte, 2018: Ch. 15. Tribes and Indigenous Peoples. In: *Impacts, Risks, and Adaptation in the United States: Fourth National Climate Assessment, Volume II*. Reidmiller, D.R., C.W. Avery, D.R. Easterling, K.E. Kunkel, K.L.M. Lewis, T.K. Maycock, and B.C. Stewart, Eds. U.S. Global Change Research Program,, Washington, DC, USA, 572–603. https://doi.org/10.7930/nca4.2018.ch15

95. Lynn, K., J. Daigle, J. Hoffman, F. Lake, N. Michelle, D. Ranco, C. Viles, G. Voggesser, and P. Williams, 2014: Ch. 4. The impacts of climate change on tribal traditional foods. In: *Climate Change and Indigenous Peoples in the United States: Impacts, Experiences and Actions*. Maldonado, J.K., B. Colombi, and R. Pandya, Eds. Springer, Cham, Switzerland, 37–48. https://doi.org/10.1007/978-3-319-05266-3_4

96. Prevéy, J.S., L.E. Parker, C.A. Harrington, C.T. Lamb, and M.F. Proctor, 2020: Climate change shifts in habitat suitability and phenology of huckleberry (*Vaccinium membranaceum*). *Agricultural and Forest Meteorology*, **280**, 107803. https://doi.org/10.1016/j.agrformet.2019.107803

97. Front and Centered, 2020: Accelerating a Just Transition in Washington State: Climate Justice Strategies from the Frontlines. Front and Centered, 6 pp. https://frontandcentered.org/accelerating-a-just-transition-in-wa-state/

98. Shi, L. and S. Moser, 2021: Transformative climate adaptation in the United States: Trends and prospects. *Science*, **372** (6549), 8054. https://doi.org/10.1126/science.abc8054

99. Hellman, D. and V. Shandas, 2020: Community Resilience to Climate Change: Theory, Research and Practice. Portland State University. https://doi.org/10.15760/pdxopen-24

100. Makido, Y., D. Hellman, and V. Shandas, 2019: Nature-based designs to mitigate urban heat: The efficacy of green infrastructure treatments in Portland, Oregon. *Atmosphere*, **10** (5), 282. https://doi.org/10.3390/atmos10050282

101. Puget Sound Sage, 2020: Powering the Transition: Community Priorities for a Renewable and Equitable Future. Puget Sound Sage. https://pugetsoundsage.org/research/clean-healthy-environment/community-energy/

102. Blazina, A. and K. Davis, 2022: The Wildland-Urban Interface: Mapping Washington State's Fastest-Growing Environment. Washington State Department of Natural Resources. https://storymaps.arcgis.com/stories/7016c437623a445997c072a05e26afbb

103. Mockrin, M.H., D. Helmers, S. Martinuzzi, T.J. Hawbaker, and V.C. Radeloff, 2022: Growth of the wildland-urban interface within and around U.S. National Forests and Grasslands, 1990–2010. *Landscape and Urban Planning*, **218**, 104283. https://doi.org/10.1016/j.landurbplan.2021.104283

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

105. City of Boise, 2021: Boise's Climate Action Roadmap: Our Community's Plan for Climate Action. City of Boise. https://www.cityofboise.org/media/15045/boise-climate-roadmap.pdf

106. King County Climate Equity Community Task Force, 2020: Section II: Sustainable & resilient frontline communities. In: *King County 2020 Strategic Climate Action Plan*. Stroble, J. and S. Rahman, Eds., King County, WA. https://your.kingcounty.gov/dnrp/climate/documents/scap-2020-approved/2020-scap-sustainable-and-resilient-frontline-communities-section.pdf

107. Germain, S.J. and J.A. Lutz, 2020: Climate extremes may be more important than climate means when predicting species range shifts. *Climatic Change*, **163** (1), 579–598. https://doi.org/10.1007/s10584-020-02868-2

108. Noy-Meir, I., 1973: Desert ecosystems: Environment and producers. *Annual Review of Ecology and Systematics*, **4** (1), 25–51. https://doi.org/10.1146/annurev.es.04.110173.000325

109. Rangwala, I., W. Moss, J. Wolken, R. Rondeau, K. Newlon, J. Guinotte, and W.R. Travis, 2021: Uncertainty, complexity and constraints: How do we robustly assess biological responses under a rapidly changing climate? *Climate*, **9** (12), 177. https://doi.org/10.3390/cli9120177

110. Singer, M.C., 2017: Shifts in time and space interact as climate warms. *Proceedings of the National Academy of Sciences of the United States of America*, **114** (49), 12848–12850. https://doi.org/10.1073/pnas.1718334114

111. Fogarty, F.A., D.R. Cayan, L.L. DeHaan, and E. Fleishman, 2020: Associations of breeding-bird abundance with climate vary among species and trait-based groups in southern California. *PLoS ONE*, **15** (3), e0230614. https://doi.org/10.1371/journal.pone.0230614

112. Harsch, M.A. and J. HilleRisLambers, 2016: Climate warming and seasonal precipitation change interact to limit species distribution shifts across western North America. *PLoS ONE*, **11** (7), e0159184. https://doi.org/10.1371/journal.pone.0159184

113. Abatzoglou, J.T. and A.P. Williams, 2016: Impact of anthropogenic climate change on wildfire across western US forests. *Proceedings of the National Academy of Sciences of the United States of America*, **113** (42), 11770–11775. https://doi.org/10.1073/pnas.1607171113

114. Alizadeh, M.R., J.T. Abatzoglou, C.H. Luce, J.F. Adamowski, A. Farid, and M. Sadegh, 2021: Warming enabled upslope advance in western US forest fires. *Proceedings of the National Academy of Sciences of the United States of America*, **118** (22), e2009717118. https://doi.org/10.1073/pnas.2009717118

115. Holden, Z.A., A. Swanson, C.H. Luce, W.M. Jolly, M. Maneta, J.W. Oyler, D.A. Warren, R. Parsons, and D. Affleck, 2018: Decreasing fire season precipitation increased recent western US forest wildfire activity. *Proceedings of the National Academy of Sciences of the United States of America*, **115** (36), E8349–E8357. https://doi.org/10.1073/pnas.1802316115

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

117. Halofsky, J.E., D.L. Peterson, and B.J. Harvey, 2020: Changing wildfire, changing forests: The effects of climate change on fire regimes and vegetation in the Pacific Northwest, USA. *Fire Ecology*, **16** (1), 4. https://doi.org/10.1186/s42408-019-0062-8

118. Coop, J.D., S.A. Parks, C.S. Stevens-Rumann, S.D. Crausbay, P.E. Higuera, M.D. Hurteau, A. Tepley, E. Whitman, T. Assal, B.M. Collins, K.T. Davis, S. Dobrowski, D.A. Falk, P.J. Fornwalt, P.Z. Fulé, B.J. Harvey, V.R. Kane, C.E. Littlefield, E.Q. Margolis, M. North, M.-A. Parisien, S. Prichard, and K.C. Rodman, 2020: Wildfire-driven forest conversion in western North American landscapes. *BioScience*, **70** (8), 659–673. https://doi.org/10.1093/biosci/biaa061

119. Parks, S.A., S.Z. Dobrowski, J.D. Shaw, and C. Miller, 2019: Living on the edge: Trailing edge forests at risk of fire-facilitated conversion to non-forest. *Ecosphere*, **10** (3), e02651. https://doi.org/10.1002/ecs2.2651

120. Bradley, B.A., C.A. Curtis, and J.C. Chambers, 2016: Ch. 9. *Bromus* response to climate and projected changes with climate change. In: *Exotic Brome-Grasses in Arid and Semiarid Ecosystems of the Western US: Causes, Consequences, and Management Implications*. Germino, M.J., J.C. Chambers, and C.S. Brown, Eds. Springer, Cham, Switzerland, 257–274. https://doi.org/10.1007/978-3-319-24930-8_9

121. Williamson, M.A., E. Fleishman, R.C. Mac Nally, J.C. Chambers, B.A. Bradley, D.S. Dobkin, D.I. Board, F.A. Fogarty, N. Horning, M. Leu, and M. Wohlfeil Zillig, 2020: Fire, livestock grazing, topography, and precipitation affect occurrence and prevalence of cheatgrass (*Bromus tectorum*) in the Central Great Basin, USA. *Biological Invasions*, **22** (2), 663–680. https://doi.org/10.1007/s10530-019-02120-8

122. Mack, R.N. and J.N. Thompson, 1982: Evolution in steppe with few large, hooved mammals. *The American Naturalist*, **119** (6), 757–773. http://www.jstor.org/stable/2460961

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

124. Gervais, J.A., R. Kovach, A. Sepulveda, R. Al-Chokhachy, J. Joseph Giersch, and C.C. Muhlfeld, 2020: Climate-induced expansions of invasive species in the Pacific Northwest, North America: A synthesis of observations and projections. *Biological Invasions*, **22** (7), 2163–2183. https://doi.org/10.1007/s10530-020-02244-2

125. Abrams, J., H. Huber-Stearns, M. Steen-Adams, E.J. Davis, C. Bone, M.F. Nelson, and C. Moseley, 2021: Adaptive governance in a complex social-ecological context: Emergent responses to a native forest insect outbreak. *Sustainability Science*, **16** (1), 53–68. https://doi.org/10.1007/s11625-020-00843-5

126. Agne, M.C., P.A. Beedlow, D.C. Shaw, D.R. Woodruff, E.H. Lee, S.P. Cline, and R.L. Comeleo, 2018: Interactions of predominant insects and diseases with climate change in Douglas-fir forests of western Oregon and Washington, U.S.A. *Forest Ecology and Management*, **409**, 317–332. https://doi.org/10.1016/j.foreco.2017.11.004

127. Bentz, B.J., J. Régnière, C.J. Fettig, E.M. Hansen, J.L. Hayes, J.A. Hicke, R.G. Kelsey, J.F. Negrón, and S.J. Seybold, 2010: Climate change and bark beetles of the western United States and Canada: Direct and indirect effects. *BioScience*, **60** (8), 602–613. https://doi.org/10.1525/bio.2010.60.8.6

128. Elliott, J., S.I. Passy, K.L. Pound, G. Merritt, S. Polkowske, and C.A. Larson, 2022: Strong but heterogeneous distributional responses to climate change are projected for temperate and semi-arid stream vertebrates. *Aquatic Conservation: Marine and Freshwater Ecosystems*, **32** (8), 1291–1305. https://doi.org/10.1002/aqc.3805

129. Jacobs, G.R., R.F. Thurow, J.M. Buffington, D.J. Isaak, and S.J. Wenger, 2021: Climate, fire regime, geomorphology, and conspecifics influence the spatial distribution of Chinook salmon Redds. *Transactions of the American Fisheries Society*, **150** (1), 8–23. https://doi.org/10.1002/tafs.10270

130. Reid, A.J., A.K. Carlson, I.F. Creed, E.J. Eliason, P.A. Gell, P.T.J. Johnson, K.A. Kidd, T.J. MacCormack, J.D. Olden, S.J. Ormerod, J.P. Smol, W.W. Taylor, K. Tockner, J.C. Vermaire, D. Dudgeon, and S.J. Cooke, 2019: Emerging threats and persistent conservation challenges for freshwater biodiversity. *Biological Reviews*, **94** (3), 849–873. https://doi.org/10.1111/brv.12480

131. Wenger, S.J., D.J. Isaak, C.H. Luce, H.M. Neville, K.D. Fausch, J.B. Dunham, D.C. Dauwalter, M.K. Young, M.M. Elsner, B.E. Rieman, A.F. Hamlet, and J.E. Williams, 2011: Flow regime, temperature, and biotic interactions drive differential declines of trout species under climate change. *Proceedings of the National Academy of Sciences of the United States of America*, **108** (34), 14175–14180. https://doi.org/10.1073/pnas.1103097108

132. Al-Chokhachy, R., M. Lien, B.B. Shepard, and B. High, 2021: The interactive effects of stream temperature, stream size, and non-native species on Yellowstone cutthroat trout. *Canadian Journal of Fisheries and Aquatic Sciences*, **78** (8), 1073–1083. https://doi.org/10.1139/cjfas-2020-0408

133. Rubenson, E.S., D.J. Lawrence, and J.D. Olden, 2020: Threats to rearing juvenile Chinook salmon from nonnative smallmouth bass inferred from stable isotope and fatty acid biomarkers. *Transactions of the American Fisheries Society*, **149** (3), 350–363. https://doi.org/10.1002/tafs.10237

134. Rubenson, E.S. and J.D. Olden, 2020: An invader in salmonid rearing habitat: Current and future distributions of smallmouth bass (*Micropterus dolomieu*) in the Columbia River Basin. *Canadian Journal of Fisheries and Aquatic Sciences*, **77** (2), 314–325. https://doi.org/10.1139/cjfas-2018-0357

135. Freeman, M.C., K.R. Bestgen, D. Carlisle, E.A. Frimpong, N.R. Franssen, K.B. Gido, E. Irwin, Y. Kanno, C. Luce, S. Kyle McKay, M.C. Mims, J.D. Olden, N. LeRoy Poff, D.L. Propst, L. Rack, A.H. Roy, E.S. Stowe, A. Walters, and S.J. Wenger, 2022: Toward improved understanding of streamflow effects on freshwater fishes. *Fisheries*, **47** (7), 290–298. https://doi.org/10.1002/fsh.10731

136. Goode, J.R., J.M. Buffington, D. Tonina, D.J. Isaak, R.F. Thurow, S. Wenger, D. Nagel, C. Luce, D. Tetzlaff, and C. Soulsby, 2013: Potential effects of climate change on streambed scour and risks to salmonid survival in snow-dominated mountain basins. *Hydrological Processes*, **27** (5), 750–765. https://doi.org/10.1002/hyp.9728

137. Gould, G.K., M. Liu, M.E. Barber, K.A. Cherkauer, P.R. Robichaud, and J.C. Adam, 2016: The effects of climate change and extreme wildfire events on runoff erosion over a mountain watershed. *Journal of Hydrology*, **536**, 74–91. https://doi.org/10.1016/j.jhydrol.2016.02.025

138. Nicol, C.L., J.C. Jorgensen, C.B. Fogel, B. Timpane-Padgham, and T.J. Beechie, 2022: Spatially overlapping salmon species have varied population response to early life history mortality from increased peak flows. *Canadian Journal of Fisheries and Aquatic Sciences*, **79** (2), 342–351. https://doi.org/10.1139/cjfas-2021-0038

139. Srivastava, A., E.S. Brooks, M. Dobre, W.J. Elliot, J.Q. Wu, D.C. Flanagan, J.A. Gravelle, and T.E. Link, 2020: Modeling forest management effects on water and sediment yield from nested, paired watersheds in the interior Pacific Northwest, USA using WEPP. *Science of The Total Environment*, **701**, 134877. https://doi.org/10.1016/j.scitotenv.2019.134877

140. Dunham, J.B., M.K. Young, R.E. Gresswell, and B.E. Rieman, 2003: Effects of fire on fish populations: Landscape perspectives on persistence of native fishes and nonnative fish invasions. *Forest Ecology and Management*, **178** (1), 183–196. https://doi.org/10.1016/s0378-1127(03)00061-6

141. Isaak, D.J., C.H. Luce, B.E. Rieman, D.E. Nagel, E.E. Peterson, D.L. Horan, S. Parkes, and G.L. Chandler, 2010: Effects of climate change and wildfire on stream temperatures and salmonid thermal habitat in a mountain river network. *Ecological Applications*, **20** (5), 1350–1371. https://doi.org/10.1890/09-0822.1

142. Goode, J.R., C.H. Luce, and J.M. Buffington, 2012: Enhanced sediment delivery in a changing climate in semi-arid mountain basins: Implications for water resource management and aquatic habitat in the northern Rocky Mountains. *Geomorphology*, **139**, 1–15. https://doi.org/10.1016/j.geomorph.2011.06.021

143. Maturana, O., D. Tonina, J.A. McKean, J.M. Buffington, C.H. Luce, and D. Caamaño, 2014: Modeling the effects of pulsed versus chronic sand inputs on salmonid spawning habitat in a low-gradient gravel-bed river. *Earth Surface Processes and Landforms*, **39** (7), 877–889. https://doi.org/10.1002/esp.3491

144. Rieman, B., D. Lee, D. Burns, R. Gresswell, M. Young, R. Stowell, J. Rinne, and P. Howell, 2003: Status of native fishes in the western United States and issues for fire and fuels management. *Forest Ecology and Management*, **178** (1), 197–211. https://doi.org/10.1016/s0378-1127(03)00062-8

145. Free, C.M., S.C. Anderson, E.A. Hellmers, B.A. Muhling, M.O. Navarro, K. Richerson, L.A. Rogers, W.H. Satterthwaite, A.R. Thompson, J.M. Burt, S.D. Gaines, K.N. Marshall, J.W. White, and L.F. Bellquist, 2023: Impact of the 2014–2016 marine heatwave on US and Canada West Coast fisheries: Surprises and lessons from key case studies. *Fish and Fisheries*, **24** (4), 652–674. https://doi.org/10.1111/faf.12753

146. Morgan, C.A., B.R. Beckman, L.A. Weitkamp, and K.L. Fresh, 2019: Recent ecosystem disturbance in the Northern California Current. *Fisheries*, **44** (10), 465–474. https://doi.org/10.1002/fsh.10273

147. Shanks, A.L., L.K. Rasmuson, J.R. Valley, M.A. Jarvis, C. Salant, D.A. Sutherland, E.I. Lamont, M.A.H. Hainey, and R.B. Emlet, 2020: Marine heat waves, climate change, and failed spawning by coastal invertebrates. *Limnology and Oceanography*, **65** (3), 627–636. https://doi.org/10.1002/lno.11331

148. McCabe, R.M., B.M. Hickey, R.M. Kudela, K.A. Lefebvre, N.G. Adams, B.D. Bill, F.M.D. Gulland, R.E. Thomson, W.P. Cochlan, and V.L. Trainer, 2016: An unprecedented coastwide toxic algal bloom linked to anomalous ocean conditions. *Geophysical Research Letters*, **43** (19), 10366–10376. https://doi.org/10.1002/2016gl070023

149. Akmajian, A.M., J.J. Scordino, and A. Acevedo-Gutiérrez, 2017: Year-round algal toxin exposure in free-ranging sea lions. *Marine Ecology Progress Series*, **583**, 243–258. https://doi.org/10.3354/meps12345

150. Piatt, J.F., J.K. Parrish, H.M. Renner, S.K. Schoen, T.T. Jones, M.L. Arimitsu, K.J. Kuletz, B. Bodenstein, M. García-Reyes, R.S. Duerr, R.M. Corcoran, R.S.A. Kaler, G.J. McChesney, R.T. Golightly, H.A. Coletti, R.M. Suryan, H.K. Burgess, J. Lindsey, K. Lindquist, P.M. Warzybok, J. Jahncke, J. Roletto, and W.J. Sydeman, 2020: Extreme mortality and reproductive failure of common murres resulting from the northeast Pacific marine heatwave of 2014–2016. *PLoS ONE*, **15** (1), e0226087. https://doi.org/10.1371/journal.pone.0226087

151. Ford, M.J., 2022: Biological Viability Assessment Update for Pacific Salmon and Steelhead Listed Under the Endangered Species Act: Pacific Northwest. NOAA Technical Memorandum NMFS-NWFSC-171. National Oceanic and Atmospheric Administration, National Marine Fisheries Service. https://doi.org/10.25923/kq2n-ke70

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

153. Frölicher, T.L., E.M. Fischer, and N. Gruber, 2018: Marine heatwaves under global warming. *Nature*, **560** (7718), 360–364. https://doi.org/10.1038/s41586-018-0383-9

154. Smith, K.E., M.T. Burrows, A.J. Hobday, N.G. King, P.J. Moore, A. Sen Gupta, M.S. Thomsen, T. Wernberg, and D.A. Smale, 2023: Biological impacts of marine heatwaves. *Annual Review of Marine Science*, **15** (1), 119–145. https://doi.org/10.1146/annurev-marine-032122-121437

155. Samhouri, J.F., B.E. Feist, M.C. Fisher, O. Liu, S.M. Woodman, B. Abrahms, K.A. Forney, E.L. Hazen, D. Lawson, J. Redfern, and L.E. Saez, 2021: Marine heatwave challenges solutions to human-wildlife conflict. *Proceedings of the Royal Society B: Biological Sciences*, **288** (1964), 20211607. https://doi.org/10.1098/rspb.2021.1607

156. Cline, T.J., J. Ohlberger, and D.E. Schindler, 2019: Effects of warming climate and competition in the ocean for life-histories of Pacific salmon. *Nature Ecology & Evolution*, **3** (6), 935–942. https://doi.org/10.1038/s41559-019-0901-7

157. Litzow, M.A., F.J. Mueter, and A.J. Hobday, 2014: Reassessing regime shifts in the North Pacific: Incremental climate change and commercial fishing are necessary for explaining decadal-scale biological variability. *Global Change Biology*, **20** (1), 38–50. https://doi.org/10.1111/gcb.12373

158. Ohlberger, J., E.J. Ward, D.E. Schindler, and B. Lewis, 2018: Demographic changes in Chinook salmon across the northeast Pacific Ocean. *Fish and Fisheries*, **19** (3), 533–546. https://doi.org/10.1111/faf.12272

159. Welch, D.W., A.D. Porter, and E.L. Rechisky, 2021: A synthesis of the coast-wide decline in survival of West Coast Chinook salmon (*Oncorhynchus tshawytscha*, Salmonidae). *Fish and Fisheries*, **22** (1), 194–211. https://doi.org/10.1111/faf.12514

160. Crozier, L.G., B.J. Burke, B.E. Chasco, D.L. Widener, and R.W. Zabel, 2021: Climate change threatens Chinook salmon throughout their life cycle. *Communications Biology*, **4** (1), 222. https://doi.org/10.1038/s42003-021-01734-w

161. Crozier, L.G., J.E. Siegel, L.E. Wiesebron, E.M. Trujillo, B.J. Burke, B.P. Sandford, and D.L. Widener, 2020: Snake River sockeye and Chinook salmon in a changing climate: Implications for upstream migration survival during recent extreme and future climates. *PLoS ONE*, **15** (9), e0238886. https://doi.org/10.1371/journal.pone.0238886

162. Isaak, D.J., C.H. Luce, D.L. Horan, G.L. Chandler, S.P. Wollrab, and D.E. Nagel, 2018: Global warming of salmon and trout rivers in the northwestern U.S.: Road to ruin or path through purgatory? *Transactions of the American Fisheries Society*, **147** (3), 566–587. https://doi.org/10.1002/tafs.10059

163. Isaak, D.J., S.J. Wenger, E.E. Peterson, J.M. Ver Hoef, D.E. Nagel, C.H. Luce, S.W. Hostetler, J.B. Dunham, B.B. Roper, S.P. Wollrab, G.L. Chandler, D.L. Horan, and S. Parkes-Payne, 2017: The NorWeST summer stream temperature model and scenarios for the Western U.S.: A crowd-sourced database and new geospatial tools foster a user community and predict broad climate warming of rivers and streams. *Water Resources Research*, **53** (11), 9181–9205. https://doi.org/10.1002/2017wr020969

164. Keefer, M.L., T.S. Clabough, M.A. Jepson, E.L. Johnson, C.A. Peery, and C.C. Caudill, 2018: Thermal exposure of adult Chinook salmon and steelhead: Diverse behavioral strategies in a large and warming river system. *PLoS ONE*, **13** (9), e0204274. https://doi.org/10.1371/journal.pone.0204274

165. Zhang, X., H.-Y. Li, Z.D. Deng, L.R. Leung, J.R. Skalski, and S.J. Cooke, 2019: On the variable effects of climate change on Pacific salmon. *Ecological Modelling*, **397**, 95–106. https://doi.org/10.1016/j.ecolmodel.2019.02.002

166. Moore, S.K., J.A. Johnstone, N.S. Banas, and E.P. Salathé, 2015: Present-day and future climate pathways affecting *Alexandrium* blooms in Puget Sound, WA, USA. *Harmful Algae*, **48**, 1–11. https://doi.org/10.1016/j.hal.2015.06.008

167. Ralston, D.K. and S.K. Moore, 2020: Modeling harmful algal blooms in a changing climate. *Harmful Algae*, **91**, 101729. https://doi.org/10.1016/j.hal.2019.101729

168. Munsch, S.H., C.M. Greene, N.J. Mantua, and W.H. Satterthwaite, 2022: One hundred-seventy years of stressors erode salmon fishery climate resilience in California's warming landscape. *Global Change Biology*, **28** (7), 2183–2201. https://doi.org/10.1111/gcb.16029

169. Sullaway, G.H., A.O. Shelton, and J.F. Samhouri, 2021: Synchrony erodes spatial portfolios of an anadromous fish and alters availability for resource users. *Journal of Animal Ecology*, **90** (11), 2692–2703. https://doi.org/10.1111/1365-2656.13575

170. Crozier, L.G., M.M. McClure, T. Beechie, S.J. Bograd, D.A. Boughton, M. Carr, T.D. Cooney, J.B. Dunham, C.M. Greene, M.A. Haltuch, E.L. Hazen, D.M. Holzer, D.D. Huff, R.C. Johnson, C.E. Jordan, I.C. Kaplan, S.T. Lindley, N.J. Mantua, P.B. Moyle, J.M. Myers, M.W. Nelson, B.C. Spence, L.A. Weitkamp, T.H. Williams, and E. Willis-Norton, 2019: Climate vulnerability assessment for Pacific salmon and steelhead in the California Current Large Marine Ecosystem. *PLoS ONE*, **14** (7), e0217711. https://doi.org/10.1371/journal.pone.0217711

171. WCR, 2015: ESA Recovery Plan for Snake River Sockeye Salmon (*Oncorhynchus nerka*). National Oceanic and Atmospheric Administration, National Marine Fisheries Service, West Coast Region. https://repository.library.noaa.gov/view/noaa/16001

172. Waples, R.S., O.W. Johnson, and R.P. Jones Jr., 1991: Status Review for Snake River Sockeye Salmon. NOAA Technical Memorandum NMFS F/NWC-19. National Oceanic and Atmospheric Administration, National Marine Fisheries Service. https://repository.library.noaa.gov/view/noaa/21168

173. Johnson, E.L., C.C. Kozfkay, J.H. Powell, M.P. Peterson, D.J. Baker, J.A. Heindel, K.E. Plaster, J.L. McCormick, and P.A. Kline, 2020: Evaluating artificial propagation release strategies for recovering endangered Snake River sockeye salmon. *North American Journal of Aquaculture*, **82** (3), 331–344. https://doi.org/10.1002/naaq.10148

174. Kozfkay, C.C., M. Peterson, B.P. Sandford, E.L. Johnson, and P. Kline, 2019: The productivity and viability of Snake River sockeye salmon hatchery adults released into Redfish Lake, Idaho. *Transactions of the American Fisheries Society*, **148** (2), 308–323. https://doi.org/10.1002/tafs.10136

175. Selbie, D.T., B.A. Lewis, J.P. Smol, and B.P. Finney, 2007: Long-term population dynamics of the endangered Snake River sockeye salmon: Evidence of past influences on stock decline and impediments to recovery. *Transactions of the American Fisheries Society*, **136** (3), 800–821. https://doi.org/10.1577/t06-100.1

176. Good, T.P., R.S. Waples, and P. Adams, 2005: Updated Status of Federally Listed ESUs of West Coast Salmon and Steelhead. NOAA Technical Memorandum NMFS-NWFSC-66. National Oceanic and Atmospheric Administration, National Marine Fisheries Service, Northwest Fisheries Science Center, 598 pp. https://repository.library.noaa.gov/view/noaa/3413

177. Kalinowski, S.T., D.M. Van Doornik, C.C. Kozfkay, and R.S. Waples, 2012: Genetic diversity in the Snake River sockeye salmon captive broodstock program as estimated from broodstock records. *Conservation Genetics*, **13** (5), 1183–1193. https://doi.org/10.1007/s10592-012-0363-9

178. Crozier, L.G., L.E. Weisebron, J.E. Siegel, B.J. Burke, T.M. Marsh, B.P. Sandford, and D.L. Widener, 2018: Passage and Survival of Adult Snake River Sockeye Salmon Within and Upstream from the Federal Columbia River Power System: 2008–2017 National Oceanic and Atmospheric Administration, National Marine Fisheries Service, Northwest Fisheries Science Center, Fish Ecology Division, Seattle, WA. https://www.webapps.nwfsc.noaa.gov/assets/26/9567_03132020_144513_Crozier.et.al.2018-Adult-Sockeye-2008-2017-USACE.pdf

179. NMFS, 2016: 2015 Adult Sockeye Salmon Passage Report. National Oceanic and Atmospheric Administration, National Marine Fisheries Service. https://www.columbiariverkeeper.org/sites/default/files/2017/08/8.pdf

180. WCR, 2021: Endangered Species Act Section 7 Formal Consultation and Magnuson-Stevens Fishery Conservation and Management Act Essential Fish Habitat Consultation for Authorizing Operation and Maintenance of Water Diversions Located on the Salmon-Challis National Forest in the Lemhi River Watershed, HUC 17060204, Lemhi County, Idaho. National Oceanic and Atmospheric Administration, National Marine Fisheries Service, West Coast Region. https://doi.org/10.25923/r94p-xe17

181. Walters, A.W., K.K. Bartz, and M.M. Mcclure, 2013: Interactive effects of water diversion and climate change for juvenile Chinook salmon in the Lemhi River Basin (U.S.A.). *Conservation Biology*, **27** (6), 1179–1189. https://doi.org/10.1111/cobi.12170

182. Evans, M.L., A.E. Kohler, R.G. Griswold, K.A. Tardy, K.R. Eaton, and J.D. Ebel, 2020: Salmon-mediated nutrient flux in Snake River sockeye salmon nursery lakes: The influence of depressed population size and hatchery supplementation. *Lake and Reservoir Management*, **36** (1), 75–86. https://doi.org/10.1080/10402381.2019.1654571

183. Krueger, C.C., W.W. Taylor, and S.-J. Youn, 2019: Ch. 1. Fishery management success: Action, collaboration, communication, and commitment. In: *From Catastrophe to Recovery: Stories of Fishery Management Success*. Krueger, C.C., W.W. Taylor, and S.-J. Youn, Eds. American Fisheries Society. https://doi.org/10.47886/9781934874554.ch1

184. Crozier, L.G., M.D. Scheuerell, and R.W. Zabel, 2011: Using time series analysis to characterize evolutionary and plastic responses to environmental change: A case study of a shift toward earlier migration date in sockeye salmon. *The American Naturalist*, **178** (6), 755–773. https://doi.org/10.1086/662669

185. Quinn, T.P. and D.J. Adams, 1996: Environmental changes affecting the migratory timing of American shad and sockeye salmon. *Ecology*, **77** (4), 1151–1162. https://doi.org/10.2307/2265584

186. Bennett, J.M., R.H. Clarke, G.F.B. Horrocks, J.R. Thomson, and R. Mac Nally, 2015: Climate drying amplifies the effects of land-use change and interspecific interactions on birds. *Landscape Ecology*, **30** (10), 2031–2043. https://doi.org/10.1007/s10980-015-0229-x

187. Habel, J.C. and F.E. Zachos, 2012: Habitat fragmentation versus fragmented habitats. *Biodiversity and Conservation*, **21** (11), 2987–2990. https://doi.org/10.1007/s10531-012-0349-4

188. Carja, O. and J.B. Plotkin, 2019: Evolutionary rescue through partly heritable phenotypic variability. *Genetics*, **211** (3), 977–988. https://doi.org/10.1534/genetics.118.301758

189. Nimmo, D.G., A. Haslem, J.Q. Radford, M. Hall, and A.F. Bennett, 2016: Riparian tree cover enhances the resistance and stability of woodland bird communities during an extreme climatic event. *Journal of Applied Ecology*, **53** (2), 449–458. https://doi.org/10.1111/1365-2664.12535

190. Thompson, L.M., L.L. Thurman, C.N. Cook, E.A. Beever, C.M. Sgrò, A. Battles, C.A. Botero, J.E. Gross, K.R. Hall, A.P. Hendry, A.A. Hoffmann, C. Hoving, O.E. LeDee, C. Mengelt, A.B. Nicotra, R.A. Niver, F. Pérez-Jvostov, R.M. Quiñones, G.W. Schuurman, M.K. Schwartz, J. Szymanski, and A. Whiteley, 2023: Connecting research and practice to enhance the evolutionary potential of species under climate change. *Conservation Science and Practice*, **5** (2), e12855. https://doi.org/10.1111/csp2.12855

191. UNEP, 2019: Sand and Sustainability: Finding New Solutions for Environmental Governance of Global Sand Resources. United Nations Environment Programme. https://wedocs.unep.org/handle/20.500.11822/28163;jsessionid=333820b5a8c38cdd7f7f44fc1984d9ae

192. Grossman, E.E., A.W. Stevens, D. P, D. George, and D. Finlayson, 2020: Sediment export and impacts associated with river delta channelization compound estuary vulnerability to sea-level rise. *Marine Geology*, **430**, 106336. https://doi.org/10.1016/j.margeo.2020.106336

193. Knox, R.L., E.E. Wohl, and R.R. Morrison, 2022: Levees don't protect, they disconnect: A critical review of how artificial levees impact floodplain functions. *Science of The Total Environment*, **837**, 155773. https://doi.org/10.1016/j.scitotenv.2022.155773

194. Bond, M.H., T.G. Nodine, T.J. Beechie, and R.W. Zabel, 2019: Estimating the benefits of widespread floodplain reconnection for Columbia River Chinook salmon. *Canadian Journal of Fisheries and Aquatic Sciences*, **76** (7), 1212–1226. https://doi.org/10.1139/cjfas-2018-0108

195. Grossman, E.E., S.C. Crosby, A.W. Stevens, D.J. Nowacki, N.R. vanAredonk, and C.A. Curran, 2022: Assessment of Vulnerabilities and Opportunities to Restore Marsh Sediment Supply at Nisqually River Delta, West-Central Washington. USGS Open-File Report 2022–1088. U.S. Geological Survey, 50 pp. https://doi.org/10.3133/ofr20221088

196. Moritsch, M.M., K.B. Byrd, M. Davis, A. Good, J.Z. Drexler, J.T. Morris, I. Woo, L. Windham-Myers, E. Grossman, G. Nakai, K.L. Poppe, and J.M. Rybczyk, 2022: Can coastal habitats rise to the challenge? Resilience of estuarine habitats, carbon accumulation, and economic value to sea-level rise in a Puget Sound estuary. *Estuaries and Coasts*, **45** (8), 2293–2309. https://doi.org/10.1007/s12237-022-01087-5

197. Copeland, T., B.J. Bowersox, M.W. Ackerman, and C. Camacho, 2019: Patterns of iteroparity in wild Snake River steelhead. *Transactions of the American Fisheries Society*, **148** (5), 926–937. https://doi.org/10.1002/tafs.10187

198. Morley, S.A., M.M. Foley, J.J. Duda, M.M. Beirne, R.L. Paradis, R.C. Johnson, M.L. McHenry, M. Elofson, E.M. Sampson, R.E. McCoy, J. Stapleton, and G.R. Pess, 2020: Shifting food web structure during dam removal—Disturbance and recovery during a major restoration action. *PLoS ONE*, **15** (9), e0239198. https://doi.org/10.1371/journal.pone.0239198

199. Penaluna, B.E., G.H. Reeves, Z.C. Barnett, P.A. Bisson, J.M. Buffington, C.A. Dolloff, R.L. Flitcroft, C.H. Luce, K.H. Nislow, J.D. Rothlisberger, and M.L. Warren Jr, 2018: Using natural disturbance and portfolio concepts to guide aquatic–riparian ecosystem management. *Fisheries*, **43** (9), 406–422. https://doi.org/10.1002/fsh.10097

200. Quinn, T.P., M.H. Bond, S.J. Brenkman, R. Paradis, and R.J. Peters, 2017: Re-awakening dormant life history variation: Stable isotopes indicate anadromy in bull trout following dam removal on the Elwha River, Washington. *Environmental Biology of Fishes*, **100** (12), 1659–1671. https://doi.org/10.1007/s10641-017-0676-0

201. Hessburg, P.F., S.J. Prichard, R.K. Hagmann, N.A. Povak, and F.K. Lake, 2021: Wildfire and climate change adaptation of western North American forests: A case for intentional management. *Ecological Applications*, **31** (8), e02432. https://doi.org/10.1002/eap.2432

202. Prichard, S.J., P.F. Hessburg, R.K. Hagmann, N.A. Povak, S.Z. Dobrowski, M.D. Hurteau, V.R. Kane, R.E. Keane, L.N. Kobziar, C.A. Kolden, M. North, S.A. Parks, H.D. Safford, J.T. Stevens, L.L. Yocom, D.J. Churchill, R.W. Gray, D.W. Huffman, F.K. Lake, and P. Khatri-Chhetri, 2021: Adapting western North American forests to climate change and wildfires: 10 common questions. *Ecological Applications*, **31** (8), e02433. https://doi.org/10.1002/eap.2433

203. Vose, J.M., D.L. Peterson, C.H. Luce, and T. Patel-Weynand, 2019: Effects of Drought on Forests and Rangelands in the United States: Translating Science into Management Responses. Gen. Tech. Rep. WO-98. U.S. Department of Agriculture, Forest Service, Washington Office, Washington, DC, 227 pp. https://doi.org/10.2737/wo-gtr-98

204. Halofsky, J.E., D.L. Peterson, and H.R. Prendeville, 2018: Assessing vulnerabilities and adapting to climate change in northwestern U.S. forests. *Climatic Change*, **146** (1-2), 89–102. https://doi.org/10.1007/s10584-017-1972-6

205. Reilly, M.J., A. Zuspan, J.S. Halofsky, C. Raymond, A. McEvoy, A.W. Dye, D.C. Donato, J.B. Kim, B.E. Potter, N. Walker, R.J. Davis, C.J. Dunn, D.M. Bell, M.J. Gregory, J.D. Johnston, B.J. Harvey, J.E. Halofsky, and B.K. Kerns, 2022: Cascadia burning: The historic, but not historically unprecedented, 2020 wildfires in the Pacific Northwest, USA. *Ecosphere*, **13** (6), e4070. https://doi.org/10.1002/ecs2.4070

206. Endter-Wada, J., K.M. Kettenring, and A.E. Sutton-Grier, 2018: Sustaining wetlands to mitigate disasters and protect people. *Frontiers in Ecology and the Environment*, **16** (8), 431–431. https://doi.org/10.1002/fee.1959

207. WA State Department of Ecology, 2022: Mitigation Bank Projects. State of Washington, Department of Ecology. https://ecology.wa.gov/water-shorelines/wetlands/mitigation/wetland-mitigation-banking/mitigation-bank-projects

208. Van den Bosch, K. and J.W. Matthews, 2017: An assessment of long-term compliance with performance standards in compensatory mitigation wetlands. *Environmental Management*, **59** (4), 546–556. https://doi.org/10.1007/s00267-016-0804-1

209. Oja, E.B., L.K. Swartz, E. Muths, and B.R. Hossack, 2021: Amphibian population responses to mitigation: Relative importance of wetland age and design. *Ecological Indicators*, **131**, 108123. https://doi.org/10.1016/j.ecolind.2021.108123

210. Khanal, R., M.P. Brady, C.O. Stöckle, K. Rajagopalan, J. Yoder, and M.E. Barber, 2021: The economic and environmental benefits of partial leasing of agricultural water rights. *Water Resources Research*, **57** (11), e2021WR029712. https://doi.org/10.1029/2021wr029712

211. Leonard, B., C. Costello, and G.D. Libecap, 2019: Expanding water markets in the western United States: barriers and lessons from other natural resource markets. *Review of Environmental Economics and Policy*, **13** (1), 43–61. https://doi.org/10.1093/reep/rey014

212. Gienapp, P., C. Teplitsky, J.S. Alho, J.A. Mills, and J. Merilä, 2008: Climate change and evolution: Disentangling environmental and genetic responses. *Molecular Ecology*, **17** (1), 167–178. https://doi.org/10.1111/j.1365-294x.2007.03413.x

213. Merilä, J. and A.P. Hendry, 2014: Climate change, adaptation, and phenotypic plasticity: The problem and the evidence. *Evolutionary Applications*, **7** (1), 1–14. https://doi.org/10.1111/eva.12137

214. Bigelow, D.P. and A. Borchers, 2017: Major Uses of Land in the United States, 2012. EIB-178. U.S. Department of Agriculture, Economic Research Service. https://www.ers.usda.gov/publications/pub-details/?pubid=84879

215. ERS, 2023: Data Files: U.S. and State-Level Farm Income and Wealth Statistics. U.S. Department of Agriculture, Economic Research Service, accessed March 20, 2023. https://www.ers.usda.gov/data-products/farm-income-and-wealth-statistics/data-files-u-s-and-state-level-farm-income-and-wealth-statistics/

216. Rajagopalan, K., K.J. Chinnayakanahalli, C.O. Stockle, R.L. Nelson, C.E. Kruger, M.P. Brady, K. Malek, S.T. Dinesh, M.E. Barber, A.F. Hamlet, G.G. Yorgey, and J.C. Adam, 2018: Impacts of near-term climate change on irrigation demands and crop yields in the Columbia River Basin. *Water Resources Research*, **54** (3), 2152–2182. https://doi.org/10.1002/2017wr020954

217. Noorazar, H., L. Kalcsits, V.P. Jones, M.S. Jones, and K. Rajagopalan, 2022: Climate change and chill accumulation: Implications for tree fruit production in cold-winter regions. *Climatic Change*, **171** (3), 34. https://doi.org/10.1007/s10584-022-03339-6

218. Willsea, N., V. Blanco, K. Rajagopalan, T. Campbell, O. Howe, and L. Kalcsits, 2023: Reviewing the tradeoffs between sunburn mitigation and red color development in apple under a changing climate. *Horticulturae*, **9** (4), 492. https://doi.org/10.3390/horticulturae9040492

219. Gallinat, A.S., R.B. Primack, and D.L. Wagner, 2015: Autumn, the neglected season in climate change research. *Trends in Ecology & Evolution*, **30** (3), 169–176. https://doi.org/10.1016/j.tree.2015.01.004

220. Rajagopalan, K., G. DeGrandi-Hoffman, M. Pruett, V.P. Jones, V. Corby-Harris, J. Pireaud, R. Curry, B. Hopkins, and T. Northfield, 2022: Changing Honey Bee Overwintering Dynamics Under Warmer Autumns and Winters Create New Risks for Pollination Services. Research Square. https://doi.org/10.21203/rs.3.rs-1394621/v1

221. Jones, G. and H. Schultz, 2016: Climate change and emerging cool climate wine regions. *Wine and Viticulture Journal*, **31** (6), 51–53. https://search.informit.org/doi/10.3316/informit.523901697092406

222. Mirabelli-Montan, Y.A., M. Marangon, A. Graça, C.M. Mayr Marangon, and K.L. Wilkinson, 2021: Techniques for mitigating the effects of smoke taint while maintaining quality in wine production: A review. *Molecules*, **26** (6), 1672. https://doi.org/10.3390/molecules26061672

223. Ansah, E.O. and O.S. Walsh, 2021: Impact of 2021 drought in the Pacific Northwest. *Crops & Soils*, **54** (6), 46–49. https://doi.org/10.1002/crso.20145

224. NASS, 2021: Small Grains 2021 Summary. U.S. Department of Agriculture, National Agricultural Statistics Service. https://www.nass.usda.gov/publications/todays_reports/reports/smgr0921.pdf

225. Winford, E. and K. Lee, 2021: Rangelands report. In: *Idaho Climate-Economy Impacts Assessment*. James A. and Louise McClure Center for Public Policy Research, University of Idaho, Boise, ID. https://www.uidaho.edu/president/direct-reports/mcclure-center/iceia/land

226. Chengot, R., J.W. Knox, and I.P. Holman, 2021: Evaluating the feasibility of water sharing as a drought risk management tool for irrigated agriculture. *Sustainability*, **13** (3). https://doi.org/10.3390/su13031456

227. Coppock, D.L., 2020: Improving drought preparedness among Utah cattle ranchers. *Rangeland Ecology & Management*, **73** (6), 879–890. https://doi.org/10.1016/j.rama.2020.08.003

228. Peck, D., J. Derner, W. Parton, M. Hartman, and B. Fuchs, 2019: Flexible stocking with Grass-Cast: A new grassland productivity forecast to translate climate outlooks for ranchers. *Western Economics Forum*, **17** (1), 24–39. https://doi.org/10.22004/ag.econ.287342

229. Diffenbaugh, N.S., F.V. Davenport, and M. Burke, 2021: Historical warming has increased U.S. crop insurance losses. *Environmental Research Letters*, **16** (8), 084025. https://doi.org/10.1088/1748-9326/ac1223

230. Reyes, J.J. and E. Elias, 2019: Spatio-temporal variation of crop loss in the United States from 2001 to 2016. *Environmental Research Letters*, **14** (7), 074017. https://doi.org/10.1088/1748-9326/ab1ac9

231. Malek, K., P. Reed, J. Adam, T. Karimi, and M. Brady, 2020: Water rights shape crop yield and revenue volatility tradeoffs for adaptation in snow dependent systems. *Nature Communications*, **11** (1), 3473. https://doi.org/10.1038/s41467-020-17219-z

232. Gaines, W.L., P.F. Hessburg, G.H. Aplet, P. Henson, S.J. Prichard, D.J. Churchill, G.M. Jones, D.J. Isaak, and C. Vynne, 2022: Climate change and forest management on federal lands in the Pacific Northwest, USA: Managing for dynamic landscapes. *Forest Ecology and Management*, **504**, 119794. https://doi.org/10.1016/j.foreco.2021.119794

233. Davis, K.T., P.E. Higuera, S.Z. Dobrowski, S.A. Parks, J.T. Abatzoglou, M.T. Rother, and T.T. Veblen, 2020: Fire-catalyzed vegetation shifts in ponderosa pine and Douglas-fir forests of the western United States. *Environmental Research Letters*, **15** (10), 1040b8. https://doi.org/10.1088/1748-9326/abb9df

234. Halofsky, J.E., D.L. Peterson, and R.A. Gravenmier, 2022: Climate Change Vulnerability and Adaptation in Southwest Oregon. Gen. Tech. Rep. PNW-GTR-995. U.S. Department of Agriculture, Forest Service, Pacific Northwest Research Station, Portland, OR, 445 pp. https://doi.org/10.2737/pnw-gtr-995

235. Hashida, Y. and D.J. Lewis, 2022: Estimating welfare impacts of climate change using a discrete-choice model of land management: An application to western U.S. forestry. *Resource and Energy Economics*, **68**, 101295. https://doi.org/10.1016/j.reseneeco.2022.101295

236. Restaino, C.M., D.L. Peterson, and J. Littell, 2016: Increased water deficit decreases Douglas fir growth throughout western US forests. *Proceedings of the National Academy of Sciences of the United States of America*, **113** (34), 9557–9562. https://doi.org/10.1073/pnas.1602384113

237. Hudec, J.L., J.E. Halofsky, D.L. Peterson, and J.J. Ho, 2019: Climate Change Vulnerability and Adaptation in Southwest Washington. Gen. Tech. Rep. PNW-GTR-977. U.S. Department of Agriculture, Forest Service. Pacific Northwest Research Station, Portland, OR, 249 pp. https://doi.org/10.2737/pnw-gtr-977

238. Kerns, B.K., D.C. Powell, S. Mellmann-Brown, G. Carnwath, and J.B. Kim, 2018: Effects of projected climate change on vegetation in the Blue Mountains ecoregion, USA. *Climate Services*, **10**, 33–43. https://doi.org/10.1016/j.cliser.2017.07.002

239. Hicke, J.A., A.J.H. Meddens, and C.A. Kolden, 2016: Recent tree mortality in the western United States from bark beetles and forest fires. *Forest Science*, **62** (2), 141–153. https://doi.org/10.5849/forsci.15-086

240. Morgan, P., E.K. Heyerdahl, E.K. Strand, S.C. Bunting, J.P. Riser Ii, J.T. Abatzoglou, M. Nielsen-Pincus, and M. Johnson, 2020: Fire and land cover change in the Palouse Prairie–forest ecotone, Washington and Idaho, USA. *Fire Ecology*, **16** (1), 2. https://doi.org/10.1186/s42408-019-0061-9

241. Paveglio, T.B., C. Moseley, M.S. Carroll, D.R. Williams, E.J. Davis, and A.P. Fischer, 2015: Categorizing the social context of the wildland urban interface: Adaptive capacity for wildfire and community "archetypes". *Forest Science*, **61** (2), 298–310. https://doi.org/10.5849/forsci.14-036

242. Hashida, Y. and D.J. Lewis, 2019: The intersection between climate adaptation, mitigation, and natural resources: An empirical analysis of forest management. *Journal of the Association of Environmental and Resource Economists*, **6** (5), 893–926. https://doi.org/10.1086/704517

243. Scouse, A., S.S. Kelley, S. Liang, and R. Bergman, 2020: Regional and net economic impacts of high-rise mass timber construction in Oregon. *Sustainabile Cities and Society*, **61**, 102154. https://doi.org/10.1016/j.scs.2020.102154.

244. Law, B.E., T.W. Hudiburg, L.T. Berner, J.J. Kent, P.C. Buotte, and M.E. Harmon, 2018: Land use strategies to mitigate climate change in carbon dense temperate forests. *Proceedings of the National Academy of Sciences of the United States of America*, **115** (14), 3663–3668. https://doi.org/10.1073/pnas.1720064115

245. Mucioki, M., J. Sowerwine, D. Sarna-Wojcicki, F.K. Lake, and S. Bourque, 2021: Conceptualizing Indigenous Cultural Ecosystem Services (ICES) and benefits under changing climate conditions in the Klamath River Basin and their implications for land management and governance. *Journal of Ethnobiology*, **41** (3), 313–330. https://doi.org/10.2993/0278-0771-41.3.313

246. WA DNR, 2020: Summary of Natural and Working Lands Carbon Inventories and Incentive Programs in Washington. Washington Department of Natural Resources. https://app.leg.wa.gov/reportstothelegislature/home/getpdf?filename=dnr%20carbon%20sequestration%20report_8f19b00b-5acf-4c97-83b4-16cecb559803.pdf

247. Bellquist, L., V. Saccomanno, B.X. Semmens, M. Gleason, and J. Wilson, 2021: The rise in climate change-induced federal fishery disasters in the United States. *PeerJ*, **9**, e11186. https://doi.org/10.7717/peerj.11186

248. Cramer, L.A., C. Flathers, D. Caracciolo, S.M. Russell, and F. Conway, 2018: Graying of the fleet: Perceived impacts on coastal resilience and local policy. *Marine Policy*, **96**, 27–35. https://doi.org/10.1016/j.marpol.2018.07.012

249. Haugen, B.I., L.A. Cramer, G.G. Waldbusser, and F.D.L. Conway, 2021: Resilience and adaptive capacity of Oregon's fishing community: Cumulative impacts of climate change and the graying of the fleet. *Marine Policy*, **126**, 104424. https://doi.org/10.1016/j.marpol.2021.104424

250. Ritzman, J., A. Brodbeck, S. Brostrom, S. McGrew, S. Dreyer, T. Klinger, and S.K. Moore, 2018: Economic and sociocultural impacts of fisheries closures in two fishing-dependent communities following the massive 2015 U.S. West Coast harmful algal bloom. *Harmful Algae*, **80**, 35–45. https://doi.org/10.1016/j.hal.2018.09.002

251. Chang, M., H. Kennard, L. Nelson, K. Wrubel, S. Gagnon, R. Monette, and J. Ledford, 2020: Makah traditional knowledge and cultural resource assessment: A preliminary framework to utilize traditional knowledge in climate change planning. *Parks Stewardship Forum*, **36** (1). https://doi.org/10.5070/p536146381

252. Schlinger, C., O. Conroy-Ben, C. Cooley, N. Cooley, M. Cruz, D. Dotson, J. Doyle, M.J. Eggers, P. Hardison, M. Hatch, C. Hogue, K. Jacobson Hedin, C. Jones, K. Lanphier, D. Marks-Marino, D. Mosley, F. Olsen Jr., and M. Peacock, 2021: Ch. 4.2. Water. In: *Status of Tribes and Climate Change Report*. Marks-Marino, D., Ed. Institute for Tribal Environmental Professionals, Flagstaff, AZ, 98–141. http://nau.edu/stacc2021

253. NWIFC, 2016: Climate Change and Our Natural Resources: A Report from the Treaty Tribes in Western Washington. Northwest Indian Fisheries Commission. https://nwifc.org/w/wp-content/uploads/downloads/2017/01/CC_and_Our_NR_Report_2016-1.pdf

254. Mojica, J., K. Cousins, and T. Madsen, 2021: Economic Analysis of Outdoor Recreation in Oregon. Earth Economics, Tacoma, WA. https://static1.squarespace.com/static/561dcdc6e4b039470e9afc00/t/5ffe3084ce56a6552b7a3c71/1610494115376/EconomicAnalysisofOutdoorRecreationinOregon_OTC-EarthEconomics_SmallRes.pdf

255. Snover, A.K., N.J. Mantua, J.S. Littell, M.A. Alexander, M.M. McClure, and J. Nye, 2013: Choosing and using climate change scenarios for ecological-impact assessments and conservation decisions. *Conservation Biology*, **27** (6), 1147–1157. https://doi.org/10.1111/cobi.12163

256. Maas, A. and K.E. Himes, 2021: Recreation and tourism report. In: *Idaho Climate-Economy Impacts Assessment*. James A. & Louise McClure Center for Public Policy Research, University of Idaho, Boise, ID. https://www.uidaho.edu/president/direct-reports/mcclure-center/iceia/recreation-and-tourism

257. Wlostowski, A.N., K.S. Jennings, R.E. Bash, J. Burkhardt, C.W. Wobus, and G. Aggett, 2021: Dry landscapes and parched economies: A review of how drought impacts nonagricultural socioeconomic sectors in the US Intermountain West. *WIREs Water*, **9** (1). https://doi.org/10.1002/wat2.1571

258. Tohver, I.M., A.F. Hamlet, and S.-Y. Lee, 2014: Impacts of 21st-century climate change on hydrologic extremes in the Pacific Northwest region of North America. *Journal of the American Water Resources Association*, **50** (6), 1461–1476. https://doi.org/10.1111/jawr.12199

259. Musselman, K.N., F. Lehner, K. Ikeda, M.P. Clark, A.F. Prein, C. Liu, M. Barlage, and R. Rasmussen, 2018: Projected increases and shifts in rain-on-snow flood risk over western North America. *Nature Climate Change*, **8** (9), 808–812. https://doi.org/10.1038/s41558-018-0236-4

260. Kim, M.-K. and P.M. Jakus, 2019: Wildfire, national park visitation, and changes in regional economic activity. *Journal of Outdoor Recreation and Tourism*, **26**, 34–42. https://doi.org/10.1016/j.jort.2019.03.007

261. Peterson, D.L., M.S. Hand, J.J. Ho, and S.K. Dante-Wood, 2022: Ch. 7. Climate change effects on outdoor recreation in Southwest Oregon. In: *Climate Change Vulnerability and Adaptation in Southwest Oregon*. Halofsky, J.E., Peterson D.L., and R.A. Gravenmier, Eds. U.S. Department of Agriculture Forest Service, Pacific Northwest Research Station, Portland, OR, 361–398. https://www.fs.usda.gov/pnw/pubs/pnw-gtr995.pdf

262. Chan, N.W. and C.J. Wichman, 2020: Climate change and recreation: Evidence from North American cycling. *Environmental and Resource Economics*, **76** (1), 119–151. https://doi.org/10.1007/s10640-020-00420-5

263. Hjerpe, E., A. Hussain, and T. Holmes, 2020: Amenity migration and public lands: Rise of the protected areas. *Environmental Management*, **66** (1), 56–71. https://doi.org/10.1007/s00267-020-01293-6

264. NRDC, 2019: Climate Change and Health in Washington. IB: 19-09-B. National Research Defense Council, 11 pp. https://www.nrdc.org/sites/default/files/climate-change-health-impacts-washington-ib.pdf

265. Whyte, K., C. Avery, E. Azzuz, J. Breckinridge, C. Cooley, K. Cozzetto, R. Croll, M. Cruz, P. Ezcurra, P. Hardison, C. Jones, F. Lake, C. Magee, D.M. Marks-Marino, D., H. Mullen, C. Nelson, A. Pairis, H. Panci, B. Rodriguez, H. Sorensen, C. Spriggs, and A. Warneke, 2021: Ch. 4. Ecosystems & biodiversity. In: *Status of Tribes and Climate Change Report*. Marks-Marino, D., Ed. Institute for Tribal Environmental Professionals, 56–80. http://nau.edu/stacc2021

266. NIFA, 2021: Improving the Ecological Services of Nez Perce Lands Through Agriculture Management and Decision Support Tools. U.S. Department of Agriculture, National Institue of Food and Agriculture. https://portal.nifa.usda.gov/web/crisprojectpages/1024991-improving-the-ecological-services-of-nez-perce-lands-through-agriculture-management-and-decision-support-tools.html

267. King, A., 2021: Yakama Nation seeks food sovereignty in new farming venture with weighty history. *Oregon Public Broadcasting*, December 13, 2021. https://www.opb.org/article/2021/12/12/yakama-nation-food-sovereignty-farming-venture/

268. Yakama Nation, 2019: Climate Action Plan for the Territories of the Yakama Nation. Yakama Nation. https://mrsc.org/getmedia/7e788879-99dd-4711-9cc8-c6cacefe6cd4/m58totyncap.pdf.aspx

269. Matsumoto, S., 2022: Environmental justice for food system workers: Heat-illness prevention standards as one step toward just transition. *Pace Environmental Law Review*, **40** (1). https://ssrn.com/abstract=4338860

270. Henry, M.S., M.D. Bazilian, and C. Markuson, 2020: Just transitions: Histories and futures in a post-COVID world. *Energy Research & Social Science*, **68**, 101668. https://doi.org/10.1016/j.erss.2020.101668

271. Roemer, K.F. and J.H. Haggerty, 2021: Coal communities and the U.S. energy transition: A policy corridors assessment. *Energy Policy*, **151**, 112112. https://doi.org/10.1016/j.enpol.2020.112112

272. Proctor, K.W., G.S. Murthy, and C.W. Higgins, 2021: Agrivoltaics align with Green New Deal goals while supporting investment in the US' rural economy. *Sustainability*, **13** (1), 137. https://doi.org/10.3390/su13010137

273. Shortridge, J. and J.S. Camp, 2019: Addressing climate change as an emerging risk to infrastructure systems. *Risk Analysis*, **39** (5), 959–967. https://doi.org/10.1111/risa.13234

274. Araújo, K., 2022: Ch. 1. The evolving field of energy transitions. In: *Routledge Handbook of Energy Transitions*. Araújo, K., Ed. Taylor & Francis, London, UK, 17. https://doi.org/10.4324/9781003183020

275. Araújo, K. and D. Shropshire, 2021: A meta-level framework for evaluating resilience in net-zero carbon power systems with extreme weather events in the United States. *Energies*, **14** (14), 4243. https://doi.org/10.3390/en14144243.

276. Guidotti, R., H. Chmielewski, V.U. Unnikrishnan, P. Gardoni, T. McAllister, and J.W. Lindt, 2016: Modeling the resilience of critical infrastructure: The role of network dependencies. *Sustainable and Resilient Infrastructure*, **1** (3–4), 153–168. https://doi.org/10.1080/23789689.2016.1254999

277. Bumbaco, K.A., M.H. Rogers, L.W. O'Neill, D.J. Hoekema, and C.L. Raymond, 2022: 2021 Pacific Northwest Water Year Impacts Assessment. Office of the Washington State Climatologist, Climate Impacts Group, Oregon State Climatologist, Idaho Department of Water Resources, and the National Oceanic and Atmospheric Administration's National Integrated Drought Information System. https://www.drought.gov/documents/2021-pacific-northwest-water-year-impacts-assessment

278. Bumbaco, K.A., C.L. Raymond, L.W. O'Neill, A. Mehta, and D.J. Hoekema, 2023: 2022 Pacific Northwest Water Year Impacts Assessment. Office of the Washington State Climatologist, Climate Impacts Group, Oregon State Climatologist, Idaho Department of Water Resources, and the National Oceanic and Atmospheric Administration's National Integrated Drought Information System. https://www.drought.gov/documents/2022-pacific-northwest-water-year-impacts-assessment

279. Bumbaco, K.A., C.L. Raymond, L.W. O'Neill, and D.J. Hoekema, 2021: 2020 Pacific Northwest Water Year Impacts Assessment. Office of the Washington State Climatologist, Climate Impacts Group, Oregon State Climatologist, Idaho Department of Water Resources, and the National Oceanic and Atmospheric Administration's National Integrated Drought Information System. https://cig.uw.edu/publications/2020-pacific-northwest-water-year-impacts-assessment/

280. U.S. Census Bureau, 1990: Historical Census of Housing Tables: Sewage Disposal. U.S. Department of Commerce, U.S. Census Bureau. https://www.census.gov/data/tables/time-series/dec/coh-sewage.html

281. Cox, A.H., D. Surabian, G.W. Loomis, J.D. Turenne, and J.A. Amador, 2020: Temporal variability in the vertical separation distance of septic system drainfields along the southern Rhode Island coast. *Water, Air, & Soil Pollution*, **231** (3), 107. https://doi.org/10.1007/s11270-020-04488-z

282. Kohler, L.E., J. Silverstein, and B. Rajagopalan, 2016: Modeling on-site wastewater treatment system performance fragility to hydroclimate stressors. *Water Science and Technology*, **74** (12), 2917–2926. https://doi.org/10.2166/wst.2016.467

283. Hoghooghi, N., J.S. Pippin, B.K. Meyer, J.B. Hodges, and B.P. Bledsoe, 2021: Frontiers in assessing septic systems vulnerability in coastal Georgia, USA: Modeling approach and management implications. *PLoS ONE*, **16** (8), e0256606. https://doi.org/10.1371/journal.pone.0256606

284. Devereux, R., Y. Wan, J.L. Rackley, V. Fasselt, and D.N. Vivian, 2021: Comparative analysis of nitrogen concentrations and sources within a coastal urban bayou watershed: A multi-tracer approach. *Science of The Total Environment*, **776**, 145862. https://doi.org/10.1016/j.scitotenv.2021.145862

285. Mauger, G.S. and J.S. Won, 2019: Expanding the Ensemble of Precipitation Projections for King County. University of Washington, Climate Impacts Group, Seattle, WA. https://cig.uw.edu/publications/expanding-the-ensemble-of-precipitation-projections-for-king-county/

286. Morgan, H., G. Mauger, J. Won, and D. Gould, 2021: Projected Changes in Extreme Precipitation Web Tool. University of Washington Climate Impacts Group. https://doi.org/10.6069/79cv-4233

287. Salathé Jr., E.P., A.F. Hamlet, C.F. Mass, S.-Y. Lee, M. Stumbaugh, and R. Steed, 2014: Estimates of twenty-first-century flood risk in the Pacific Northwest based on regional climate model simulations. *Journal of Hydrometeorology*, **15** (5), 1881–1899. https://doi.org/10.1175/jhm-d-13-0137.1

288. Van Abs, D.J., 2016: Climate Change Adaptation in the Water Supply Sector. Rutgers, The State University of New Jersey. https://njadapt.rutgers.edu/docman-lister/conference-materials/166-climate-change-adaptation-in-water-supply-sector-final-1/file

289. EIA, n.d.: U.S. State Profiles and Energy Estimates. U.S. Energy Information Administration. https://www.eia.gov/state/

290. Turner, S.W., N. Voisin, K.D. Nelson, and V.C. Tidwell, 2022: Drought Impacts on Hydroelectric Power Generation in the Western United States: A Multiregional Analysis of 21st Century Hydropower Generation. PNNL-33212. U.S. Department of Energy, Pacific Northwest National Laboratory, Richland, WA. https://doi.org/10.2172/1887470

291. Voisin, N., A. Dyreson, T. Fu, M. O'Connell, S.W.D. Turner, T. Zhou, and J. Macknick, 2020: Impact of climate change on water availability and its propagation through the western U.S. power grid. *Applied Energy*, **276**, 115467. https://doi.org/10.1016/j.apenergy.2020.115467

292. Pitcock, B., T. Lazarte, and C. Christen, 2020: Lower Snake River Hydropower Dams: A Resilience Assessment of Regional Impacts with Proposed Dam Removal. Boise State University, 19 pp. https://wpwww-prod.s3.us-west-2.amazonaws.com/uploads/sites/151/2020/05/Resilience-with-Dams.pdf

293. Hall, S.M., 2021: Energy report. In: *Idaho Climate-Economy Impacts Assessment*. James A. & Louise McClure Center for Public Policy Research, University of Idaho, Boise, ID. https://www.uidaho.edu/president/direct-reports/mcclure-center/iceia

294. Turner, S.W.D., N. Voisin, J. Fazio, D. Hua, and M. Jourabchi, 2019: Compound climate events transform electrical power shortfall risk in the Pacific Northwest. *Nature Communications*, **10** (1), 8. https://doi.org/10.1038/s41467-018-07894-4

295. Cederholm, C.J., D.H. Johnson, R.E. Bilby, L.G. Dominguez, A.M. Garrett, W.H. Graeber, E.L. Greda, M.D. Kunze, B.G. Marcot, J.F. Palmisano, R.W. Plotnikoff, W.G. Pearcy, C.A. Simenstad, and P.C. Trotter, 2000: Pacific Salmon and Wildlife—Ecological Contexts, Relationships, and Implications for Management. Special Edition Technical Report. Washington Department of Fish and Wildlife, Olympia, WA. https://wdfw.wa.gov/publications/00063

296. Yoder, J., C. Raymond, R. Basu, S. Deol, A. Fremier, K. Garcia, G. Mauger, J. Padowski, M. Rogers, and A. Stahl, 2022: Climate Change and Stream Flow: Barriers and Opportunities. Preliminary project report to the Washington State Department of Ecology. Washington State, Department of Ecology, Water Resources Program, Olympia, WA. https://apps.ecology.wa.gov/publications/documents/2211029.pdf

297. Nez Perce Tribe, 2022: *Nimiipuu Energy May 2022*. Nez Perce Tribe. https://vimeo.com/710582042

298. EPI, 2023: Wildfire-Grid Risk, Power Talk. Boise State University, Energy Policy Institute. https://www.boisestate.edu/epi/upcomingevents/

299. Utility Wildland Fire Prevention Advisory Committee—Duties—Report—Membership—Immunity. RCW 76.04.780, Washington State Legislature, 2022. https://app.leg.wa.gov/rcw/default.aspx?cite=76.04.780

300. Araújo, K.M., T.J. Foxon, J. Markard, R. Raven, and R. Schaeffer, 2022: Ch. 29. Reconceptualizing the next frontier in energy transitions. In: *Routledge Handbook of Energy Transitions*. Araújo, K.M., Ed. Taylor & Francis, London, UK, 6. https://doi.org/10.4324/9781003183020-34

301. Black, G., D. Shropshire, and K. Araújo, 2021: Ch. 22. Small modular reactor (SMR) adoption: Opportunities and challenges for emerging markets. In: *Handbook of Small Modular Nuclear Reactors*, 2nd ed. Ingersoll, D.T. and M.D. Carelli, Eds. Woodhead Publishing, 557–593. https://doi.org/10.1016/b978-0-12-823916-2.00022-9

302. Araújo, K.M., 2018: *Low Carbon Energy Transitions: Turning Points in National Policy and Innovation*. Oxford University Press. https://doi.org/10.1093/oso/9780199362554.001.0001

303. Idaho Power, 2021: Integrated Resource Plan. Idaho Power. https://docs.idahopower.com/pdfs/aboutus/planningforfuture/irp/2021/2021%20irp_web.pdf

304. Araújo, K., D. Mahajan, R. Kerr, and M. da Silva, 2017: Global biofuels at the crossroads: An overview of technical, policy, and investment complexities in the sustainability of biofuel development. *Agriculture*, **7** (4). https://doi.org/10.3390/agriculture7040032

305. Aumeier, S.E., D.E. Shropshire, T. Allen, K. Araújo, C. Bell, M. Craig, J. Parsons, and T. Righetti, 2021: Emerging Energy Market Analysis Initiative, Methodological Framework. INL/EXT-21-65347. U.S. Department of Energy, Idaho National Laboratory, Idaho Falls, ID. https://doi.org/10.2172/1838119

306. Shropshire, D.E., K. Araujo, C. Koerner, C. Bell, R. Johnson, J. Parsons, S. Gerace, E. Holubynak, T. Righetti, and S.E. Aumeier, 2023: Microreactor Applications in U.S. Markets, Evaluation of State-Level Legal, Regulatory, Economic and Technology Implications. INL/RPT-23-71733. U.S. Department of Energy, Idaho National Laboratory, Idaho Falls, ID. https://doi.org/10.2172/1964093

307. Ellingwood, B.R., H. Cutler, P. Gardoni, W.G. Peacock, J.W. van de Lindt, and N. Wang, 2016: The Centerville virtual community: A fully integrated decision model of interacting physical and social infrastructure systems. *Sustainable and Resilient Infrastructure*, **1** (3-4), 95–107. https://doi.org/10.1080/23789689.2016.1255000

308. Markolf, S.A., C. Hoehne, A. Fraser, M.V. Chester, and B.S. Underwood, 2019: Transportation resilience to climate change and extreme weather events—Beyond risk and robustness. *Transport Policy*, **74**, 174–186. https://doi.org/10.1016/j.tranpol.2018.11.003

309. Dye, A.W., J.B. Kim, A. McEvoy, F. Fang, and K.L. Riley, 2021: Evaluating rural Pacific Northwest towns for wildfire evacuation vulnerability. *Natural Hazards*, **107** (1), 911–935. https://doi.org/10.1007/s11069-021-04615-x

310. Rodrigue, J.-P., 2020: *The Geography of Transport Systems*, 5th ed. Routledge, London, UK, 480 pp. https://doi.org/10.4324/9780429346323

311. Rempel, A. and M. Babbar-Sebens, 2021: Built environment. In: *Fifth Oregon Climate Assessment*. Oregon Climate Change Research Institute, Oregon State University, Corvallis, OR, 113–136. https://ir.library.oregonstate.edu/concern/technical_reports/pz50h457p

312. Oregon DOT, 2014: Climate Change Vulnerability Assessment and Adaptation Options Study. Oregon Department of Transportation. https://www.fhwa.dot.gov/environment/sustainability/resilience/pilots/2013-2015_pilots/oregon/final_report/odotreport.pdf

313. WSDOT, 2011: Climate Impacts Vulnerability Assessment. Washington State, Department of Transportation. https://wsdot.wa.gov/sites/default/files/2021-10/Climate-Impact-AssessmentforFHWA-12-2011.pdf

314. Faria, R., P. Marques, P. Moura, F. Freire, J. Delgado, and A.T. de Almeida, 2013: Impact of the electricity mix and use profile in the life-cycle assessment of electric vehicles. *Renewable and Sustainable Energy Reviews*, **24**, 271–287. https://doi.org/10.1016/j.rser.2013.03.063

315. Hawkins, T.R., B. Singh, G. Majeau-Bettez, and A.H. Strømman, 2013: Comparative environmental life cycle assessment of conventional and electric vehicles. *Journal of Industrial Ecology*, **17** (1), 53–64. https://doi.org/10.1111/j.1530-9290.2012.00532.x

316. Peng, T., X. Ou, and X. Yan, 2018: Development and application of an electric vehicles life-cycle energy consumption and greenhouse gas emissions analysis model. *Chemical Engineering Research and Design*, **131**, 699–708. https://doi.org/10.1016/j.cherd.2017.12.018

317. Gober, P., A. Middel, A. Brazel, S. Myint, H. Chang, J.D. Duh, and L. House-Peters, 2012: Tradeoffs between water conservation and temperature amelioration in Phoenix and Portland: Implications for urban sustainability. *Urban Geography*, **33** (7), 1030–1054. https://doi.org/10.2747/0272-3638.33.7.1030

318. Kramer, H.A., M.H. Mockrin, P.M. Alexandre, and V.C. Radeloff, 2019: High wildfire damage in interface communities in California. *International Journal of Wildand Fire*, **28** (9), 641–650. https://doi.org/10.1071/wf18108

319. May, N.W., C. Dixon, and D.A. Jaffe, 2021: Impact of wildfire smoke events on indoor air quality and evaluation of a low-cost filtration method. *Aerosol and Air Quality Research*, **21** (7), 210046. https://doi.org/10.4209/aaqr.210046

320. Stauffer, D.A., D.A. Autenrieth, J.F. Hart, and S. Capoccia, 2020: Control of wildfire-sourced $PM_{2.5}$ in an office setting using a commercially available portable air cleaner. *Journal of Occupational and Environmental Hygiene*, **17** (4), 109–120. https://doi.org/10.1080/15459624.2020.1722314

321. Liu, J.C., L.J. Mickley, M.P. Sulprizio, F. Dominici, X. Yue, K. Ebisu, G.B. Anderson, R.F.A. Khan, M.A. Bravo, and M.L. Bell, 2016: Particulate air pollution from wildfires in the Western US under climate change. *Climatic Change*, **138** (3), 655–666. https://doi.org/10.1007/s10584-016-1762-6

322. Liu, Y., E. Austin, J. Xiang, T. Gould, T. Larson, and E. Seto, 2021: Health impact assessment of the 2020 Washington state wildfire smoke episode: Excess health burden attributable to increased $PM_{2.5}$ exposures and potential exposure reductions. *GeoHealth*, **5** (5), e2020GH000359. https://doi.org/10.1029/2020gh000359

323. Durairajan, R., C. Barford, and P. Barford, 2018: Lights out: Climate change risk to Internet infrastructure. *Proceedings of the Applied Networking Research Workshop*, Montreal, QC, Canada. Association for Computing Machinery, 9–15. https://doi.org/10.1145/3232755.3232775

324. Adams-Schoen, S.J. and M. Smith, 2023: Land-use law and climate change. In: *Sixth Oregon Climate Assessment*. Fleishman, E., Ed. Oregon State University, Oregon Climate Change Research Institute, Corvallis, OR. https://doi.org/10.5399/osu/1161

325. Adams-Schoen, S.J., 2018: Beyond localism: Harnessing state adaptation lawmaking to facilitate local climate resilience. *Michigan Journal of Environmental & Administrative Law*, **8** (1). https://repository.law.umich.edu/mjeal/vol8/iss1/5

326. Grannis, J., J. Wyman, M. Singer, and J. Shoaf, 2012: Coastal management in the face of rising seas: Legal strategies for Connecticut. *Sea Grant Law and Policy Journal*, **5** (1), 59–88. https://www.georgetownclimate.org/reports/coastal-management-in-the-face-of-rising-seas-legal-strategies-for-connecticut.html

327. Siders, A., 2013: Managed Coastal Retreat: A Legal Handbook on Shifting Development away from Vulnerable Areas. Columbia Public Law Research Paper No. 14-365. Columbia University. https://doi.org/10.2139/ssrn.2349461

328. Bumbaco, K.A., K.D. Dello, and N.A. Bond, 2013: History of Pacific Northwest heat waves: Synoptic pattern and trends. *Journal of Applied Meteorology and Climatology*, **52** (7), 1618–1631. https://doi.org/10.1175/jamc-d-12-094.1

329. NWS, 2021: Weather Related Fatality and Injury Statistics. National Oceanic and Atmospheric Administration, National Weather Service. https://www.weather.gov/hazstat/

330. Silberner, J., 2021: Heat wave causes hundreds of deaths and hospitalisations in Pacific Northwest. *British Medical Journal*, **374**. https://doi.org/10.1136/bmj.n1696

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

332. Zhang, X., T. Zhou, W. Zhang, L. Ren, J. Jiang, S. Hu, M. Zuo, L. Zhang, and W. Man, 2023: Increased impact of heat domes on 2021-like heat extremes in North America under global warming. *Nature Communications*, **14** (1), 1690. https://doi.org/10.1038/s41467-023-37309-y

333. Thompson, V., A.T. Kennedy-Asser, E. Vosper, Y.T.E. Lo, C. Huntingford, O. Andrews, M. Collins, G.C. Hegerl, and D. Mitchell, 2022: The 2021 western North America heat wave among the most extreme events ever recorded globally. *Science Advances*, **8** (18), 6860. https://doi.org/10.1126/sciadv.abm6860

334. Isaksen, T.B., M. Yost, E. Hom, and R. Fenske, 2014: Projected health impacts of heat events in Washington State associated with climate change. *Reviews on Environmental Health*, **29** (1-2), 119–123. https://doi.org/10.1515/reveh-2014-0029

335. Schramm, P.J., A. Vaidyanathan, L. Radhakrishnan, A. Gates, K. Hartnett, and P. Breysse, 2021: Heat-related emergency department visits during the Northwestern heat wave—United States. *Morbidity and Mortality Weekly Report*, **70**, 1020–1021. https://doi.org/10.15585/mmwr.mm7029e1

336. Stowell, J.D., C.-E. Yang, J.S. Fu, N.C. Scovronick, M.J. Strickland, and Y. Liu, 2022: Asthma exacerbation due to climate change-induced wildfire smoke in the western US. *Environmental Research Letters*, **17** (1), 014023. https://doi.org/10.1088/1748-9326/ac4138

337. Zhou, X., K. Josey, L. Kamareddine, M.C. Caine, T. Liu, L.J. Mickley, M. Cooper, and F. Dominici, 2021: Excess of COVID-19 cases and deaths due to fine particulate matter exposure during the 2020 wildfires in the United States. *Science Advances*, **7** (33), 8789. https://doi.org/10.1126/sciadv.abi8789

338. Kochi, I., G.H. Donovan, P.A. Champ, and J.B. Loomis, 2010: The economic cost of adverse health effects from wildfire-smoke exposure: A review. *International Journal of Wildland Fire*, **19** (7), 803–817. https://doi.org/10.1071/wf09077

339. McDermot, D. and M. Kadlec, 2022: Increased Medical and Emergency Department Claims for Asthma Following Wildfire Smoke Exposure in Washington State, 2014–2018. Washington State Health Services Research Project Research Brief No. 104. Washington State Office of Financial Management. https://ofm.wa.gov/sites/default/files/public/dataresearch/researchbriefs/brief104.pdf

340. Gasparrini, A., Y. Guo, M. Hashizume, E. Lavigne, A. Zanobetti, J. Schwartz, and A. Tobias, 2015: Mortality risk attributable to high and low ambient temperature: A multicountry observational study. *The Lancet*, **386** (9991), 369–375. https://doi.org/10.1016/s0140-6736(14)62114-0

341. Clayton, S., C. Manning, K. Krygsman, and M. Speiser, 2017: Mental Health and Our Changing Climate: Impacts, Implications, and Guidance. American Psychological Association and ecoAmerica, Washington, DC. https://www.apa.org/news/press/releases/2017/03/mental-health-climate.pdf

342. Pacheco, S.E., 2020: Catastrophic effects of climate change on children's health start before birth. *The Journal of Clinical Investigation*, **130** (2), 562–564. https://doi.org/10.1172/jci135005

343. Korsiak, J., L. Pinault, T. Christidis, R.T. Burnett, M. Abrahamowicz, and S. Weichenthal, 2022: Long-term exposure to wildfires and cancer incidence in Canada: A population-based observational cohort study. *The Lancet Planetary Health*, **6** (5), e400–e409. https://doi.org/10.1016/s2542-5196(22)00067-5

344. Belova, A., C.A. Gould, K. Munson, M. Howell, C. Trevisan, N. Obradovich, and J. Martinich, 2022: Projecting the suicide burden of climate change in the United States. *GeoHealth*, **6** (5), e2021GH000580. https://doi.org/10.1029/2021gh000580

345. Cianconi, P., S. Betrò, and L. Janiri, 2020: The impact of climate change on mental health: A systematic descriptive review. *Frontiers in Psychiatry*, **11**, 74. https://doi.org/10.3389/fpsyt.2020.00074

346. Jones, R.T., D.P. Ribbe, P. Cunningham, and J.D. Weddle, 2003: Psychosocial correlates of wildfire disaster: Post disaster adult reactions. *Fire Technology*, **39** (2), 103–117. https://doi.org/10.1023/a:1024229812303

347. Ursano, R.J., J.C. Morganstein, and R. Cooper, 2017: APA Resource Document: Resource Document on Mental Health and Climate Change. American Psychological Association. https://www.psychiatry.org/file%20library/psychiatrists/directories/library-and-archive/resource_documents/2017-resource-document-mental-health-climate-change.pdf

348. WHO, 2013: *Mental Health Action Plan 2013-2020*. World Health Organization, Geneva, Switzerland. https://www.who.int/publications/i/item/9789241506021

349. Mental Health America, 2020: Ranking the States. Mental Health America. https://mhanational.org/sites/default/files/State%20of%20Mental%20Health%20in%20America%20-%202020_0.pdf

350. Cerveny, L.K. and J.W. Baur, 2020: Homelessness and nonrecreational camping on national forests and grasslands in the United States: Law enforcement perspectives and regional trends. *Journal of Forestry*, **118** (2), 139–153. https://doi.org/10.1093/jofore/fvz065

351. Goldman, L., 2022: *Climate Change and Youth: Turning Grief and Anxiety into Activism*, 1st ed. Taylor & Francis, New York, 352 pp. https://doi.org/10.4324/9781003051770

352. Vickery, J. and L.M. Hunter, 2016: Native Americans: Where in environmental justice research? *Society & Natural Resources*, **29** (1), 36–52. https://doi.org/10.1080/08941920.2015.1045644

353. Anderson, C.A., 2001: Heat and violence. *Current Directions in Psychological Science*, **10** (1), 33–38. https://doi.org/10.1111/1467-8721.00109

354. Enenkel, M., L. See, R. Bonifacio, V. Boken, N. Chaney, P. Vinck, L. You, E. Dutra, and M. Anderson, 2015: Drought and food security—Improving decision-support via new technologies and innovative collaboration. *Global Food Security*, **4**, 51–55. https://doi.org/10.1016/j.gfs.2014.08.005

355. Friel, S., H. Berry, H. Dinh, L. O'Brien, and H.L. Walls, 2014: The impact of drought on the association between food security and mental health in a nationally representative Australian sample. *BMC Public Health*, **14** (1), 1102. https://doi.org/10.1186/1471-2458-14-1102

356. Hetherington, E., S. McDonald, M. Wu, and S. Tough, 2018: Risk and protective factors for mental health and community cohesion after the 2013 Calgary flood. *Disaster Medicine and Public Health Preparedness*, **12** (4), 470–477. https://doi.org/10.1017/dmp.2017.91

357. Stanke, C., V. Murray, R. Amlôt, J. Nurse, and R. Williams, 2012: The effects of flooding on mental health: Outcomes and recommendations from a review of the literature. *PLoS Currents*, **4**. https://doi.org/10.1371/4f9f1fa9c3cae

358. Hearst, M.O., J. Yang, S. Friedrichsen, K. Lenk, C. Caspi, and M.N. Laska, 2021: The availability of culturally preferred fruits, vegetables and whole grains in corner stores and non-traditional food stores. *International Journal of Environmental Research and Public Health*, **18** (9), 5030. https://doi.org/10.3390/ijerph18095030

359. Patchell, B. and K. Edwards, 2014: The role of traditional foods in diabetes prevention and management among Native Americans. *Current Nutrition Reports*, **3** (4), 340–344. https://doi.org/10.1007/s13668-014-0102-6

360. Sarkar, D., J. Walker-Swaney, and K. Shetty, 2020: Food diversity and indigenous food systems to combat diet-linked chronic diseases. *Current Developments in Nutrition*, **4** (Supplement_1), 3–11. https://doi.org/10.1093/cdn/nzz099

361. Bildfell, R.J., J.W. Mertins, J.A. Mortenson, and D.F. Cottam, 2004: Hair-loss syndrome in black-tailed deer of the Pacific Northwest. *Journal of Wildlife Diseases*, **40** (4), 670–681. https://doi.org/10.7589/0090-3558-40.4.670

362. Byers, J.E., 2021: Marine parasites and disease in the era of global climate change. *Annual Review of Marine Science*, **13** (1), 397–420. https://doi.org/10.1146/annurev-marine-031920-100429

363. Donatuto, J., L. Campbell, C. Cooley, M. Cruz, J. Doyle, M. Eggers, T. Farrow Ferman, S. Gaughen, P. Hardison, C. Jones, D. Marks-Marino, A. Pairis, W. Red Elk, D. Sambo Dorough, and C. Sanders, 2021: Ch. 5. Health & wellbeing. In: *Status of Tribes and Climate Change Report*. Marks-Marino, D., Ed. Institute for Tribal Environmental Professionals, 159–173. http://nau.edu/stacc2021

364. Norton-Smith, K., K. Lynn, K. Chief, K. Cozzetto, J. Donatuto, M.H. Redsteer, L.E. Kruger, J. Maldonado, C. Viles, and K.P. Whyte, 2016: Climate Change and Indigenous Peoples: A Synthesis of Current Impacts and Experiences. Gen. Tech. Rep. PNW-GTR-944. U.S. Department of Agriculture, Forest Service, Pacific Northwest Research Station, Portland, OR, 136 pp. https://www.fs.usda.gov/treesearch/pubs/53156

365. Doubleday, A., N.A. Errett, K.L. Ebi, and J.J. Hess, 2020: Indicators to guide and monitor climate change adaptation in the US Pacific Northwest. *American Journal of Public Health*, **110** (2), 180–188. https://doi.org/10.2105/ajph.2019.305403

366. State of Oregon, 2021: State of Oregon Climate Equity Blueprint. State of Oregon. https://www.oregon.gov/lcd/cpu/documents/2021_jan_climate-equity-blueprint.pdf

367. Powell, J., S. Menendian, and W. Ake, 2019: Targeted Universalism Policy & Practice. University of California, Berkeley, Haas Institute for a Fair and Inclusive Society. https://belonging.berkeley.edu/sites/default/files/targeted_universalism_primer.pdf?file=1&force=1

368. Filigrana, P., J.I. Levy, J. Gauthier, S. Batterman, and S.D. Adar, 2022: Health benefits from cleaner vehicles and increased active transportation in Seattle, Washington. *Journal of Exposure Science & Environmental Epidemiology*, **32** (4), 538–544. https://doi.org/10.1038/s41370-022-00423-y

369. Rempel, A.R., J. Danis, A.W. Rempel, M. Fowler, and S. Mishra, 2022: Improving the passive survivability of residential buildings during extreme heat events in the Pacific Northwest. *Applied Energy*, **321**, 119323. https://doi.org/10.1016/j.apenergy.2022.119323

370. Adger, W.N., J. Barnett, K. Brown, N. Marshall, and K. O'Brien, 2013: Cultural dimensions of climate change impacts and adaptation. *Nature Climate Change*, **3** (2), 112–117. https://doi.org/10.1038/nclimate1666

371. Guy, K., 2020: A Security Threat Assessment of Global Climate Change: How Likely Warming Scenarios Indicate a Catastrophic Security Future. Product of the National Security, Military, and Intelligence Panel on Climate Change, Femia, F. and C. Werrell, Eds. The Center for Climate and Security, an Institute of the Council on Strategic Risks, Washington, DC. https://climateandsecurity.org/a-security-threat-assessment-of-global-climate-change/

372. McKelvey, K.S., W.M. Block, T.B. Jain, C.H. Luce, D.S. Page-Dumroese, B.A. Richardson, V.A. Saab, A.W. Schoettle, C.H. Sieg, and D.R. Williams, 2021: Adapting research, management, and governance to confront socioecological uncertainties in novel ecosystems. *Frontiers in Forests and Global Change*, **4**, 644696. https://doi.org/10.3389/ffgc.2021.644696

373. Insley, M. and M. Lei, 2007: Hedges and trees: Incorporating fire risk into optimal decisions in forestry using a no-arbitrage approach. *Journal of Agricultural and Resource Economics*, **32** (3), 492–514. https://doi.org/10.22004/ag.econ.7084

374. Palaiologou, P., A.A. Ager, M. Nielsen-Pincus, C.R. Evers, and M.A. Day, 2019: Social vulnereability to large wildfires in the western USA. *Landscape and Urban Planning*, **189**, 99–116. https://doi.org/10.1016/j.landurbplan.2019.04.006

375. Jasechko, S. and D. Perrone, 2021: Global groundwater wells at risk of running dry. *Science*, **372** (6540), 418–421. https://doi.org/10.1126/science.abc2755

376. Holmes, T.P., E.A. Murphy, and K.P. Bell, 2006: Exotic forest insects and residential property values. *Agricultural and Resource Economics Review*, **35** (1), 155–166. https://doi.org/10.1017/s1068280500010121

377. Warziniack, T., R.G. Haight, D. Yemshanov, J.L. Apriesnig, T.P. Holmes, A.M. Countryman, J.D. Rothlisberger, and C. Haberland, 2021: Ch. 14. Economics of invasive species. In: *Invasive Species in Forests and Rangelands of the United States: A Comprehensive Science Synthesis for the United States Forest Sector*. Poland, T.M., T. Patel-Weynand, D.M. Finch, C.F. Miniat, D.C. Hayes, and V.M. Lopez, Eds. Springer, Cham, Switzerland, 305–320. https://doi.org/10.1007/978-3-030-45367-1_14

378. Wolf, D. and H.A. Klaiber, 2017: Bloom and bust: Toxic algae's impact on nearby property values. *Ecological Economics*, **135**, 209–221. https://doi.org/10.1016/j.ecolecon.2016.12.007

379. Baldauf, M., L. Garlappi, and C. Yannelis, 2020: Does climate change affect real estate prices? Only if you believe in it. *The Review of Financial Studies*, **33** (3), 1256–1295. https://doi.org/10.1093/rfs/hhz073

380. Hino, M. and M. Burke, 2021: The effect of information about climate risk on property values. *Proceedings of the National Academy of Sciences of the United States of America*, **118** (17), e2003374118. https://doi.org/10.1073/pnas.2003374118

381. Headwaters Economics, 2016: Do Insurance Policies and Rates Influence Development on Fire-Prone Lands? Headwaters Economics, 14 pp. https://headwaterseconomics.org/wildfire/solutions/insurance-wildfire-home-development/

382. Garber-Yonts, B.E., 2004: The Economics of Amenities and Migration in the Pacific Northwest: Review of Selected Literature with Implications for National Forest Management. Gen. Tech. Rep. PNW-GTR-617. U.S. Department of Agriculture, Forest Service. Pacific Northwest Research Station, Portland, OR, 48 pp. https://doi.org/10.2737/pnw-gtr-617

383. Lambers, J.H.R., A.F. Cannistra, A. John, E. Lia, R.D. Manzanedo, M. Sethi, J. Sevigny, E.J. Theobald, and J.K. Waugh, 2021: Climate change impacts on natural icons: Do phenological shifts threaten the relationship between peak wildflowers and visitor satisfaction? *Climate Change Ecology*, **2**, 100008. https://doi.org/10.1016/j.ecochg.2021.100008

384. Wobus, C., E.E. Small, H. Hosterman, D. Mills, J. Stein, M. Rissing, R. Jones, M. Duckworth, R. Hall, M. Kolian, J. Creason, and J. Martinich, 2017: Projected climate change impacts on skiing and snowmobiling: A case study of the United States. *Global Environmental Change*, **45**, 1–14. https://doi.org/10.1016/j.gloenvcha.2017.04.006

385. Sánchez, J.J., R. Marcos-Martinez, L. Srivastava, and N. Soonsawad, 2021: Valuing the impacts of forest disturbances on ecosystem services: An examination of recreation and climate regulation services in U.S. national forests. *Trees, Forests and People*, **5**, 100123. https://doi.org/10.1016/j.tfp.2021.100123

386. Vose, J.M., J.S. Clark, C.H. Luce, and T. Patel-Weynand, 2016: Effects of Drought on Forests and Rangelands in the United States: A Comprehensive Science Synthesis. Gen. Tech. Rep. WO-93b. U.S. Department of Agriculture, Forest Service, Washington Office, Washington, DC, 289 pp. https://doi.org/10.2737/wo-gtr-93b

387. Paine, L.A., 1971: Accident Hazard Evaluation and Control Decisions on Forested Recreation Sites. Res. Paper PSW-68. U.S. Department on Agriculture, Forest Service, Pacific Southwest Forest and Range Experiment Station, Berkeley, CA, 10 pp. https://www.fs.usda.gov/research/treesearch/28669

388. Burns, S.F., R. Pirot, K. Williams, and S. Sobieschezk, 2015: Massive debris flow event on Pacific Northwest volcanoes, USA, November 2006: Causes, effects and relationship to climate change. In: *Engineering Geology for Society and Territory - Volume 2*, Lollino, G., D. Giordan, G.B. Crosta, J. Corominas, R. Azzam, J. Wasowski, and N. Sciarra, Eds. Cham, Switzerland. Springer, 545–550. https://doi.org/10.1007/978-3-319-09057-3_90

389. Gellman, J., M. Walls, and M. Wibbenmeyer, 2022: Wildfire, smoke, and outdoor recreation in the western United States. *Forest Policy and Economics*, **134**, 102619. https://doi.org/10.1016/j.forpol.2021.102619

390. Idaho DHW, n.d.: Activity Guidelines for Wildfire Smoke Events. Idaho Department of Health and Welfare. https://idhsaa.org/asset/sports%20medicine/wildfire-table-for-schools%20mkedits.pdf

391. Inkley, D., 2013: New report addresses climate change and freshwater fish. *Fisheries*, **38** (11), 518–518. https://doi.org/10.1080/03632415.2013.848402

392. Weiskopf, S.R., O.E. Ledee, and L.M. Thompson, 2019: Climate change effects on deer and moose in the Midwest. *The Journal of Wildlife Management*, **83** (4), 769–781. https://doi.org/10.1002/jwmg.21649

393. Kourantidou, M., D. Jin, and E.J. Schumacker, 2022: Socioeconomic disruptions of harmful algal blooms in indigenous communities: The case of Quinault Indian Nation. *Harmful Algae*, **118**, 102316. https://doi.org/10.1016/j.hal.2022.102316

394. Moss, L.A.G. and R.S. Glorioso, Eds., 2014: *Global Amenity Migration: Transforming Rural Culture, Economy and Landscape*. New Ecology Press, Kaslo, BC, 435 pp.

395. Winkler, R.L. and M.D. Rouleau, 2021: Amenities or disamenities? Estimating the impacts of extreme heat and wildfire on domestic US migration. *Population and Environment*, **42** (4), 622–648. https://doi.org/10.1007/s11111-020-00364-4

396. Abrams, J.B., H. Gosnell, N.J. Gill, and P.J. Klepeis, 2012: Re-creating the rural, reconstructing nature: An international literature review of the environmental implications of amenity migration. *Conservation and Society*, **10** (3), 270–284. https://doi.org/10.4103/0972-4923.101837

397. Rickman, D.S. and H. Wang, 2020: Whither the American west economy? Natural amenities, mineral resources and nonmetropolitan county growth. *The Annals of Regional Science*, **65** (3), 673–701. https://doi.org/10.1007/s00168-020-00999-z

398. Hjerpe, E., C.A. Armatas, and M. Haefele, 2022: Amenity-based development and protected areas in the American West. *Land Use Policy*, **116**, 106064. https://doi.org/10.1016/j.landusepol.2022.106064

399. Donatuto, J., L. Campbell, and W. Trousdale, 2020: The "value" of values-driven data in identifying Indigenous health and climate change priorities. *Climatic Change*, **158** (2), 161–180. https://doi.org/10.1007/s10584-019-02596-2

400. Wang, C.J., H.A. Schaller, K.C. Coates, M.C. Hayes, and R.K. Rose, 2020: Climate change vulnerability assessment for Pacific lamprey in rivers of the western United States. *Journal of Freshwater Ecology*, **35** (1), 29–55. https://doi.org/10.1080/02705060.2019.1706652

401. Gaughen, S., S. Bliss, J. Mauck, and T. Romero, 2021: Ch. 8. Cultural resources. In: *Status of Tribes and Climate Change Report*. Marks-Marino, D., Ed. Institute for Tribal Environmental Professionals, 210–221. http://nau.edu/stacc2021

402. Long, J.W. and F.K. Lake, 2018: Escaping social-ecological traps through tribal stewardship on national forest lands in the Pacific Northwest, United States of America. *Ecology and Society*, **23** (2). https://doi.org/10.5751/es-10041-230210

403. Long, J.W., F.K. Lake, R.W. Goode, and B.M. Burnette, 2020: How traditional tribal perspectives influence ecosystem restoration. *Ecopsychology*, **12** (2). https://doi.org/10.1089/eco.2019.0055

404. Lake, F.K., V. Wright, P. Morgan, M. McFadzen, D. McWethy, and C. Stevens-Rumann, 2017: Returning fire to the land: Celebrating traditional knowledge and fire. *Journal of Forestry*, **115** (5), 343–353. https://doi.org/10.5849/jof.2016-043r2

405. Voggesser, G., K. Lynn, J. Daigle, F.K. Lake, and D. Ranco, 2014: Ch. 9. Cultural impacts to tribes from climate change influences on forests. In: *Climate Change and Indigenous Peoples in the United States: Impacts, Experiences and Actions*. Maldonado, J.K., B. Colombi, and R. Pandya, Eds. Springer, Cham, Switzerland, 107–118. https://doi.org/10.1007/978-3-319-05266-3_9

406. Warner, E.A.K., 2015: Everything old is new again: Enforcing tribal treaty provisions to protect climate change-threatened resources. *Nebraska Law Review*, **94** (4). https://digitalcommons.unl.edu/nlr/vol94/iss4/4

407. Whyte, K., 2017: Indigenous climate change studies: Indigenizing futures, decolonizing the Anthropocene. *English Language Notes*, **55** (1), 153–162. https://doi.org/10.1215/00138282-55.1-2.153

408. Whyte, K.P., 2013: Ch. 2. Justice forward: Tribes, climate adaptation and responsibility. In: *Climate Change and Indigenous Peoples in the United States: Impacts, Experiences and Actions*. Maldonado, J.K., B. Colombi, and R. Pandya, Eds. Springer, Cham, Switzerland, 9–22. https://doi.org/10.1007/978-3-319-05266-3_2

409. Flores, D. and G. Russell, 2020: Ch. 5.5. Integrating tribes and culture Into public land management. In: *Northeastern California Plateaus Bioregion Science Synthesis*. Dumroese, R.K. and W.K. Moser, Eds. U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station, Fort Collins, CO, 177–185. https://www.fs.usda.gov/research/treesearch/60223

410. Long, J., F.K. Lake, K. Lynn, and C. Viles, 2018: Ch. 11. Tribal ecocultural resources and engagement. In: *Synthesis of Science to Inform Land Management Within the Northwest Forest Plan Area*. Spies, T.A., P.A. Stine, R. Gravenmier, J.W. Long, and M.J. Reilly, Eds. U.S. Department of Agriculture, Forest Service, Pacific Northwest Research Station, Portland, OR, 851–917. https://www.fs.usda.gov/research/treesearch/56333

411. Donatuto, J., E.E. Grossman, J. Konovsky, S. Grossman, and L.W. Campbell, 2014: Indigenous community health and climate change: Integrating biophysical and social science indicators. *Coastal Management*, **42** (4), 355–373. https://doi.org/10.1080/08920753.2014.923140

412. Fink, J.H., 2019: Contrasting governance learning processes of climate-leading and -lagging cities: Portland, Oregon, and Phoenix, Arizona, USA. *Journal of Environmental Policy and Planning*, **21** (1), 16–29. https://doi.org/10.1080/1523908x.2018.1487280.

413. Levenda, A.M., J. Richter, T. Miller, and E. Fisher, 2019: Regional sociotechnical imaginaries and the governance of energy innovations. *Futures*, **109**, 181–191. https://doi.org/10.1016/j.futures.2018.03.001.

414. Davies, I.P., R.D. Haugo, J.C. Robertson, and P.S. Levin, 2018: The unequal vulnerability of communities of color to wildfire. *PLoS ONE*, **13** (11), 0205825. https://doi.org/10.1371/journal.pone.0205825

415. Ward, E.J., J.H. Anderson, T.J. Beechie, G.R. Pess, and M.J. Ford, 2015: Increasing hydrologic variability threatens depleted anadromous fish populations. *Global Change Biology*, **21** (7), 2500–2509. https://doi.org/10.1111/gcb.12847

416. Kurtz, K., B. Hins-Turner, A. Abbott, L. Eschenbach, L. Williams, and M. Nepean, 2021: Roadmap to a Green Economy: Aligning Education, Workforce and Economic Development Systems. Pacific Education Institute, 59 pp. https://wsac.wa.gov/sites/default/files/2021-03-17-Green-Economy-Report.pdf

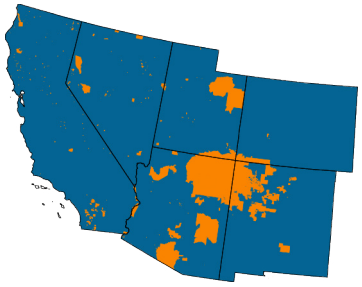
417. Van de Graaf, T. and B.K. Sovacool, 2020: *Global Energy Politics*. Wiley, 240 pp. https://www.wiley.com/en-us/global+energy+politics-p-9781509530489

418. WA DNR, 2020: Electric Utilities Wildland Fire Prevention Task Force–Final Report. Washington Department of Natural Resources, 17 pp. https://www.dnr.wa.gov/publications/rp_fire_electric_utility_taskforce_report.pdf

419. U.S. Federal Government, 2021: U.S. Climate Resilience Toolkit: Energy [Webpage]. https://toolkit.climate.gov/topics/energy-supply-and-use

Fifth National Climate Assessment: Chapter 28

Southwest



Chapter 28. Southwest

Authors and Contributors

Federal Coordinating Lead Author

Emile H. Elias, USDA Agricultural Research Service, Southwest Climate Hub

Chapter Lead Author

Dave D. White, Arizona State University

Agency Chapter Lead Author

Kathryn A. Thomas, US Geological Survey, Southwest Biological Science Center

Chapter Authors

Cristina E. Bradatan, US Census Bureau, International Programs Center

Mark W. Brunson, Utah State University, Department of Environment and Society

Ann Marie Chischilly, Northern Arizona University, Institute for Tribal Environmental Professionals

Carolyn A.F. Enquist, US Geological Survey, Southwest Climate Adaptation Science Center

Leah R. Fisher, California Department of Transportation

Halley E. Froehlich, University of California, Santa Barbara

Elizabeth A. Koebele, University of Nevada, Reno

Michael Méndez, University of California, Irvine

Steven M. Ostoja, USDA Agricultural Research Service, California Climate Hub

Caitriana Steele, New Mexico State University

Jennifer K. Vanos, Arizona State University

Technical Contributors

Grace Di Cecco, Eagle Rock Analytics

Owen M. Doherty, Eagle Rock Analytics

Victoria L. Ford, Eagle Rock Analytics

Gerald C. Nelson, University of Illinois at Urbana–Champaign

Ashley Quay, unaffiliated

Scott Stephens, University of California, Berkeley, Department of Environmental Science, Policy, and Management

Review Editor

Olivia T. Yip, San Jose State University

Cover Art

Diya P.

Recommended Citation

White, D.D., E.H. Elias, K.A. Thomas, C.E. Bradatan, M.W. Brunson, A.M. Chischilly, C.A.F. Enquist, L.R. Fisher, H.E. Froehlich, E.A. Koebele, M. Méndez, S.M. Ostoja, C. Steele, and J.K. Vanos, 2023: Ch. 28. Southwest. In: *Fifth National Climate Assessment*. Crimmins, A.R., C.W. Avery, D.R. Easterling, K.E. Kunkel, B.C. Stewart, and T.K. Maycock, Eds. U.S. Global Change Research Program, Washington, DC, USA. https://doi.org/10.7930/NCA5.2023.CH28

Table of Contents

Introduction 6

Key Message 28.1
Drought and Increasing Aridity Threaten Water Resources 9

Drought and Aridification 9
Flooding 11
Disproportionate Impacts 11
Adaptation Pathways 11
Box 28.1. First Water Shortage Declaration on the Colorado River 12

Key Message 28.2
Adaptation Efforts Increase to Address Accelerating Impacts to the Region's Coast and Ocean 13

Ocean Extremes and Adaptation 13
Sea Level Rise Impacts and Adaptation Planning 15

Key Message 28.3
Increasing Challenges Confront Food and Fiber Production in the Southwest 18

Impacts to Farming 18
Cascading Impacts of Climate Change to Agriculture 20
Frontline Communities and Food Insecurity 20
Adaptation for Agriculture 21

Key Message 28.4
Climate Change Compromises Human Health and Reshapes Demographics 22

Extreme Heat Impacts 22
Air Quality and Health Impacts 24
Flooding and Disease 24
Impacts to Outdoor Workers 24
Demographic Shifts Related to Climate 25
Adaptation Efforts for Health 26

Key Message 28.5
Changes in Wildfire Patterns Pose Challenges for Southwest Residents and Ecosystems 26

Impacts on Ecosystems 27
Impacts on People and Communities 28
Ecosystem Management Challenges and Adaptation Solutions 29

Traceable Accounts 31
Process Description 31
Key Message 28.1 31
Key Message 28.2 33
Key Message 28.3 35
Key Message 28.4 36
Key Message 28.5 38

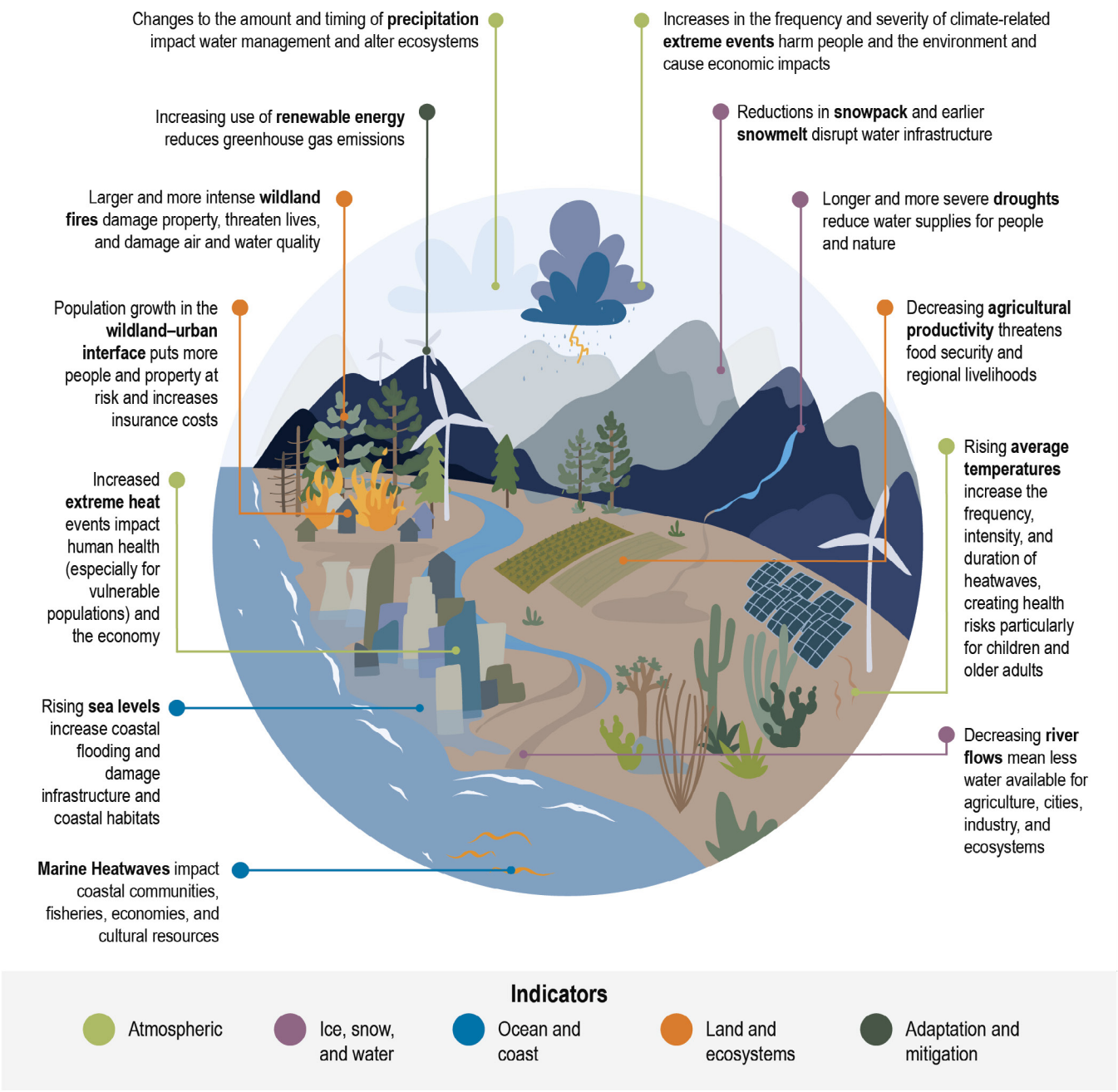
References 40

Introduction

The Southwest encompasses diverse natural ecosystems, vibrant cultures, and productive economies. This vast region spans nearly 700,000 square miles, or 18% of the US land area.[1] The Southwest is home to more than 60 million people and is among the fastest growing and most economically productive areas of the country. Southwest ecosystems provide society with food, energy, and water; regulate climate; protect against disasters and disturbances; and offer the settings and inspiration for meaningful social, cultural, recreational, and spiritual experiences (Figure 8.17).

Climate change is negatively impacting human health and well-being (KM 15.1), cultural heritage, property, built infrastructure, economic prosperity, natural capital, and ecosystem services across the Southwest (Figure 28.1). Impacts include rising air temperatures[2] and sea surface temperatures, both attributable in part to human activities;[3] changes to the timing, form, and amount of precipitation;[4,5,6] sea level rise and associated flooding events;[7] increases in extreme heat events;[8] summertime heat stress[9,10] and heat-related mortality;[11] surface and groundwater reductions;[12,13,14,15,16] increased wildfire risks;[17,18,19,20,21] and changes to ocean chemistry. These impacts pose heightened risks to overburdened and frontline communities and to Indigenous Peoples (KMs 4.2, 15.2, 16.1).

Climate Change Indicators, Impacts, and Responses in the Southwest



Indicators highlight important climate impacts and adaptation and mitigation efforts.

Figure 28.1. Indicators track the impacts of climate change on the atmosphere; ice, snow, and water; ocean and coast; and land and ecosystems, as well as adaptation and mitigation efforts. Monitoring these indicators helps us understand how impacts are experienced and how to adapt to risks. See Appendix 4 for more Indicators. Figure credit: Arizona State University. See figure metadata for additional contributors.

Southwest ecosystems transition from deserts and grasslands in hotter and lower elevations to forests and alpine meadows in cooler, higher elevations. The region supports important terrestrial and marine biodiversity and ecosystems, including the Sonoran Desert, the Sierra Nevada, and the Pacific Coast. The southern deserts commonly see temperatures between 105° and 115°F, and Phoenix has the hottest climate of all major US cities. The California coast stretches 3,400 miles (5,500 km), and its coastal wetlands provide critical habitat for fish and wildlife, protect water quality, and buffer against storms and floods.

The region is heavily urbanized, with 9 out of 10 people living in cities such as Albuquerque, Denver, Las Vegas, Los Angeles, Phoenix, Salt Lake City, and San Francisco. The region is also a major hub for software innovation, information technology, and semiconductor manufacturing. California's economy alone contributed more than $3.21 trillion (in 2022 dollars) to the US GDP in 2021, about 12% of the total US economy.[22] The region also encompasses expansive rural areas with livelihoods centered on ranching, mining, agriculture, and tourism.

Indigenous Peoples and Tribal lands are essential to the social, cultural, and geographic identity of the region. The Southwest is home to 182 Federally Recognized Tribes,[23] as well as numerous state-recognized Tribes and Tribes seeking state or federal recognition. California has the largest number of Federally Recognized Tribes (109) and the largest Indigenous population of any state.[23] Arizona, New Mexico, Colorado, and Utah are home to seven of the most populous Tribes, ranging from 10,000 to more than 300,000 members. Nine Tribes in the Southwest are considered "large land-holding Tribes," five of which are among the ten largest reservations in the US, ranging in size from 600,000 to 16 million acres. The largest US federal Indian reservation—the 16-million-acre Navajo Nation Reservation—occupies portions of Arizona, New Mexico, and Utah.

The Federal Government manages nearly half of the total land area of the region through national parks, forests, fish and wildlife reserves, military installations, and public lands.[24] In Nevada, the Federal Government is responsible for managing more than 80% of the total acreage of the state.[24] Thus, the Federal Government is central to adaptation and mitigation in the Southwest.

Over the past five years, climate change impacts in the Southwest have become increasingly apparent and widespread.[25] At the same time, understanding and modeling of how these impacts affect specific sectors and processes have improved. For instance, advances have been made in understanding and modeling of water,[26,27,28] food and agriculture,[29] wildfire,[19] invasive species, biodiversity loss (KM 8.2), ecosystem transformations, human health,[30] and human migration across the Southwest.[31,32] Furthermore, research has advanced understanding and modeling of interdependencies, feedbacks, and cascading risks for interconnected systems (KM 18.1) such as the food–energy–water nexus (KM 18.3).[33,34]

To address these climate change impacts, governments, nongovernmental organizations, and private enterprises are increasingly responding with planning and actions to reduce current and future risks and increase adaptive capacity. Adaptation efforts that are effective, feasible, and just—including nature-based solutions such as green infrastructure for flood mitigation—have been shown to reduce climate risk, increase resilience, and provide co-benefits to related societal goals (KM 8.3).[35] There is an awareness of new approaches to equity and environmental justice for frontline communities, as well as Indigenous Peoples (KM 16.2) across the Southwest. These approaches recognize, protect, and apply diverse knowledge systems, including Indigenous Knowledges (KM 16.3). Social science has also improved our understanding of inclusive, participatory, and collaborative decision-making to solve problems in this region and beyond.[36,37,38]

While this chapter focuses on climate impacts, risks, and adaptation actions in the Southwest, it also recognizes efforts underway to mitigate greenhouse gas emissions (Figure 32.20) throughout the region at multiple scales. California, Colorado, and New Mexico are members of the US Climate Alliance, committed to reducing net greenhouse gas (GHG) emissions in line with the Paris Agreement (KM 32.5). California has committed to carbon neutrality by 2045[39,40] and released a detailed plan with targets to achieve this goal,[41] as well as augmenting funding across sectors.[42] Both Colorado and New Mexico have statewide greenhouse gas reduction goals.[43,44] At the local level, dozens of cities in all Southwest states are committed to emissions reductions in line with the Paris Agreement through the bipartisan Climate Mayors network (KM 32.5). For example, the Phoenix Climate Action Plan states that the city is on track to meet its goal of 50% reduction in GHG emissions (below its 2018 baseline) by 2030 and is committed to carbon neutrality by 2050.

Key Message 28.1

Drought and Increasing Aridity Threaten Water Resources

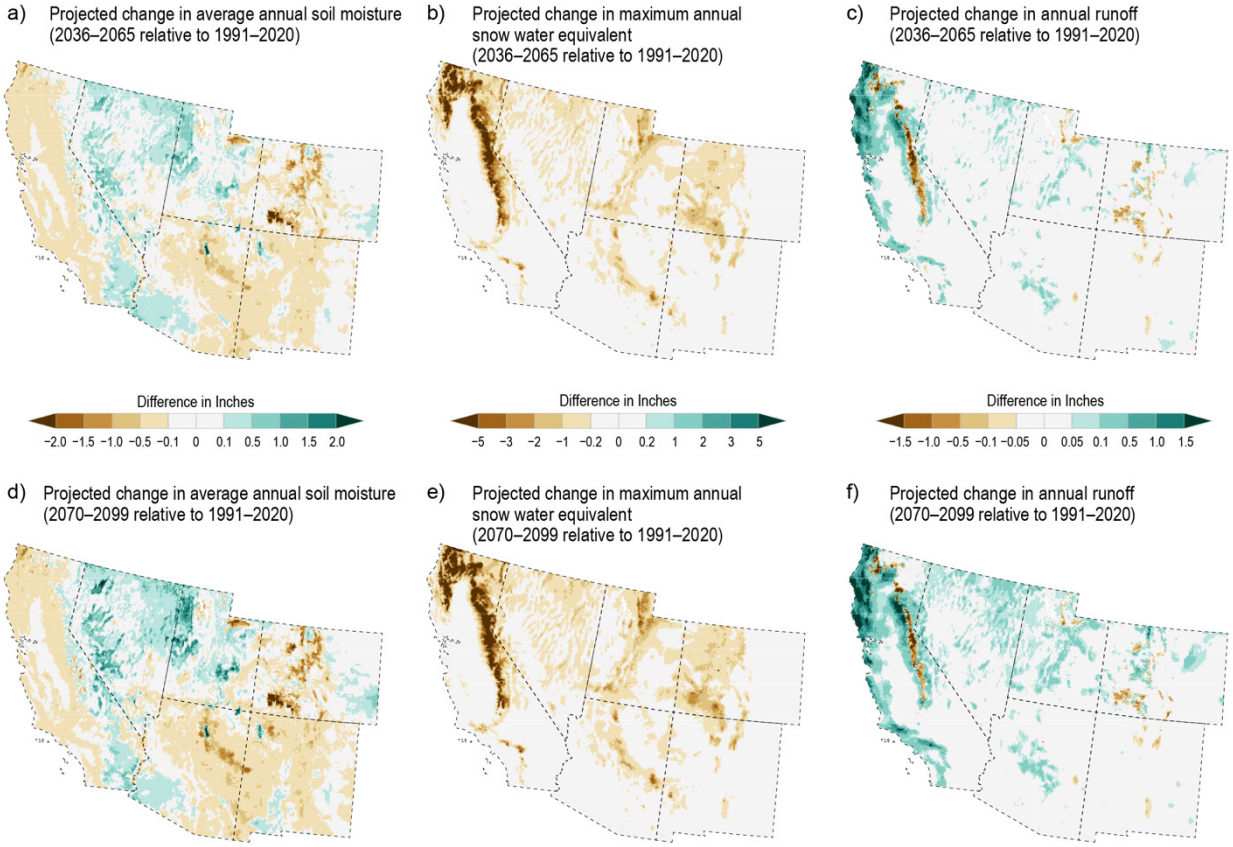
Climate change has reduced surface water and groundwater availability for people and nature in the Southwest (*very high confidence*), and there are inequities in how these impacts are experienced (*high confidence*). Higher temperatures have intensified drought and will lead to a more arid future (*very likely*, *high confidence*); without adaptation, these changes will exacerbate existing water supply–demand imbalances (*likely*, *high confidence*). At the same time, the region is experiencing more intense precipitation events, including atmospheric rivers, which contribute to increased flooding (*high confidence*). Flexible and adaptive approaches to water management have the potential to mitigate the impacts of these changes on people, the environment, and the economy (*medium confidence*).

Drought and Aridification

The Southwest region is historically arid and marked by episodes of intense drought and precipitation (KM 4.1).[45,46] Climate change is exacerbating these conditions, as increasing temperatures are leading to hotter extreme heat events, drier soils, greater atmospheric evaporative demand, and reduced flows in major river basins such as the Colorado and Rio Grande.[14,47,48,49,50] For example, between 1913 and 2017, annual average discharge from the Colorado River decreased by 9.3% for each degree Celsius of warming (Box 28.1).[49] Additionally, since 2000 the Southwest has experienced an exceptional "megadrought"—defined as an episode of intense aridity that persists for multiple decades—that is recognized as the driest 22-year period in 1,200 years.[51]

Mountain snowpack is one of the most important sources of water in the Southwest, serving as a natural reservoir to supply water to drier, lower elevations for irrigated agricultural, municipal and industrial uses, and ecosystems (KM 4.1). Observed declines in western snowpack over the last century have been predominantly driven by warming trends,[4] leading to smaller snowpack volumes, higher-elevation snow lines, and earlier snowmelt (KM 3.4).[6,52] These processes are exacerbated by the deposition of dust and other light-absorbing particles on snowpack, which accelerates snowmelt.[53] The resulting decrease in snow cover also reduces the albedo, or reflectivity, of the land surface, resulting in a positive feedback cycle that further increases solar radiation absorption, warming, and snowmelt.[49,54,55] These changing snowpack dynamics are expected to have different influences on the timing and volume of snowmelt-driven streamflow in different basins,[56] potentially disrupting the ability of existing water infrastructure, including hydropower, to meet the region's needs[5,49] and altering ecosystem dynamics. Persistent low-snow years are projected to occur in the next half century if climate change continues unabated (Figure 28.2).[5]

Projected Changes in Soil Moisture, Snow Water Equivalent, and Runoff



Climate change is projected to reduce snow water equivalent and alter trends in soil moisture and annual runoff.

Figure 28.2. These maps show projected average mid-21st-century (2036–2065; top row) and late-21st-century (2070–2099; bottom row) differences in annual soil moisture, snow water equivalent (the amount of water contained within the snowpack), and runoff over the Southwest region relative to the baseline period, 1991–2020. The data in these maps come from a land-surface hydrological model that simulates different parts of the water and energy balance. The model takes temperature and precipitation data from an ensemble of downscaled Coupled Model Intercomparison Project, Phase 5 (CMIP5) global climate models using an intermediate scenario (RCP4.5)[57] to create future projections of soil moisture, snow water equivalent, and runoff.[58] Warming temperatures and precipitation variability are expected to reduce snow water equivalent and alter trends in soil moisture and annual runoff (KM 4.1). The historical record shows that the climatology of 1991–2020 was substantially warmer than the climatology of preceding 30-year periods. Thus, the areas of projected lower soil moisture, snow water equivalent, and runoff in this figure, especially at higher elevations, present marked deficits in comparison to 30-year periods in the 20th century. There are also areas of projected increases in soil moisture and runoff. Some CMIP5 global climate models project increased precipitation over parts of the Southwest, and when these are included in calculating average soil moisture or runoff, the result indicates wetter conditions in some locations, predominantly in Nevada, Utah, southwest Arizona, and southeast California. For more detail on variability, Figures 4.5, 4.6, and 4.7 show data from the same source that illustrate the wet to dry range of projections for the mid-21st century. Figure credit: New Mexico State University; Arizona State University; University of Nevada, Reno; NOAA NCEI; and CISESS NC.

In addition to extended periods of record-low precipitation, higher temperatures driven by climate change have increased evapotranspiration and reduced soil moisture, which can reduce the volume of runoff produced from a given amount of precipitation.[16,47,50,59] These trends have negatively impacted natural resource management and agricultural production (KM 11.1) by increasing stress on vegetation.[60] Coupled with increases in demand and subsequent water withdrawals, reduced streamflow has caused many

of the region's lakes and reservoirs, such as the Great Salt Lake, to reach historically low water levels.[61] Furthermore, greater variability in streamflow threatens the region's ability to consistently produce and use hydropower, impacting a typically reliable and low-carbon source of energy.[62]

Climate warming will also reduce groundwater recharge from rainfall, snowmelt, and runoff in some areas, thereby reducing groundwater storage.[63,64] These effects are exacerbated by groundwater pumping to satisfy the needs of agricultural irrigation,[65,66] which is the biggest consumer of fresh water in the region. The Central Valley aquifer of California is one of the most stressed aquifers in the world; during the 2012–2016 drought, about two-thirds of the valley's surface water deficit was due to groundwater pumping, which caused land subsidence (the gradual sinking of land) in some areas[67] and declines in groundwater quality.

Flooding

Despite the region's increasing aridity, flooding from extreme precipitation events (KM 3.5) and snowmelt conditions (KM 4.1) also poses a threat to life and property, as well as to freshwater ecosystems.[68,69] Due to climate change, snowmelt-driven flooding is expected to occur earlier in the year due to earlier runoff.[70] Moreover, atmospheric rivers, which have driven much of historical flooding in the region, are expected to intensify under a warming climate.[71,72] Flooding from sea level rise may also threaten water infrastructure and supplies in areas such as the Sacramento–San Joaquin Bay Delta region.[73,74]

Disproportionate Impacts

Critically, the impacts of these climate-driven changes are experienced disproportionately by certain communities in the region, including Indigenous communities (KM 16.1). A lack of clean water and sanitation services in Indigenous communities came to national light in 2020 due to COVID-19, which spread 3.5 times faster among Indigenous than non-Indigenous communities in the initial stage of the pandemic,[75] due in part to the lack of access to potable water in some Indigenous communities. A major impediment to water access is the cost of water infrastructure, which averages $600 per acre-foot of water for non-Indigenous families with piped delivery, compared to $43,000 per acre-foot of water for Navajo families relying on hauled water (no dollar year available).[76,77] Furthermore, many Tribes in the region continue to lack access to water because their water rights have not been adjudicated through settlements or other processes, which could further exacerbate water shortages for other users.[78]

Other examples of overburdened communities experiencing disproportionate water-related impacts of climate change include certain Black communities, which face disproportionately higher flood risk in Los Angeles,[79] and Hispanic and low-wealth communities, which receive lower-quality drinking water[80] and may be systematically excluded from water management processes (KM 4.3).[81]

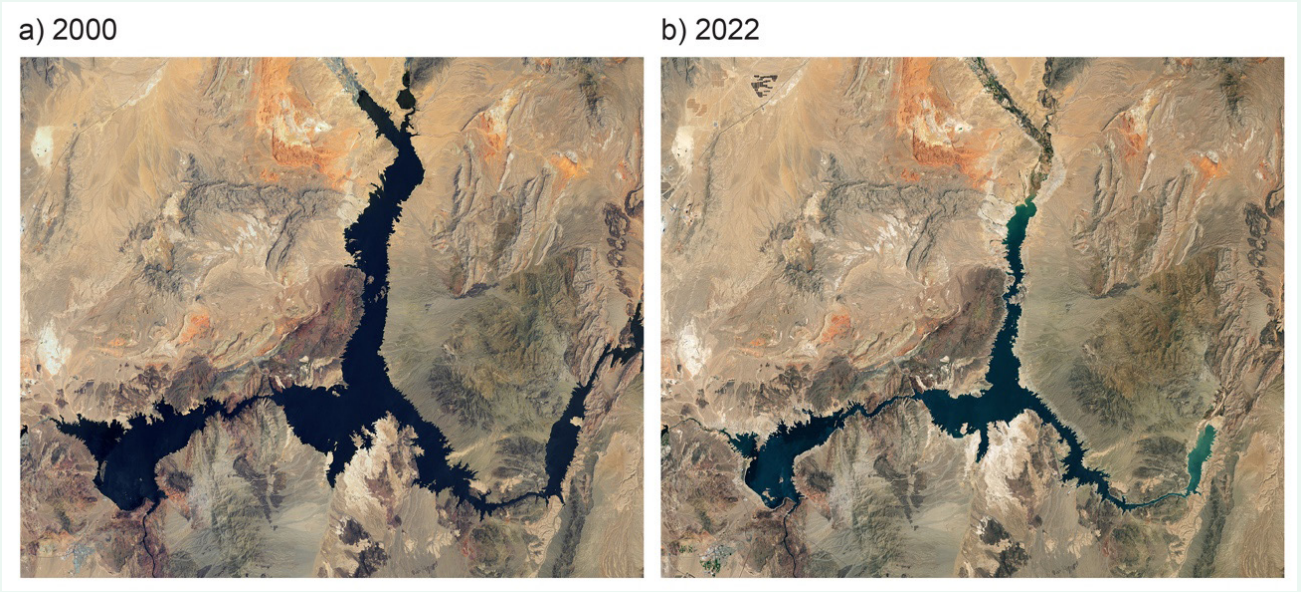
Adaptation Pathways

In response to these interrelated climate challenges, people across the Southwest have implemented adaptive water governance and management approaches. Examples include California's Sustainable Groundwater Management Act[82] and various conservation and drought response measures in the Colorado River basin,[37,38,83] which incentivize collaboration among diverse participants to develop innovative solutions (KM 12.4). Transitions toward more sustainable water management under climate change also include innovative infrastructure (e.g., enhanced aquifer storage, recharge, and recovery) and institutional practices (e.g., integrative land and water management practices, changes in rate structures, water sharing agreements, and reservoir operations).[84,85,86,87] Social science studies in Southwest cities such as Denver, Phoenix, and Las Vegas indicate widespread support for innovative management strategies for urban water sustainability[88] and opportunities for targeted educational interventions for demand management strategies based on residents' attitudes toward climate change.[89] The extent to which these adaptation actions mitigate changes in water availability depends on interacting climate and social dynamics (KM 3.4).

Box 28.1. First Water Shortage Declaration on the Colorado River

In response to more than 22 years of historic drought exacerbated by climate change and a growing imbalance between water supply and demand in the Southwest, the US Bureau of Reclamation declared the first-ever water shortage on the Colorado River in August 2021 (Figure 4.18).[90] The decision came after the agency projected that the water level in Lake Mead, the Nation's largest reservoir, would fall to 1,066 feet above sea level, or just 36% of capacity, by the end of 2021, the lowest level since the reservoir was initially filled in the 1930s (Figure 28.3). In addition to impacting water supply reliability for all users, low reservoir levels could disrupt hydropower generation, which provides electricity to several communities in the region. The initial round of water supply cuts implemented under the declaration, following previously negotiated policies, affected Arizona, Nevada, and Mexico, with Arizona farmers taking the biggest cuts. Since then, deeper and more widespread cuts, as well as calls for additional conservation measures, have been made and are expected to expand as climate change impacts continue. In response, the federal governments of the United States and Mexico, the seven US Colorado River basin states, and Indigenous Peoples are developing a range of adaptation pathways and solutions to enhance long-standing collaboration on the Colorado River (KM 16.3), including modeling the impact of more extreme climate change scenarios on water resources in the basin. Multisector conservation and demand management is seen by many as a major solution. Farms can reduce agricultural consumption by increasing water-use efficiency using technologies such as drip irrigation and alternative crop choice. Urban and industrial water conservation, recycling, and reuse improvements could support "water-smart" and economically productive industries in the Southwest. Through a partnership with Mexico on coastal water desalination, the region could free up Colorado River water for the United States while providing Mexico with a secure new supply.[91] Desalination proposals, however, have raised concerns about carbon-intensive energy demands, cost, brine management, and inequitable impacts on Mexico, including environmental impacts from brine disposal. Innovative, decentralized water treatment facilities could directly benefit communities in both countries, including those on Tribal lands.

Satellite Images of Lake Mead



Lake Mead water levels have declined, with potential water supply implications for millions of people.

Figure 28.3. Lake Mead, the largest reservoir in the US, supplies water to tens of millions of people across the Southwest; irrigates millions of acres of agricultural land; supports biodiversity, cultural heritage, ecosystems, and ecosystem services; and provides recreational opportunities. From 2000 (**a**) to 2022 (**b**), the water levels in Lake Mead declined from 98% to just 27% of its capacity, as shown in these satellite images. Satellite images: NASA Earth Observatory.

Key Message 28.2

Adaptation Efforts Increase to Address Accelerating Impacts to the Region's Coast and Ocean

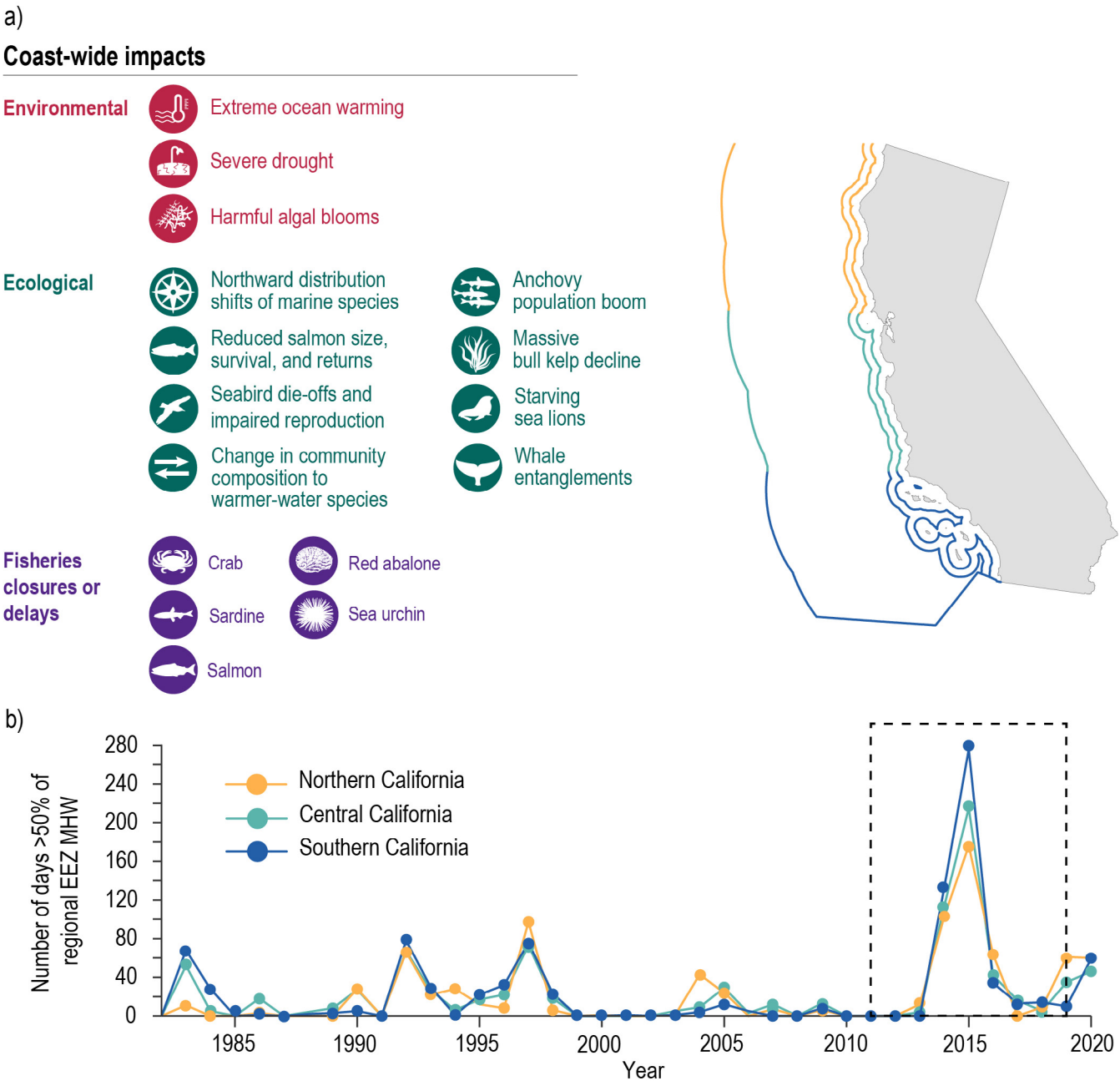
Large-scale marine heatwaves and harmful algal blooms have caused profound and cascading impacts on marine coastal ecosystems and economies (*high confidence*). Without implementation of adaptation or emissions-reductions measures, human-caused warming will drive more frequent and longer marine heatwaves (*very likely*, *very high* confidence), amplifying negative coastal effects (*medium confidence*). Sea level rise, along with associated impacts such as flooding and saltwater intrusion, will have severe and disproportionate effects on infrastructure, communities, and natural resources (*likely*, *very high confidence*). The California State Government has applied climate science to planning and decision-making for sea level rise, and multiple regions are moving toward climate-informed and adaptive strategies for fisheries (*high confidence*). However, climate planning and adaptation solutions for aquaculture are less clear (*high confidence*).

The coastal region of the Southwest encompasses approximately 3,400 miles of coastline and nearly 70% of the state's 39.4 million people. California's 19 coastal counties employ more than 12 million people[92] and in 2012 accounted for 80% of the state's GDP ($57.25 billion in 2022 dollars).[93] Furthermore, California is showing leadership through adaptation actions nationally.

Ocean Extremes and Adaptation

California coastal sea surface temperature has increased an average of 0.4°–0.6°F per decade since the 1970s[94] and is projected to increase into the future under climate change (Ch. 2).[95,96] Human-caused warming also contributes to marine heatwaves (MHWs; Figure 28.4), or incidences of exceptionally warm ocean temperatures, which have already had significant impacts on human and natural systems (Box 10.1).[97,98,99,100] The change in average cumulative intensification of MHWs for the entire US coast is presented in Figure A4.11. As the ocean warms, including in California coastal waters, MHWs increasingly exceed thermal limits of ecosystems, amplifying impacts[99] including shifts in marine species composition,[101] lower abundance and nutritional quality of important small prey fishes,[102,103] and a potential influence on mass seabird mortalities and reproduction.[104,105] Similarly, Tribal/Indigenous Traditional Knowledge demonstrates significant declines in five coastal species of cultural significance for the Tolowa Dee-ni' Nation, the Cher-Ae Heights Indian Community of the Trinidad Rancheria, the Wiyot Tribe, and the InterTribal Sinkyone Wilderness Council, a Tribal consortium of ten Tribal Nations.[106] Such ecological changes disproportionately impact coastal communities and economies (KM 9.3),[107,108,109] including cultural resources for Indigenous Peoples (KM 15.2).[106,110] The 2014–2016 Northeast Pacific marine heatwave was followed by others in 2018[111]and 2019–2020.[112] These MHWs can coincide with and contribute to other climate-related extremes such as drought[100] and harmful algal blooms (HABs).[113]

California Marine Heatwaves



Pacific marine heatwaves have had coast-wide impacts on ecosystems and fisheries.

Figure 28.4. The 2014–2016 Pacific marine heatwave (MHW) was unusually long and resulted in a variety of impacts for the southwest California coast (**a**). This MHW was followed by less extensive events in 2018 and 2019–2020 (**b**). While impacts like this can be expected to continue, they demonstrate the need and potential for adaptive management and mitigation through an integrated ecosystem approach to managing marine habitats and fisheries. EEZ refers to exclusive economic zone. Figure credit: University of California, Santa Barbara; California Department of Transportation; NOAA NCEI; and CISESS NC.

Commercial and recreational wild fisheries, as well as aquaculture (aquatic farming), will continue to be negatively affected by MHWs and HABs,[107] resulting in severe economic ramifications.[113,114,115,116] Extreme ocean warming events also have compound effects: an MHW contributed to the loss of more than 90% of Northern

California's bull kelp, a foundational species for the ocean ecosystem, resulting in large economic losses in fisheries (Focus on Blue Carbon),[117,118] including the red abalone, a species now listed as critically endangered by the International Union for Conservation of Nature. Further, extreme event–related delays and closures disproportionately impacted smaller-scale fishing operations.[119]

The widespread impacts of MHWs and HABs underscore the need for effective adaptive approaches to fisheries management. While fishers in California are coping with MHWs by fishing in different areas or for different species,[108] it will be challenging to manage fisheries in the long term under extreme warming events.[115] Marine protected areas (MPAs), which are considered a management strategy for climate-driven ocean changes, may not buffer widespread effects of MHWs on species in southern California kelp forests.[120] Adopting an ecosystem approach that considers multiple management options instead of one species in isolation[121,122] appears to improve management under climate change.[123] Applying a more coordinated disaster risk management approach to MHWs and extreme HAB events appears to correspond to better adaptive fisheries management, emphasizing the need for improving coordination and consistency across governing bodies, communities, and fishers on the frontlines (KM 10.3).[124,125]

Human-caused ocean warming coincides with increasing ocean acidification (OA) and declining oxygen levels (hypoxia) of the deeper, more nutrient-rich upwelled coastal waters. Under a very high scenario (RCP8.5), sardines, a commercially and ecologically important species, are predicted to move poleward, resulting in substantial shifts in catch.[109,126] Under the same scenario, increased acidity due to the ocean's chemical response to absorption of carbon dioxide is projected to increase the mortality of calcifying invertebrates (such as oysters and other bivalves), which are important to aquaculture and the food web, and result in a loss of food sources for some fishes and invertebrates.[127]

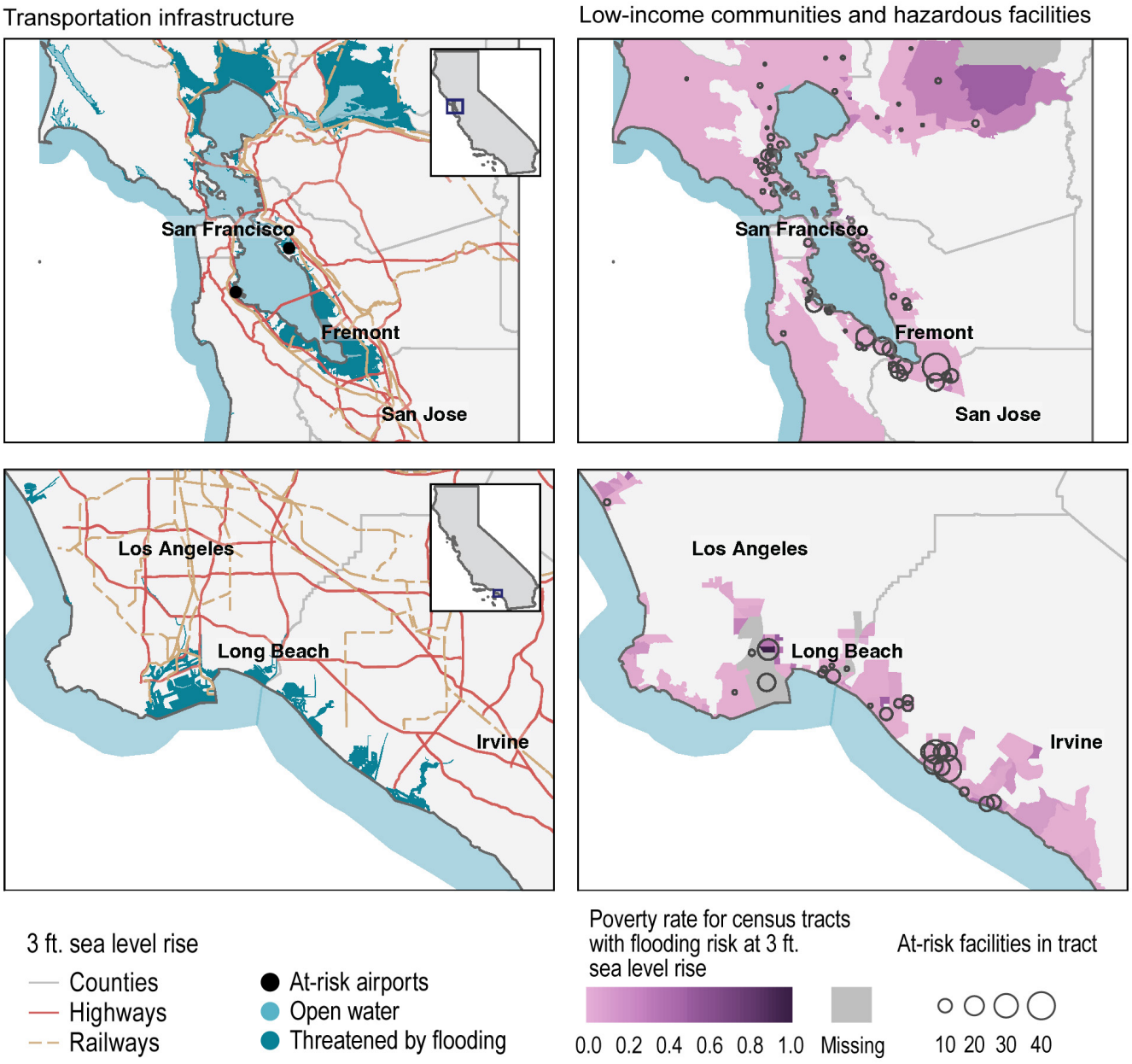
Potential adaptation solutions include an ecosystem management approach to marine habitats and fisheries, as well as enforcing water and land-use regulations, which are expected to buffer some climate impacts.[128] Protection and restoration of foundational eelgrass and kelp forests in California waters provides essential habitat, and these ecosystems can also improve local pH and oxygen conditions.[129,130] The Fishery Ecosystem Plan adopted by Pacific Fishery Management Council in 2013 includes guidance on OA and hypoxia,[128] but additional strategies—such as flexible permitting, better coordination with fishing communities, and adaptable control rules—may be needed to improve outcomes.[131] Nature-based aquaculture solutions, such as conservation and restorative aquaculture, also have potential to mitigate local OA impacts[132,133,134,135] but are just emerging in California.[136]

Sea Level Rise Impacts and Adaptation Planning

Sea level rise (SLR) poses risks to the California coast through an increase in flooding, impacts from storm surges, and loss of coastal habitats and beaches (Figure 28.5; KM 9.1). Seas are projected to rise, on average, 0.79–1.25 feet for the California coastline by 2050, 3.10–6.63 feet by 2100, and 6.11–11.90 feet by 2150 (Intermediate to High scenario).[7] California has more people living below 3.3 feet (1 m) of elevation than any other state except Louisiana;[137] the population living in the mapped 100- and 500-year coastal floodplains increased approximately 10% from 2010 to 2020.[137] SLR is also expected to exacerbate inequities in communities and result in compounding impacts, such as saltwater intrusion polluting groundwater.[7,138,139,140,141,142,143] Furthermore, coastal Tribes in California are observing rising sea levels, which, when combined with the loss of kelp forests, are increasing the risk of coastal erosion, destruction of cultural artifacts, and limited access to traditional shoreline sites.[110]

By 2050, for all emissions pathways, SLR effects on tide and storm surge are expected to cause more frequent moderate to major high tide flood events, and coastal communities are already experiencing minor to moderate high tide flooding (KM 9.1).[7]

Sea Level Rise Risks to Infrastructure and Communities



Flooding from sea level rise is expected to affect transportation infrastructure and communities along the California coast, with disproportionate impacts on lower-income communities.

Figure 28.5. These maps show the projected flood risk from 3 feet of sea level rise (SLR), as well as risks to critical infrastructure and surrounding communities, for the San Francisco Bay Area (**top row**) and the coastline from Los Angeles to San Diego (**bottom row**). Panels in the left column show transportation infrastructure threatened by flooding with 3 feet of SLR, while those in the right column show the number of hazardous facilities (indicated by circles) and census tracts at risk of flooding, with purple shading indicating the fraction of population in each census tract with income below the poverty level. Flooding from SLR will impact major transportation infrastructure along the coast; given the locations of hazardous facilities and their overlap with lower-income communities, this flooding will have disproportionate impacts on these communities. Flood risk from SLR is consistent with an Intermediate scenario in the year 2100.[7] Transportation infrastructure includes major airports, highways, and railways. Hazardous facility categories defined by EPA include manufacturing plants, power transmission plants and substations, natural gas pipelines, refineries and oil and gas wells, waste management facilities, landfills and incinerators, and animal operations. Figure credit: Eagle Rock Analytics.

Coastal energy and transportation infrastructure is expected to be negatively impacted by flooding from SLR. The projected inundation of energy substations in low-lying areas during storm events and from extreme SLR under a very high scenario (RCP8.5) is expected to cause electricity service interruptions to thousands of customers and increase maintenance and repair costs.[139] Analysis of California's transportation fuel network found that docks, terminals, and refineries are most exposed to coastal flooding.[143] The California Department of Transportation has begun adaptation planning efforts that consider a variety of strategies beyond hardening infrastructure, including nature-based strategies to limit the impacts of flooding (KM 8.3), as well as planning to avoid loss of coastal resources and access.[144]

Sea level rise and increased coastal flooding will disproportionately impact frontline communities (KM 9.2).[145] The Toxic Tides project found that under a very high scenario (RCP8.5), SLR in California[146,147] would result in increased flooding to over 400 industrial facilities and contaminated sites, including power plants, refineries, and hazardous waste sites, with 440 projected to be at risk of at least one flood event per year by 2100.[148] Any flooding of hazardous sites would increase risks of contamination in surrounding frontline communities.[149]

Residents of affordable housing, typically low-income communities, are especially vulnerable to SLR, with a greater percentage of affordable housing exposed to SLR than the general housing stock in some coastal states.[140] California is in the top four states nationwide with the most units of affordable housing exposed at least four times per year to coastal flooding based on projected sea levels for the year 2050 under a very high scenario (RCP8.5).[140] By 2050, California is also projected to see a 40% increase in the number of units at risk of flooding, compared to 2000.[140] For affordable housing residents, flood risk is compounded by the threat of displacement due to rising property values and rents. Strategic city-level adaptation and resilience efforts, combined with community and infrastructure improvements, could protect these residents from potential displacement.[140,150]

Higher seas are raising the coastal groundwater table, exposing communities to flooding from water that emerges from underground (KMs 9.1, 9.2).[138,141] Communities in low-lying areas such as San Francisco Bay are most at risk, and areas with shallow coastal water tables are projected to see widespread flooding from groundwater emergence.[138,141] Subsidence exacerbates this threat; coastal residents residing in subsiding locations experience an average relative sea level rise of up to four times faster than the global rate.[142,151] These risks have not been well addressed in adaptation planning. Furthermore, the impacts and adaptation needs are expected to be higher than reported if only overland flooding due to SLR—which does not include flooding from subsidence or groundwater intrusion—is considered in community and infrastructure planning.[142]

Adaptation planning for SLR as a field has advanced,[152] as coastal managers have reported an increased concern regarding the threat of SLR and local, regional, and state governments in California apply climate science to decision-making (KM 9.3).[153] California has instituted policies requiring consideration of climate change in state and local government decision-making and infrastructure planning.[154,155,156,157] Specifically for the coast, there is guidance on how to apply SLR risk assessment and projections into planning, including specific guidance for critical infrastructure.[158,159] This landscape of statewide policy and guidance is directly informing local coastal adaptation planning. Of 19 coastal counties, 18 have completed a vulnerability assessment, developed an adaptation policy, and/or updated the state-mandated safety elements of their general plans to include climate adaptation.[160]

While adaptation planning along the California coast has advanced significantly, many of these efforts have not yet been implemented.[160] This is partly because of financing and implementation challenges, especially for local governments that lack resources and must overcome institutional and governance issues (KM 31.5).[152,161] Despite these challenges, California is ahead of many other parts of the US coast in employing adaptation strategies and appears to be well positioned for increased adaptation.[152]

Key Message 28.3

Increasing Challenges Confront Food and Fiber Production in the Southwest

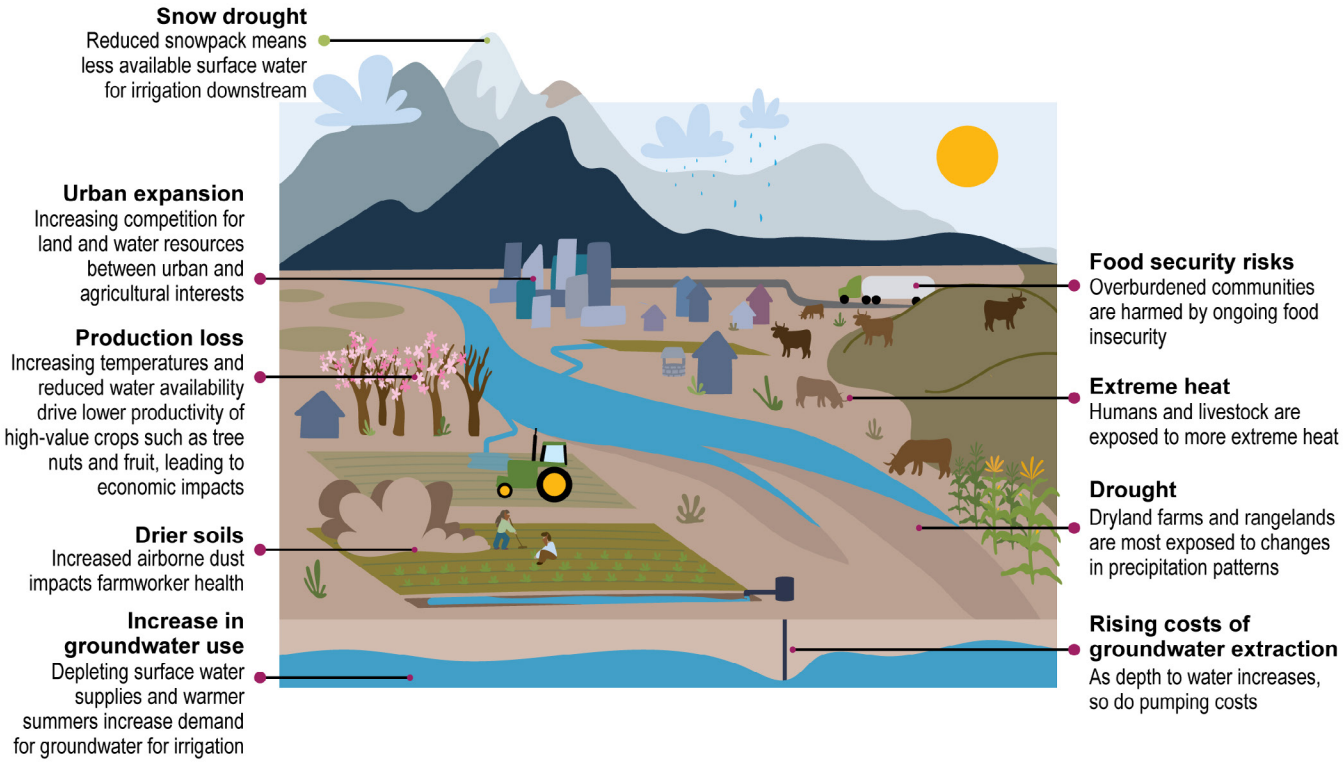
Continuing drought and water scarcity will make it more difficult to raise food and fiber in the Southwest without major shifts to new strategies and technologies (*high confidence*). Extreme heat events will increase animal stress and reduce crop quality and yield, thereby resulting in widespread economic impacts (*likely, high confidence*). Because people in the Southwest have adapted to drought impacts for millennia, incorporating Indigenous Knowledge with technological innovation can offer solutions to protect food security and sovereignty (*medium confidence*).

Across the Southwest, annual average minimum air temperatures, growing degree days, and average number of days above 86°F (the threshold used to define heat zones) are projected to increase due to climate change.[162] By midcentury under intermediate (RCP4.5) and very high (RCP8.5) scenarios, projections show longer growing seasons, a northward shift in plant hardiness zones, and expanded areas of heat stress exposure to crops and livestock (KM 11.1).[162] In California, increasing temperatures are expected to affect the timing of cool-season annual crops and the location of warm-season annual crops.[163] Warmer winters would be detrimental to the chilling requirements for orchard crops.[164] In California, fewer cold snaps are expected to reduce crop exposure to frost;[165] however, "false springs" in the intermountain West are expected to increase vulnerability to late-season freeze events.[166] During summer, a higher probability of heatwaves is expected (KM 2.2).[167] The productivity of some economically important crops, such as upland cotton in Arizona, has already declined because of heat stress.[168] While increased drought is the most prominent climate-driven risk to agriculture in the region, important farming areas such as California's Central Valley also face damage from occasional large floods caused by atmospheric river events.[169]

Impacts to Farming

Farmers and ranchers are particularly at risk from prolonged, severe drought (Figures 28.6, 8.6). Future temperature increases are expected to drive higher rates of evapotranspiration, increasing demand for fresh water for irrigation.[168] The producers most vulnerable to local precipitation deficits are dryland farmers growing rain-fed crops and producers raising livestock on rangelands. Community-based snow-fed irrigation systems in high-elevation watersheds of New Mexico and Colorado, known as *acequias*, are particularly exposed to the shortfalls in annual snowpack.[170] Under increasing aridity, agricultural practices such as fallowing and grazing on rangelands will need careful management to avoid increased wind erosion and dust production from exposed soils.[171] Rising summer temperatures also degrade protective desert soil crusts formed by communities of algae, bacteria, lichens, fungi, or mosses, adding to airborne dust loads.[172] The impacts of increasing aridity on agriculture are therefore twofold because dust deposits on mountain snowpack drive faster melting, depleting the snowpack[173] and resulting in reduced surface water for irrigation. While just 22 of the 216 counties in the region are classified as "farming-dependent" by the USDA,[174] agriculture is an important contributor to state and local economies and US food supply. California leads the Nation in agricultural cash receipts,[175] primarily from fruits, nuts, and vegetables; direct farm sales to consumers; and farm expenditures.[176] Climate change poses risks to both productivity and quality of fruit and vegetable products, requiring adaptations on farms and throughout the supply chain, including changes in crop calendars, nutrient and pest management strategies, post-harvest handling, and preservation methods.[177,178]

Agriculture and Climate Change in the Southwest US



Monitoring indicators of climate impacts on agriculture can improve understanding and help with adaptation efforts.

Figure 28.6. Climate change impacts to the Southwest's agriculture include longer growing seasons, a northward shift in plant hardiness zones, expanded areas of heat stress, and higher rates of evapotranspiration, increasing demand for fresh water for irrigation. Monitoring the indicators helps us understand how impacts are experienced and how to adapt to risks. Figure credit: New Mexico State University and Utah State University. See figure metadata for additional contributors.

Reduced crop production due to climate change will carry major economic costs. Drought events have brought significant economic impacts on regional agriculture (KM 19.1); for example, the 2021 drought cost California farming sectors an estimated $1.28 billion (in 2022 dollars) and led to the loss of 8,745 full- or part-time jobs (KM 11.3).[179] Modeling studies indicate that warming temperatures are expected to have a detrimental impact on the yields of almonds,[164] wine grapes,[180] and other high-value crops.[169] Localized adaptation strategies include crop- and locality-specific combinations of irrigation, site management (e.g., use of cover crops and increased fallowing), and cultivar selection.[181] Fallowing as a response to water shortages can bring its own challenges, such as increased dust and weed production, but it can also enhance ecosystem services such as groundwater recharge and improved ecosystem health.[182]

Climate warming is likely to lead to larger, more frequent, and more severe outbreaks of bark beetles, negatively affecting the quality and quantity of timber available to the region's forestry and forest products industries.[183] While wood products are minor economic contributors to the region's inland states, costs could be considerable in California, where the industry has been estimated to contribute $44.8 billion (in 2022 dollars) and 177,000 jobs (KM 7.2).[184]

Over time, agricultural income in the region has become more dependent on crops than livestock.[185] Because most Southwest croplands are irrigated, agriculture in the region had been thought to be less vulnerable to climate change than that in other parts of the country. However, future irrigation supply is

uncertain as it depends on dwindling ground and surface water supplies (KMs 28.1, 4.1). For example, Arizona allows up to 73% of its water to be used for crop production,[186] but the promise of continued irrigation water is less clear given the state's rapidly growing population and decreased flows in the Colorado River.[187] Crop irrigation, mainly of alfalfa, accounts for three-quarters of consumptive water use in the Great Salt Lake basin, where cuts to irrigation use are advocated as the state seeks to prevent total depletion of the lake and associated environmental and public health impacts.[188] Strategies to reduce irrigation water use include switching from gravity flow and sprinklers to more efficient systems,[186] but the costs of conversion can be difficult for farmers when climate change is already reducing yields.[185] Federal insurance programs can assist farmers after climate-related crop or forage loss, providing short-term economic relief from effects of extreme events.[189] However, some research suggests that federal insurance programs provide a disincentive for farmers to adapt to climate change impacts.[189] Non-climate-related stressors can influence the capacity of agricultural communities to adapt to climate impacts.[29] On the plains of Colorado and New Mexico, most rural counties are depopulating due to persistent out-migration of young adults, straining social services and reducing tax revenues.[190] Yet the Southwest also has some of the fastest-growing areas in the US, including high-amenity rural areas and cities expanding into agricultural zones.[191] Urban expansion can increase cropland loss while simultaneously increasing the number of small farms focusing on specialty crops rather than basic commodities,[192,193] placing greater pressure on the region's food supply as drought (KM 28.1)[51] threatens agricultural production.[194]

Livestock production is the dominant use of agricultural land in large areas of the Southwest where crop production is unprofitable or infeasible. Animal agriculture accounts for about one-third of agricultural revenue, with about 70% from cattle.[195] Climate change is expected to reduce the sustainability of cattle production that depends on rangeland ecosystems.[195,196] Negative impacts are expected on the entire livestock food supply chain, affecting production and nutritional quality of forage, livestock health on rangelands and in transport due to heat stress and pest exposure, and shelf life of products during transport and storage.[197,198] Forage from Bureau of Land Management rangelands is expected to decrease in Arizona and New Mexico, but it is less certain whether rangeland forage will hold steady in the central and northern portions of California, Colorado, Nevada, and Utah due to differences in moisture availability during the growing season.[197,199]

Cascading Impacts of Climate Change to Agriculture

The cascading impacts of climate change in combination with urban population increases and other social and cultural factors pose an increasing threat to agriculture in the region.[29] Urban growth in the Southwest has led to competition for water between farms and cities, mirroring global trends.[200] Water transfers from rural to urban areas have been a feature of the Southwest for decades, often with negative consequences for rural and low-income communities.[201,202] To meet water demands for a growing metropolitan region while preserving irrigated croplands, Colorado is experimenting with water policy innovations designed to encourage rural-to-urban transfers while minimizing impacts in rural areas, but adoption has been slow due to distrust on the part of agricultural communities and uncertainty about trade-offs.[202] Market forces in California have encouraged growers to shift to crops with a high economic value but also a large water footprint, such as tree nuts[203,204] and legal cannabis.[205]

Frontline Communities and Food Insecurity

Frontline communities including Hispanic populations, women farmers, migrant farmworkers, and Indigenous Peoples face challenges to water access in their homes as well as food security and health (KM 4.2).[201,206,207] For example, the 2012–2016 drought in California's San Joaquin Valley disrupted farmworkers' employment and reduced food security, water security, and health.[208] Mental health risks are also increasing as farmers and ranchers report moderate to severe levels of anxiety about climate change and the need

to adapt.[209] First-generation and women ranchers are disproportionately vulnerable to climate impacts because of limited experience with drought and weaker connections to rancher networks.[210]

Low-income urban communities are expected to be among the first to suffer food insecurity as climate change reduces the region's food production. Strategies have been proposed to produce more food in urban settings, but these foods often do not reach low-income consumers, who have less access to food distribution systems and often cannot afford to pay the higher prices such foods often command.[211] Indigenous Knowledge has been proposed as a significant resource for climate change adaptation (KM 16.3).[212,213] Because people in the Southwest have adapted to drought impacts for millennia, employing Indigenous Knowledge can allow the region to serve as a "laboratory" for future climate-adapted food systems[214] while enhancing food sovereignty.[215]

Adaptation for Agriculture

Adaptation solutions exist for ranching operations,[196,216] but social and economic barriers, such as distrust of experts, the financial costs and time commitments of innovation, and adherence to tradition, have slowed information uptake.[199] Climate change information is not routinely incorporated into ranchers' risk management decisions[217] and only recently has become a priority in federal agency rangeland management plans.[197]

People across the Southwest are exploring technological adaptations to climate impacts (KM 31.3). Adaptive conservation management approaches that focus on minimizing soil disturbance while maximizing soil cover, biodiversity, and the presence of living roots have been gaining traction with farmers through practices such as cover cropping and reduced-tillage and no-till farming (KM 11.1).[218,219] Combined with reduced tillage, cover cropping improves soil structure, organic carbon content, and infiltration and water-holding capacity in irrigated cropland[220] and positively impacts nutrient cycling, crop yield, and soil water conservation in limited-irrigation, semiarid cropping systems.[221,222] However, some farmers and ranchers, such as those who operate on small acreages, often find it hard to access the resources to transition practices or may perceive the risks of change to be too great, including financial expense and the perceived need to learn new skills.[223]

Irrigation efficiency can reduce risks to farming and ranching operations due to increasing temperatures, unreliable precipitation, and reduced water resources. However, access to these solutions can be complicated due to farm or ranch location, access to surface water and groundwater, water rights, current irrigation methods, and crop types.[224] In the Verde Valley of Arizona, limited access to materials, equipment, and financial resources, especially for small-scale producers, inhibits their ability to respond to water-related challenges.[224] Indigenous Peoples face barriers in accessing support from the Natural Resources Conservation Service (NRCS) related to land tenure, financial assistance, institutional mismatches, and complexities in incorporating Indigenous agricultural methods in applications for NRCS programs.[225,226]

Key Message 28.4

Climate Change Compromises Human Health and Reshapes Demographics

Increases in extreme heat, drought, flooding, and wildfire activity are negatively impacting the physical health of Southwest residents (*high confidence*). Climate change is also shaping the demographics of the region by spurring the migration of people from Central America to the Southwest (*medium confidence*). Individuals particularly vulnerable to increasing climate change impacts include older adults, outdoor workers, and people with low income (*high confidence*). Local, state, and federal adaptation initiatives are working to respond to these impacts (*high confidence*).

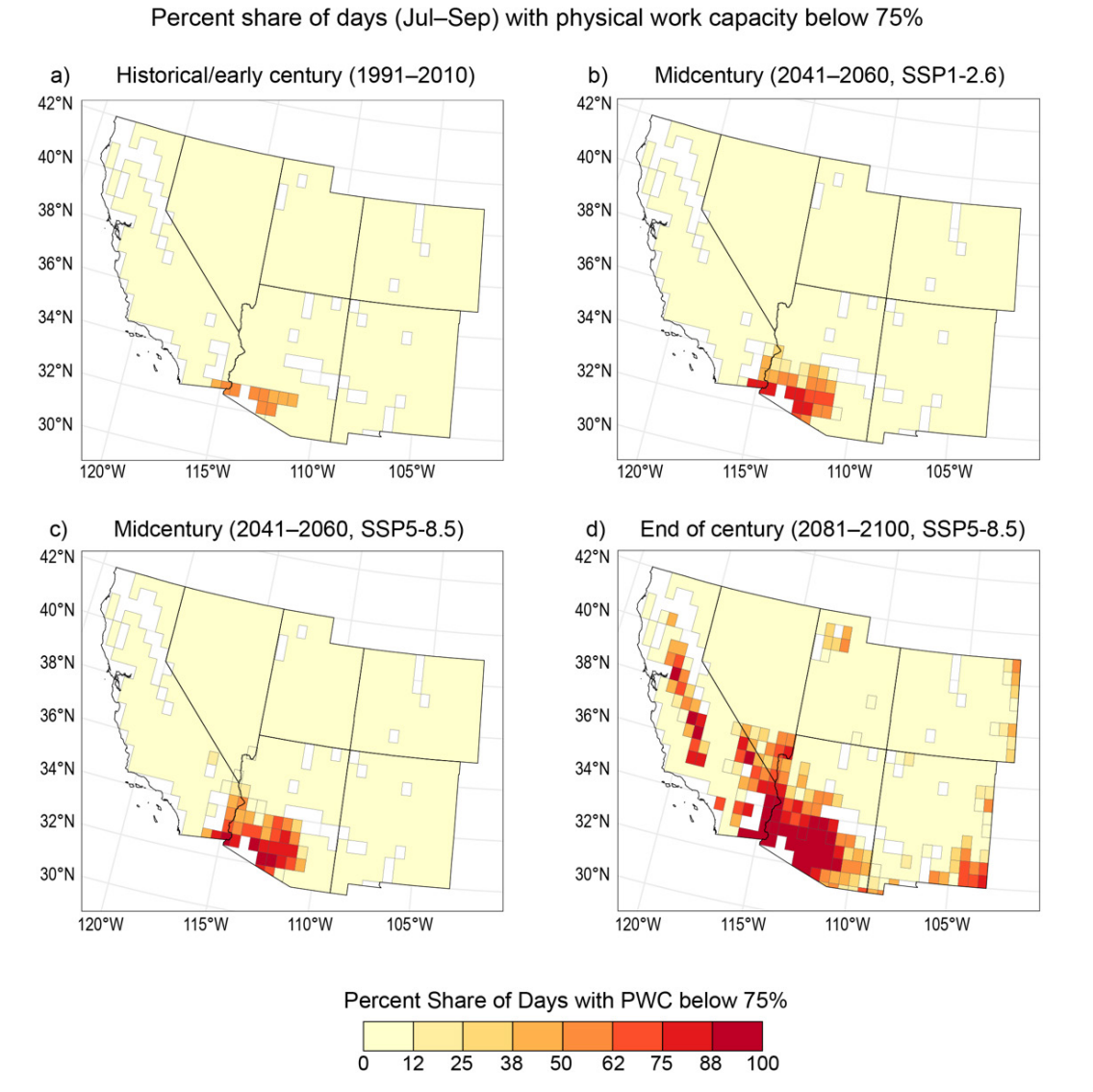
Extreme Heat Impacts

Since 2018, 31 large climate- and weather-related disasters have affected the Southwest, resulting in more than 700 fatalities and estimated damages totaling $67.3 billion (in 2022 dollars).[2] Strong evidence indicates that extreme heat disproportionately impacts the health of frontline and overburdened communities in the region (KM 15.2), including the unhoused,[227,228,229] outdoor workers, and migrant farmworkers (Figure 28.7; KM 11.2),[230,231,232,233] as well as those with low income[8,234] and older adults.[235] Between 2016 and 2020, 7,687 hospitalizations in the Southwest were due to heat and heat-related illnesses, in comparison to 5,517 in the previous five years (2011 to 2015).[236] Pre- and post-natal exposure to high heat and air pollution are shown to be particularly dangerous in the region.[237,238,239,240]

Extreme heat and high-ozone days in the region are expected to increase under climate change (KMs 2.3, 3.5).[241] These changes are expected to increase heat and air-pollution exposure, illness, and premature death.[242] Intensified aridity from higher temperatures and drought is expected to lead to more dust storms[243] and more than double the number of deaths attributed to fine dust by 2080–2099 under a very high scenario (RCP8.5), relative to 1986–2005 (KM 6.1),[244] with increasing exposures for outdoor workers during the warm season. The incidence of coccidioidomycosis (Valley fever) in the region has increased (Figure 15.2)[245] and is associated with higher air temperatures and drier soils,[246,247] with greater risk to those whose job requires dirt disruption. The annual average cost to the US economy of Valley fever for the 2000–2015 baseline was $4.8 billion per year (in 2022 dollars), which is projected to increase 390% by 2090 under a very high scenario (RCP8.5; Figure 15.2).[248]

Extreme heat exposure also affects the economy through decreased productivity and well-being in outdoor workers (Figure 28.7),[249,250,251] especially among migrant agriculture workers in the region (KM 15.1).[252,253] Impact estimates to productivity provided in Figure 28.7 are projected to result in a loss of 25% of the workday on all days in the third quarter (July–September) under a very high scenario (SSP5-8.5) by the end of century and cause important losses to the economy (KM 19.1). Dehydration due to working outdoors in extreme heat in California is linked to acute kidney illness even after a single day of exposure.[254] Research into the mechanisms of chronic kidney disease related to climate change is ongoing, yet occupational heat exposure is a causal factor.[255]

Heat Impacts in the Southwest



With extreme heat events expected to increase in frequency and severity, the ability to perform work outside is projected to decline across parts of the Southwest.

Figure 28.7. The ability to perform work outside—as measured by physical work capacity (PWC)—will decline across large swaths of the Southwest due to heat exposure throughout the century, with the greatest declines expected in southwest Arizona, southeast California, and California's Central Valley. These impacts on outdoor work will affect agricultural output, as well as earning ability for workers. PWC has a range of 100% (no loss of work capacity) to 0% (complete loss). The maps display the proportion of days in the third quarter (July to September) in which PWC is less than 75%. In historical conditions (**a**), a few locations in southern Arizona had PWC values less than 75% for half of the quarter. (**d**) Under a very high scenario (SSP5-8.5) by end of century, most of southern Arizona, southeast California, and some of California's Central Valley are projected to have less than 75% work capacity for all days in the third quarter. This daily labor loss is calculated based on a given heat load (temperature, humidity, and solar radiation) compared to temperate conditions where there is no thermal effect on work output. To provide a full range of potential impacts, maps are based on representative years for (a) historical/early century (1991–2010); (**b**) midcentury (2041–2060, SSP1-2.6 [low scenario]); (**c**) midcentury (2041–2060, SSP5-8.5 [very high scenario]); and (d) end of century (2081–2100, SSP5-8.5). Estimates are based on an individual performing moderate to heavy agricultural work outdoors over a daytime shift (about 7 hours). The PWC is an empirical estimate based on human physiological chamber studies quantifying how PWC changes with the environment heat load based on the wet-bulb globe temperature.[256,257,258,259] Land areas in white had no crops in the early 21st century. Figure credit: University of Illinois–Urbana Champaign and Arizona State University.

Air Quality and Health Impacts

While the annual average level of fine particulate matter ($PM_{2.5}$) has seen decadal decline in the region due to strengthened air quality policies reducing emissions from controllable sources, disparities in $PM_{2.5}$ exposure and related health concerns remain high in the region.[260] Moreover, the frequency and severity of smoke events with $PM_{2.5}$ exceedances of federal air quality standards have increased significantly due to wildfires (Figure 14.3). Since 2015 in Northern California, the annual average $PM_{2.5}$ has increased because of wildfire events, which have taken over as the main source of $PM_{2.5}$ exceedances.[261] $PM_{2.5}$ in wildfire smoke contributes to adverse health effects for firefighters[262] and the public[263,264] and can be more hazardous to health than similar levels of particulates from other sources.[265] The costs of adverse respiratory and cardiovascular health outcomes can exceed the billions spent on wildfire suppression (KM 28.5).[266] Chemicals in wildfire smoke also correlate with increased cancer risk.[267] Direct exposure to the 2018 Camp Fire in California has been linked to mental health disorders such as depression and post-traumatic stress disorder.[268] Wildfires can also cause other public health impacts, including water contamination when fires damage water distribution infrastructure,[269] long-term loss of access to clean drinking water,[270] and increased landslide risks (KM 28.5).

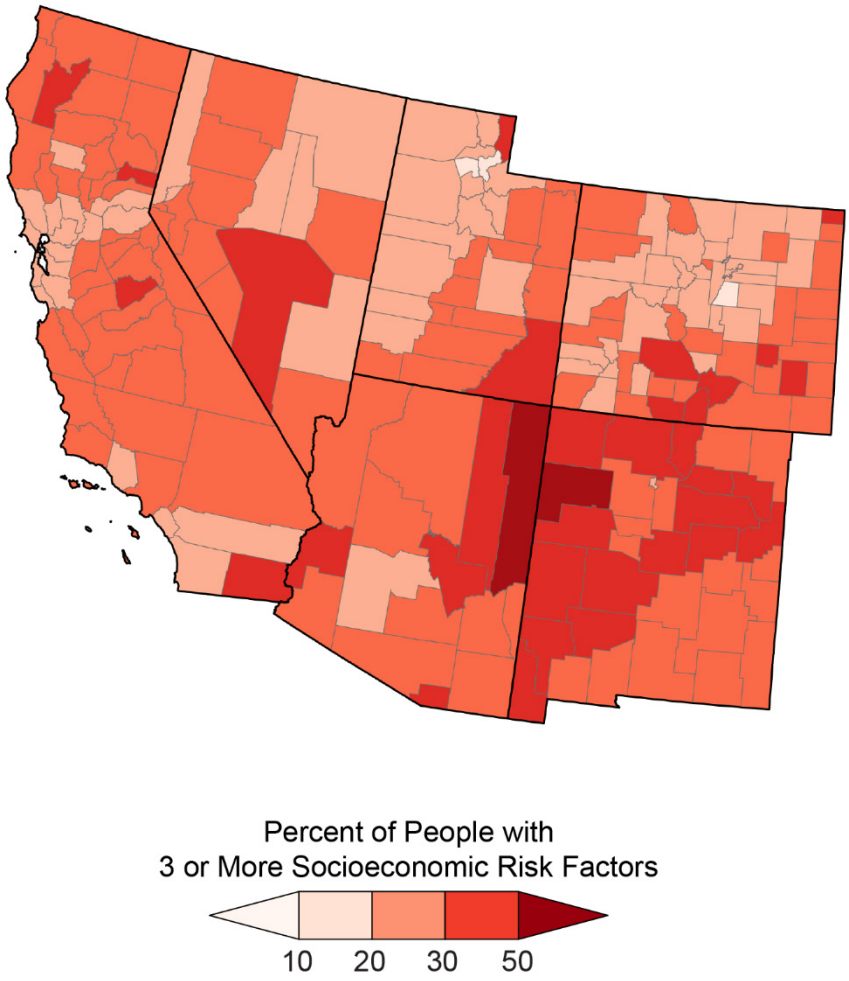
Flooding and Disease

Increases in flooding in the region are projected with continued warming.[271,272] These changes increase risks of water-borne diseases and exposure to toxic hazards and place stress on food, energy, and water supplies, as well as farmworkers' health (including interconnected sectors) and their socioeconomic insecurity.[39] Flooding exposures may increase as a greater proportion of the population across the region, on average, is living on 100-year floodplains (e.g., in California, between 1990 and 2020, 25,000 more people lived on 100-year floodplains).[137] Flooding can also interrupt vector-control programs, such as for West Nile virus.[273] The region is seeing challenges with West Nile virus, particularly in Arizona and California,[274] with projected increases due to changes in the climate, human population, and mosquito distribution (KM 24.3).[275,276]

Impacts to Outdoor Workers

Limited occupational health and safety standards for farmworkers and other outdoor workers are of key concern, as intensifying wildfires and heat collide with harvest season each year, particularly for undocumented Latino/a and Indigenous migrants.[231] The improvement of these standards at the state and national levels will be critical for health adaptation to climate impacts in the region. Moreover, the harm to farmworkers due to wildfire smoke is expected to be greater than previously thought, bolstering the argument for additional research and policies to help safeguard overburdened and stigmatized populations.[277] Many Southwest cities experienced high rates of economic and population growth during the second half of the 20th century, particularly between 2015 and 2019.[31] The region's flourishing economy and proximity to the Mexican border result in a high influx of migrants.[278,279] Migrants from Central America, spurred to migrate due to climate change in addition to poverty and violence (KM 17.2), are drawn by the Southwest's strong economy and increase the number of vulnerable people and change the demographics in the region. Local, state, and federal efforts to both mitigate climate change and support essential human adaptation to increasing exposures will be vital in protecting the health of a growing and aging population and our most vulnerable communities (Figure 28.8; KM 15.1).[280]

Community Resilience Estimates for the Southwest



Communities with higher socioeconomic risk factors are expected to be less resilient in the event of climate and weather disasters.

Figure 28.8. The map shows community resilience estimates (CREs) for the Southwest. Community resilience is the capacity of individuals and households to absorb, endure, and recover from the health, social, and economic impacts of a disaster. Individual and household characteristics from the 2019 American Community Survey were modeled, in combination with data from the Population Estimates Program, to create the CREs at the county level. Darker shading indicates a higher proportion of the population at risk. Adapted from US Census Bureau 2021.[281]

Demographic Shifts Related to Climate

The effects of climate change on other regions of the world—especially Central America—are changing the Southwest's demographics. Decreasing agricultural productivity, increasing levels of food insecurity, and adverse climate effects are among the main reasons why people emigrate from the Northern Triangle (Guatemala, Honduras, and El Salvador) to the US (KM 17.2).[32,279] In 2021, 42% of Central American immigrants to the US lived in the Southwest region,[282] and about 43% of immigrants apprehended at the Southwest border in 2019 originated from the Northern Triangle.[278] Many are poor, women, children, or Indigenous Peoples. Climate-related migration has been shown to affect people's physical and mental health, resulting from exposure to weather extremes, disruption of social ties, and overcrowding of health systems in the host communities.[283]

Adaptation Efforts for Health

Several programs have been developed to address the health impacts of climate change in the region, but financial constraints and political support affect their implementation.[284] Since 2010, the CDC's Building Resilience Against Climate Effects program in Arizona and California has developed and implemented strategies to protect communities from climate-sensitive hazards, including schools, healthcare facilities, and other at-risk populations.[285] This program, currently in 10 cities across the country, has developed important resources and programs that can be scaled up for future climate resilience efforts. To protect the health and learning of school children, the Arizona Department of Health Services created new heat policy guidance, resulting in recommendations for school heat safety and adaptation strategies.[286,287] In California, San Mateo County assessed asthma burden connected to local climate issues.[288] Public health guidance in the region should focus on co-exposures to heat and wildfire smoke in adaptation efforts,[289] particularly given the projected increase in childhood asthma due to wildfires.[290] While data on private sector investment is limited, the private sector has historically lacked incentives to invest in adaptation (KM 31.6). Globally, in 2017–2018 only 1.6% of all adaptation financing came from the private sector.[291] In the Southwest, however, certain sectors, such as insurance, came under pressure from the local authorities to get involved in tackling climate change by divesting their fossil fuel–based investments.[292]

Key Message 28.5

Changes in Wildfire Patterns Pose Challenges for Southwest Residents and Ecosystems

In recent years, the Southwest has experienced unprecedented wildfire events, driven in part by climate change (*high confidence*). Fires in the region have become larger and more severe (*high confidence*). High-severity wildfires are expected to continue in coming years, placing the people, economies, ecosystems, and water resources of the region at considerable risk (*very likely, high confidence*). Opportunities for adaptation include pre- and postfire actions that reduce wildfire risk and facilitate ecosystem restoration and include traditional land stewardship practices (*high confidence*) and the application of Indigenous cultural fire (*medium confidence*).

Fire is a natural process in many ecosystems across the Southwest and is necessary for biodiversity, ecosystem services, and nature-based solutions (KM 8.2). Fire regimes associated with fire-dependent ecosystems are highly variable with elevation and across geographies.[293] Long-standing policies and forest management—including fire suppression, widespread logging and livestock grazing, and elimination of Indigenous fire use—combined with the effects of a changing climate, have contributed to high tree densities, compromised ecosystem function, and the diversity, or heterogeneity, of forest attributes such as species, size classes, and geographic distributions.[18,21,294,295,296] Consequently, many Southwest forests and fire-prone wildlands are susceptible to climate-mediated impacts including droughts, pests and disease (Box 7.1), and devastating wildfire.[295,297] An abundance of scientific research strongly suggests that Southwest ecosystems, in the face of rapid climate change–induced transformation, will require active management interventions that increase forest heterogeneity and enhance ecosystem function and adaptive capacity (KM 7.3).[298,299,300]

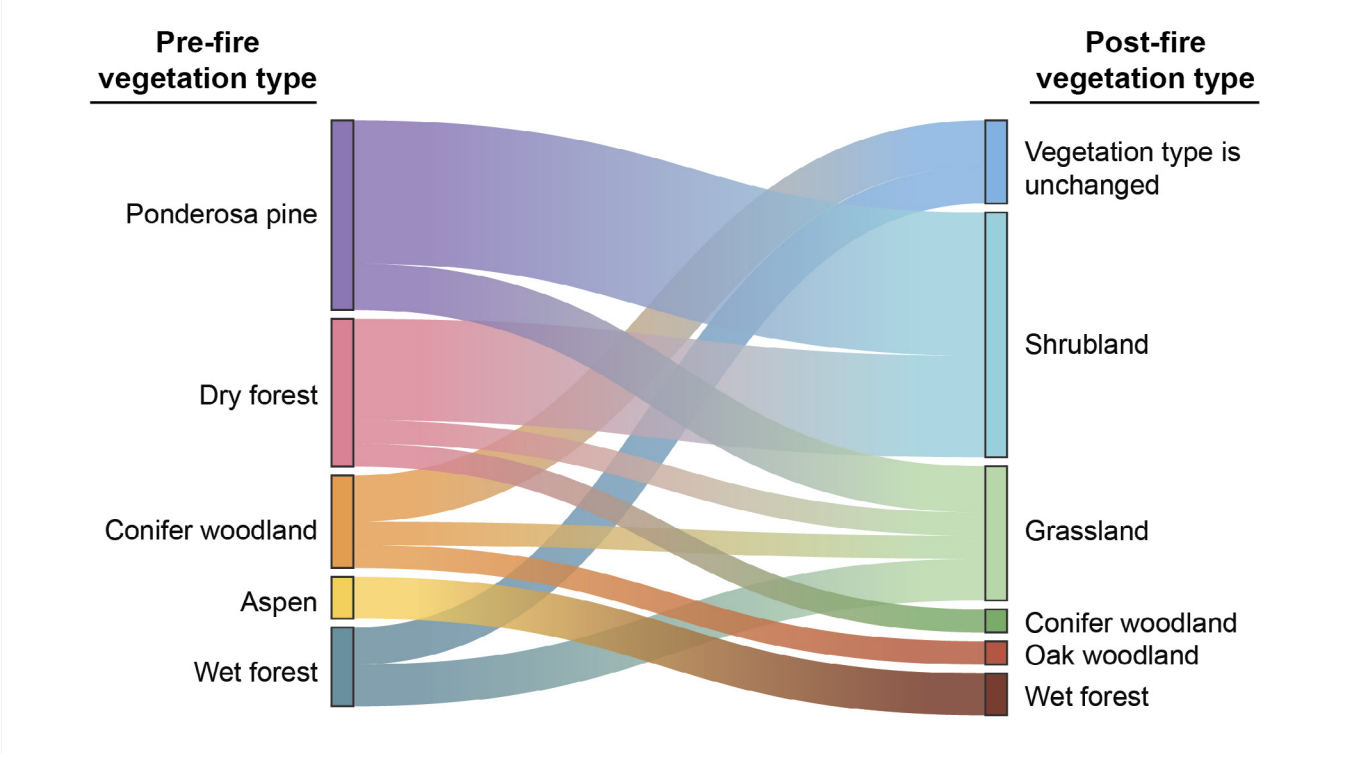
Human-induced warming temperature trends, changes in precipitation patterns, and increases in vapor pressure deficit have driven the desiccation of fuels that influence wildfire patterns and behavior across the western US (KM 7.1).[17,18,19,20,21,301] In the Southwest, fires have become larger, more frequent, and, in many

areas, more severe (KM 7.1), with clear evidence of climate change as a major cause.[302,303] Seven of the ten largest US wildfires in 2020–2021 occurred in the region. Of the 50 largest US wildfires in 2020, 22 occurred in California, and the 7 largest wildfires recorded in California have occurred since 2018.[304,305,306] The three largest wildfires recorded in Colorado occurred in 2020; the largest fires in Nevada history burned in 2018;[307] and the largest wildfires in Arizona, New Mexico, and Utah all occurred since 2007 (Figure 28.9; Focus on Western Wildfires). Large fires on non-forested western US rangelands also increased more than fivefold during the period 1984–2017.[308] Much of this increase is driven by increases in invasive annual grass cover, caused partly by climate change and increased atmospheric carbon dioxide.[309]

Impacts on Ecosystems

Climate change causes cascading effects with other factors in Southwest ecosystems that are otherwise fire-adapted. For example, large areas of high-severity fire have driven ecosystem type conversions in many parts of the region.[294,310] Semiarid to arid forest systems are particularly vulnerable to these effects and have experienced conversion to native grassland,[311] shrubland, or non-native grassland (Figures 28.9, 8.6).[294] The cumulative effects of fire-driven ecosystem changes continue to place ecosystems at high risk of vegetation type conversion (e.g., forests to shrublands), which can result in severe impacts on watersheds and aquatic resources.[294] Effects include degradation of riparian systems; risks to riparian and riverine species, as well as to threatened and endangered species, from erosion caused by extreme precipitation events; and increased invasions by non-native species.[312]

Wildfire and Vegetation Change in the Southwest



Climate change is leading to larger and hotter fires and resulting in shifts in vegetation.

Figure 28.9. Data from the states of California, Arizona, Colorado, and New Mexico show that approximately half (about 50%) of vegetation type change (e.g., forests transiting to shrublands or grasslands) is a function of high-severity fire. Adapted from Guiterman et al. 2022[294] [CC BY 4.0].

Recent climate-induced aridification, including loss of snowpack, has also hindered postfire tree seedling and shrub establishment, limiting ecosystem recovery.[313,314,315] This is particularly true of postfire conditions for water availability, quantity, and quality. Moreover, interactions between wildfire and natural drought variability are expected to increasingly exacerbate dry conditions that will further stress tree seedlings[316] and drive potential future shifts in species composition or vegetation type.[314,317] Conversions of coastal shrublands driven by human development also have interacted with climate-induced drying of vegetative fuels to generate atypical fire conditions.[318]

Projections of future climate change suggest that wildfire activity will continue to affect ecosystems and their services.[298,319,320,321,322] Specific ecosystem responses to climatic changes will depend on interactions among vegetation type, moisture stress, disturbance regimes (e.g., pests, pathogens, and high-severity fire), and human land-use changes (KM 6.2).[295,297,319] For example, climate change is predicted to lead to a loss of sagebrush ecosystems in the southern and eastern Great Basin because those ecosystems are less able to recover after fires in a warmer, drier climate.[323]

However, future wildfire trends are less certain in rangelands than in forests because fire size (measured by annual area burned) and severity (a shift from low-intensity fires to stand-replacing crown fires) depend on production of aboveground vegetation that varies annually with climatic conditions.[324] Growth of the grasses that typically fuel wildfires is expected to decrease in Arizona and New Mexico,[199,325] whereas elsewhere in the region, precipitation is projected to increase early in the growing season, which, when followed by hotter summers, will generate conditions ideal for fire ignitions.[324]

Impacts on People and Communities

Climate-related increases in the frequency, severity, and extent of wildfires in the Southwest are endangering lives and property (Focus on Western Wildfires).[17,18,19,20,21,326] Complete data across the region on wildfire-caused fatalities are sparse,[327] but three of the five deadliest fires on record in California have occurred since 2017, costing 122 lives.[304] Further, loss of life can be attributed to wildfire smoke, which has also been linked to increases in COVID-19 fatalities in Northern California[328] and postfire debris flows that can leave slopes bare of vegetation and vulnerable to rapid erosion (Ch. 7; Focus on Western Wildfires).[329] The risk of postfire debris flows in coastal communities is expected to increase due to an increase in heavy precipitation typically delivered by atmospheric river events (KMs 28.1, 8.1).[330]

Property losses due to wildfire are greatest in the Southwest compared to other regions. In 2021, 3,363 structures burned due to wildfires in California, the highest number lost in any state, while the December 2021 Marshall Fire in Colorado, a fast-burning grassland fire, burned more than 1,000 homes in just a few hours.[306] The 2022 Calf Canyon/Hermit's Peak Fire that burned 341,735 acres is New Mexico's largest fire. Secondary impacts of wildfire, such as postfire debris flows (Figures 3.13, 6.5) on recently burned slopes, impose additional hazards to property.[329] The estimated cost of fighting the 10 largest California wildfires in 2021 exceeded $2.25 billion (in 2022 dollars),[306] with suppression costs representing only a fraction of a total economic impact that also includes loss of structures and infrastructure, increased medical costs, crop losses, water quality contamination, and other factors (KM 19.1).

The increase in structures and infrastructure lost can be linked to population growth in the wildland–urban interface (WUI; Figure A4.14), where houses are built close to forests and other natural areas.[331] The number of Americans living in the WUI doubled from 1990 to 2010, and the WUI population has risen fastest in areas such as the Southwest where wildfire risk is greatest.[332,333] While migration to WUI counties shows modest reductions immediately after wildfire or extreme heat events,[334] fires do not seem to drive current residents away; fewer than 6% of Sonoma County, California, residents who lost homes to wildfires in 2017 subsequently left the county.[335]

Impacts of fire on community livelihoods depend on exposure to wildfire risk and capacity to adapt (KM 7.3). Analysis of livelihood vulnerability in 14 fire-prone states found that New Mexico and Arizona residents were most vulnerable due to relatively high risk exposure and low to moderate access to resources needed to adapt to changing conditions.[336] Low-income areas, communities of color, undocumented Indigenous migrants, sexual and gender minorities (KM 15.2),[337] and unsheltered persons are most vulnerable to wildfire impacts,[231,338] including water contamination from carcinogenic compounds.[269] Populations with medical disabilities or limited mobility, older adults, and those who rely on medical equipment are also disproportionately at high risk during wildfires.[339]

Wildfires, moreover, often occur during farm harvest seasons, increasing health risks for workers.[277] Southwest industries especially vulnerable to wildfires include wineries,[340] tourism,[341,342] forest products,[183] and legal cannabis cultivation.[343] For example, in the 2020 fires, the economic impact of smoke taint is estimated to have cost the California wine industry $4.2 billion (in 2022 dollars). Smoke taint occurs when smoke and ash permeate the skin of grapes and can affect the taste and smell of wine.[344]

Impacts of wildfire on natural environments can affect ecosystem services (KM 7.2) that people derive from those environments, including air quality (KM 28.4),[266] water quality and availability,[345] pollination,[346] livestock forage and health,[347] and outdoor recreation.[348] Ecosystem service effects vary over time as short-term declines in services can be followed by improvement over a longer term as ecosystems recover.[349] Wildfires in forested ecosystems chemically alter watersheds and can reduce drinking water quality,[350] in some cases leading municipalities to issue drinking water advisories.[351] Postfire hazards such as floods and debris flows further threaten water security (Focus on Western Wildfires).[352] Smoke from the 2020 wildfires significantly reduced industrial solar energy production in Southern California.[353]

While high-severity wildfires (i.e., stand-replacing fire) generally have negative impacts, wildfires and prescribed fires that burn at low to moderate severities can have positive effects by reducing fuel loads, curtailing plant pests and diseases, and stimulating new vegetation growth.[354] Prescribed burning, while an effective tool to reverse undesirable changes in forest vegetation structure due to fire suppression, can also reduce air quality in the short term.[266]

Ecosystem Management Challenges and Adaptation Solutions

Forest resilience may be enhanced by thinning trees, leveraging low- and moderate-severity wildfires with traditional forest management treatments that adjust fuels, and better incorporating managed wildfire.[299] Using prescribed fire in conjunction with mechanical forest treatments, such as thinning or pruning, also reduces tree densities and fuels.[300] Prescribed fire can increase forest resilience during periods of climate-related stress, such as sustained drought,[355] and can reduce the extent and intensity of the wildfire regime.[356] Cultural fire use to meet Indigenous and Tribal objectives can be compatible with traditional fire application and help advance increased resilience to climate change.[296,357]

To decrease competition for water resources and increase forest resilience, reductions in tree density and fuels can lower the risk of high-severity wildfires and drought- and pest-induced mortality (KM 6.2).[358,359] Recent evidence suggests that increasing these approaches can help adapt to the rapidly increasing risks.[299,360] However, the implementation of prescribed fire may be curtailed due to public concerns about smoke and fires that escape management prescription.[361]

Natural lands, including forests and associated woodlands, play a central role in mitigating climate change (KM 32.1).[362,363] However, climate variability, drought- and pest-driven tree mortality, wildfire, and other disturbances suggest that the Southwest will see a continued decline in terrestrial carbon storage.[362,364] As a result, securing or even increasing ecosystem carbon storage is often an objective for forest management investment.[365] Forest management treatments differ in their short-term carbon losses relative to the

expected benefits of greater fire resistance, which leads to longer-term carbon stability (Box 7.2). In Southwest forests, reducing thinning area and increasing the area burned enhances the potential for a net carbon benefit when compared to no action.[366] Reforesting areas where forest cover was lost due to mortality can help mitigate the effects of climate change,[367] but planting additional trees that increase forest density would result in elevated fire risk and drought stress and therefore is not expected be an effective adaptation solution.[300,368]

Other adaptation solutions include power shutoff policies by utilities to reduce wildfire risk when extreme wind events are predicted to topple powerlines and telecommunications infrastructure.[369,370,371] Power shutoffs are more likely in autumn due to a climate-related increase in the number of days with extreme fire weather.[18] Power shutoffs may also increase homeowners' intention to adopt solar power[372] or fossil fuel–powered generators.[373] Individuals who experienced shutoffs reported poorer physical and mental health immediately after the occurrence, yet they still supported the use of shutoffs as a wildfire risk-reduction strategy.[374]

Traceable Accounts

Process Description

Following their selection in August 2021, the chapter lead author, federal coordinating lead author, and agency chapter lead author developed a comprehensive list of author candidates based on an analysis of prior National Climate Assessments, published scientific literature, science communication outlets, and policy-relevant reports. The final chapter authors were then selected based on their depth of knowledge, diversity of expertise, and experience in issues critical to the Southwest. Furthermore, authors were selected to represent diverse perspectives in terms of race, ethnicity, and gender identity. The Southwest chapter public engagement workshop was held virtually on February 4, 2022, with more than 90 participants. The workshop included an overview, a series of breakout rooms where the participants provided feedback on key topics, and a final roundup discussion among all participants. The author team held a debriefing session on February 7, 2022, to reflect on the input provided during the workshop. The author team met weekly during the development of the chapter.

Based on discussions among the author team, input from stakeholders, and consideration of the Fourth National Climate Assessment, the authors developed five Key Messages representing the valued assets and unique characteristics of the region. These include water resources, the coast, food and agriculture, demographics and human health, and wildfire. The chapter details the observed and anticipated effects of climate change on human and natural systems across those topics and outcomes to be avoided in the absence of adaptation and mitigation.

For the scientific assessment, the authors conducted a systematic evaluation of the body of scientific and technical knowledge to synthesize published studies, data, models, and assumptions while applying best professional judgment to assess uncertainties and conflicting findings. The chapter pays specific attention to factors that make specific systems and groups more vulnerable. The chapter identifies intersections between topics, cascading risks, and paths to resilience. The chapter also addresses cross-cutting themes including adaptation solutions and challenges, climate change equity and environmental justice, Indigenous Peoples and Knowledges, economics, infrastructure, and ecosystems and ecosystem services.

Key Message 28.1

Drought and Increasing Aridity Threaten Water Resources

Description of Evidence Base

Instrumental data and paleoclimate data provide strong, abundant evidence that the early-21st-century drought in the Southwest is more severe than most, but not all, prior drought periods.[28,45,46,375] Research has identified higher temperatures as being a major driver of drought severity through the mechanism of increased atmospheric demand.[47] Recent research builds on an already-substantial evidence base demonstrating the decline of southwestern snowpacks over the last century.[5,6,49,50] Research has shown how drought-induced shortages in surface water have increased groundwater pumping in California's Central Valley,[67] which provides one example of how drought may reduce future water access, especially if aquifer recharge is also reduced.[63]

Major Uncertainties and Research Gaps

Historical data supply insight into the potential impact of precipitation deficits on surface water, and various research studies demonstrate how precipitation deficit and higher rates of evapotranspiration feed into reduced soil moisture and infiltration, both in contemporary and future warmer climates. However, there is remaining uncertainty over the precise contribution of temperature to these declines in 20th-century

Upper Colorado streamflow,[375] the impact of changing snowpack dynamics on streamflow in and across different southwestern river basins,[56] and the impacts of El Niño–Southern Oscillation on precipitation in the region.[376,377]

There are also research gaps on the impacts of climate change on the full hydrologic cycle of the Southwest. From the biophysical perspective, there's a lack of information about aquifer recharge, specifically regarding temporal variability of recharge rates and locations.[63] Another topic for further exploration is the relationship between drought, surface water supplies, and rates of groundwater pumping for agriculture in locations within the Southwest beyond California (e.g., Rio Grande and tributaries, Utah, Nevada). Further, there is limited research on climate change impacts on the dynamics of the North American Monsoon, including how to more effectively capture monsoon moisture to substitute for decreased winter precipitation, as well as on other extreme precipitation events such as atmospheric rivers.

Additionally, there are multiple paths for water adaptation in the Southwest for industry, agriculture, and communities to build resilience to a more water-scarce future. However, there are research gaps around the feasibility and long-term effects of these adaptation solutions.[378,379] Moreover, the ability of different sectors and communities—including rural, low-income, Indigenous, and other frontline communities—to adapt to climate-induced water scarcity is highly variable across the Southwest.[380] There is a gap in research on best practices to support these communities in adapting to current and future water scarcity.

Currently, Indigenous Peoples' water rights are under-utilized, while water access remains a challenge for many Indigenous Peoples. As more Indigenous Peoples gain access to and use their water rights, there is limited research on how this might impact other water users and broader water management actions, especially under Colorado River drought policies.[381]

Description of Confidence and Likelihood

Measurements of snowpack, streamflow, and groundwater over the last century support the observation, with *very high confidence*, that climate change has reduced surface water and groundwater availability for people and nature in the Southwest.[4,14,56] Moreover, evidence from the peer-reviewed literature supports the assertion of *high confidence* that certain Indigenous and frontline communities, including agriculturalists, will experience disproportionate impacts from reduced water availability and that long-standing institutional frameworks drive these inequities.[187,382,383,384]

The *high confidence* that higher temperatures have intensified drought and will *very likely* lead to a more arid future is based on recent evidence that shows that since the early 20th century higher temperatures have increased the proportion of precipitation being lost to evapotranspiration relative to its contribution to Colorado River flow—a trend that is expected to continue as the region warms.[28,51]

Without extensive adaptation, which is challenging because human systems have developed under the historical water cycle patterns (KM 4.2), there is *high confidence* and it is *likely* that these dynamics will further stress existing water supply–demand imbalances. Water supply imbalances primarily refer to the over-allocation of surface water supplies in the region's major rivers, such as the Colorado and Rio Grande, due to committing more water to what are legally known as "beneficial uses" than is currently available. Concurrently, longitudinal studies and climate models suggest that there is *high confidence* that increased flooding will occur due to more intense precipitation events, such as those caused by atmospheric rivers,[71,72] in the region's future.

There is *medium confidence* that flexible and adaptive approaches to water management have the potential to address changing climate risks and mitigate the impacts on people, the environment, and the economy (KM 4.3). While there are abundant examples of such approaches from around the world and in multiple water-use sectors, assessments of the feasibility of these examples in the Southwest are lacking.

Key Message 28.2

Adaptation Efforts Increase to Address Accelerating Impacts to the Region's Coast and Ocean

Description of Evidence Base

Recent research and observed events demonstrate that marine heatwave events will continue and increase in frequency alongside other stressors, impacting marine-resource dependent communities.[35,95] Marine heatwaves and century-scale sea surface temperature warming trends near the coast of California have been attributed to human influence on climate.[385] Adverse impacts to aquaculture and wild-capture fisheries have already been observed and are projected to worsen. Impacts are connected to the degradation of marine ecosystems from not only temperature effects but also ocean acidification, hypoxia, and harmful algal blooms. And while there is extensive literature on the California Current ecosystem and wild-capture fisheries, there are fewer studies on the long-term effects of extreme events and California aquaculture, and thus higher uncertainty.

Sea level rise impacts have been extensively modeled and compared with observed flooding. The most recent lines of evidence are synthesized with a large body of relevant literature included in the 2022 Interagency Task Force report on sea level rise[7] and the Intergovernmental Panel on Climate Change Sixth Assessment Report from Working Group I.[95]

The authors focused on findings on the impacts from sea level rise, which centered around new understandings of sea level rise impacts to groundwater and infrastructure and communities. Energy and transportation infrastructure will continue to be impacted by increased flooding. Furthermore, recent studies have shown that climate impacts will disproportionately impact overburdened communities, but additional research specific to California is lacking.

Adaptation for infrastructure and communities has been accelerating in California through state and local governments, as seen through the release of laws, executive orders, and state guidance documents, as well as an increase in state, Tribal, local, and regional vulnerability assessments and adaptation plans. Government planning requirements and guidance for different sectors are increasing. The State of California also invests in downscaled climate science to inform state and local climate decision-making; the state's climate change assessment has been codified in law. Less information on adaptive strategies for fisheries and aquaculture has been released.

Major Uncertainties and Research Gaps

Long-term, compound implications of greater extremes with other stressors and mitigation strategies are less certain. There is less research in California on combined, long-term impacts of marine heatwaves and multi-stressor effects on ecosystems, species, and aquaculture. However, multi-stressor research is advancing,[386] including for the California Current,[387] increasing our mechanistic understanding of climate change effects. Mitigation strategies of nature-based carbon dioxide removal are growing in interest and investment in the US (Ch. 32),[388] including in California. While the emerging evidence suggests that ocean-based solutions, such as seaweed aquaculture carbon sequestration, are not a global "silver bullet" to mitigate carbon emissions, they may provide some local benefits.[133] However, who benefits from such interventions and the impacts to surrounding ecosystems require further investigation to ensure positive outcomes for nature and people.[389,390,391]

There is a lack of research on the impacts of sea level rise on groundwater flooding, as well as the application of those findings to infrastructure and community analyses. These compounding threats

have not been included in most adaptation planning to date, which could result in less adaptive solutions being implemented.

As governments and communities begin building adaptation projects, uncertainties about their efficacy remain. There is limited research tracking adaptation implementation, including research identifying potential ramifications, such as displacement of overburdened communities, economic injustices in terms of resources available for adaptation, and methods to ensure communities are part of decision-making for eventual retreat or relocation. Additional work could help identify how existing funding tools can support adaptation and resilience efforts and how to develop a more robust understanding of adaptation costs and benefits.

Description of Confidence and Likelihood

There is *high confidence* that climate change will increase marine heatwaves and harmful algal blooms (HABs), resulting in impacts to coastal ecosystems and economies. There is *very high confidence* and it is *very likely* that marine heatwave frequency, intensity, and extent will increase. Laufkötter et al. (2020)[385] found that heatwaves have already increased twentyfold because of human-caused global warming and that the probability of occurrences increases in frequency under progressively warmer scenarios. Linkages between HABs and thermal conditions of the oceans have been demonstrated, but frequency and extent are linked to climate and non-climate (e.g., runoff) drivers.[392] There is high agreement and evidence of negative impacts to marine ecosystems and resource-dependent communities in the literature, but under moderate to high climate mitigation scenarios, the severity of impacts will depend on adaptative interventions (e.g., nature-based solutions, adoption of ecosystem-based management).

Sea level rise will *likely* cause increased flooding on the Southwest coast, and there is *very high confidence* that those impacts will severely affect infrastructure and communities, with inequities in how these impacts are experienced. The latest climate models and sea level rise projections demonstrate increased confidence in relative sea level rise amounts by 2050. Sweet et al. (2022)[7] state that relative sea level for the entire contiguous US coastline is expected to rise, on average, as much over the next 40 years (2020–2050) as it has over the last 100 years (1920–2020; 0.82–0.98 feet). Furthermore, by 2050 the expected relative sea level will impact tide and storm surge, leading to major and moderate high tide flood events occurring as frequently as minor high tide flood events occurred in 2022, which will impact infrastructure, communities, and ecosystems.[7]

Given the State of California's progress and leadership on climate science and adaptation planning for sea level rise, there is *high confidence* that adaptation planning and implementation will continue. As evidence, the state's fiscal year 2021–2022 budget included $4 billion (in 2022 dollars) for climate resilience programs, with other new climate resilience programs created in fiscal year 2022–2023. State agencies continue to release adaptation planning guidance (e.g., State Agency Sea Level Rise Action Plan 2022;[393] Extreme Heat Action Plan 2022;[394] State Adaptation Strategy 2021[395]) and new funding programs (e.g., Adaptation Planning Grant Program 2022;[396] Transportation Climate Adaptation Planning Grants 2022;[397] Local Transportation Infrastructure Climate Adaptation Project [LTCAP] Program 2022;[398] Regional Resilience Planning and Implementation Grant Program 2022[399]). There is limited to no inclusion of aquaculture in California state climate planning (e.g., Lester et al. 2022[400]), and comparatively less coverage overall in the scientific literature compared to wild capture and agriculture,[401] and thus there is *high confidence* that climate planning and adaptation solutions for aquaculture are less clear.

Key Message 28.3

Increasing Challenges Confront Food and Fiber Production in the Southwest

Description of Evidence Base

Temperature and precipitation data clearly show that this century has been warmer and drier than the last.[50,381,402] This drying and warming trend is already resulting in measurable impacts on rangeland forage production,[403] dryland agriculture,[404] and irrigated crop yields. A substantial literature exists showing the impact of climate change on livestock production through changes in food quantity and quality, pests and disease, and animal health and well-being.[405] Evidence shows that climate is already affecting the distribution of livestock agriculture in the east of region. The Southern Plains (in New Mexico) and Central Plains (in Colorado) saw large decreases in cow numbers in the 2011–2014 drought.[406] Increasingly the Southwest's agricultural economy relies on crop production, but research anticipates downward trends in the production of numerous high-value crops in California[169] and reduced or less reliable supply of irrigation water that supports crop production throughout the region. Numerous examples of adaptation strategies exist, such as improved irrigation technologies, soil protection strategies, and shifts to Indigenous practices and crops, although there are barriers that inhibit widespread adoption of many of these practices.

Major Uncertainties and Research Gaps

Southwestern food and fiber production is diverse, spanning rangeland livestock systems, irrigated croplands and orchards, dryland, and Indigenous farming. Each of these systems is nested within local, regional, and international contexts that can exacerbate or alleviate vulnerability to climate change. This diversity, combined with factors other than climate change (e.g., global pandemics, inflation, supply chains, access to financial support) contribute to the complexity of assessing the impacts of climate change on southwestern agriculture. There are therefore research gaps and some uncertainty on how the adaptation options described in the agronomic and range management literature can be applied in the real world.

Research gaps remain in our understanding of not only the biophysical and socioeconomic capacity to support change in southwestern agrosystems but also the will of farmers and policymakers to change the type of crops that are grown. For livestock producers who rely on forage from public lands, there is uncertainty about how climate change will affect the number of animals the land can support and how possible reductions in stocking rate will affect the viability of ranches and ranching-dependent communities.

Description of Confidence and Likelihood

There is *high confidence* that continuing drought and water scarcity will make it more difficult to raise food and fiber in the Southwest without major shifts to new strategies and technologies. Climate models agree that the Southwest will continue to warm. This impacts the thermal tolerance and chilling requirements for economically important crops. There are multiple indicators that the Southwest is undergoing aridification; as a consequence, it is expected that there will be less available water for irrigated agriculture in the future.

Given substantive evidence in the literature, there is *high confidence*, and it is *likely*, that extreme heat events will continue to occur and are expected to worsen in intensity and increase in frequency in the 21st century.[167] Extreme heat reduces crop quality and yield[181,403] and affects livestock productivity (and in some cases survival), resulting in economic impacts.[197,198,405] USDA Risk Management Agency indemnities data from 1989 to 2021 show that heat events are already driving crop production losses across the region.

There is a growing literature that advocates for greater inclusion of Indigenous Knowledge for informing adaptation solutions in Southwest agriculture. There is *medium confidence* that Indigenous Knowledge, along with technological innovation, has the potential to inform sustainable agricultural practice

regionwide, as well as increasing Indigenous food sovereignty, because there are few studies to date that demonstrate how Indigenous Knowledge can be drawn on to adapt larger acreages or commercial operations to climate change. It is also evident in the literature that technical innovations (e.g., agrivoltaics, internet of things) have yet to become more widely adopted or applied to larger acreage operations.

Key Message 28.4

Climate Change Compromises Human Health and Reshapes Demographics

Description of Evidence Base

Strong evidence and good agreement among multiple sources and lines of evidence show that extreme heat exposures already are leading to heat-associated deaths and illnesses across the region.[228,233,407] Exposures to extreme heat for city dwellers are increasing, partly due to human-caused climate change and partly due to urban-induced warming.[408,409] Regional-scale warming in the Southwest since 1901 exceeds what would be expected from natural variability and is partly attributable to human influence.[3] Climate change has doubled the likelihood of an event capable of producing catastrophic flooding for California, and future increases to this risk are expected due to continued warming.[271,272]

Multiple lines of evidence indicate current and future increases in human exposures and adverse health outcomes to wildfire smoke in the region.[277,410,411] Good agreement exists among models that the intensified arid conditions in the region will result in more dust storms[243] and thus a higher incidence of respiratory ailments, including Valley fever.[246,248]

Evidence supports the need for increased investments in adaptative strategies that support social, physical, and health systems that enhance individual and community resilience to changes in climate, particularly extreme heat.[288,412,413,414,415] Improving public health systems and community infrastructure in the region can reduce the health consequences of climate change.

Major Uncertainties and Research Gaps

Uncertainties exist in the attribution of changes in climate variables to specific health outcomes. The collection of and alignment of more environmental and health data will assist in understanding the long-term nature of how climate change affects specific health outcomes. Detecting direct relationships between climate change impacts and public health outcomes is also made more difficult due to confounding factors related to socioeconomics, vulnerability, exposure assessments, demographic shifts, migration, and community and individual characteristics. Detection and attribution studies are thus vital to the region for addressing multiple public health concerns (e.g., Ebi et al. 2020[30]).

Related uncertainties in how regional changes in climate will affect public health exist due to variability in projections of extreme precipitation; uncertainties in the occurrence and intensity of climate-sensitive exposures that impact human health, including wildfire smoke exposures; and variability in local and regional ozone based on meteorological conditions and emissions-reduction targets achieved.

Uncertainties also exist in projecting climate-related changes to the abundance of vector-borne diseases and associated disruptions. While US rates of chikungunya and Zika dropped[416] with widespread travel restrictions due to COVID-19, issues with West Nile virus (WNV) remain due to the endemic nature of the virus in the region. The most common WNV vector in the region (*Culex quinquefasciatus*) is abundant in urbans areas such as Los Angeles, Albuquerque, and Phoenix,[417] and certain water management structures (e.g., catch basins, storm drains, and retention ponds) provide favorable environments for *Cx. quinquefasciatus* reproduction.[418] There is also uncertainty around how heavy precipitation, as compared to drought

conditions, impacts the abundance and distribution of vector-borne diseases connected to human activity and management of water. Transmission of WNV is also projected to shift northward,[419] thus decreasing potential risks of transmission in parts of the Southwest.

Finally, considerable uncertainties exist in how individuals and communities will adapt to the effects of climate change in the region. Model projections of health impacts rarely account for adaptive capacity changes into the future. Improving adaptive capacity involves enhancing infrastructure, technologies, behavior, and the overall health of the population to cope with climate effects.

Description of Confidence and Likelihood

There is *high confidence* that increases in extreme heat, drought, flooding, and wildfire activity are negatively impacting the physical health of Southwest residents. Climate models agree that the Southwest is experiencing higher temperatures and more intense, longer, and more frequent heat events.[3,8,375,420]Extreme heat exposure causes mortality, morbidity, and lost productivity if dangerous exposures occur (KM 15.2).[235,421] Drier conditions lead to a greater risk of wildfires and particulate matter, which adversely affect human respiratory and cardiovascular health when exposed.[265,290,422,423,424]

Climate change is also shaping the demographics of the region by spurring the migration of people to the Southwest, primarily from Central America (*medium confidence*). In 2021, about 13 million people (representing 21.3% of total population) living in the Southwest were foreign born; 21.1% of those foreign born entered the United States in the last 10 years.[425] Decreasing agricultural productivity, increasing levels of food insecurity, and adverse climate effects are among the main reasons why people emigrate from the Northern Triangle (Guatemala, Honduras, and El Salvador) to the US (KM 17.2).[32,279] About 43% of immigrants apprehended at the Southwest border in 2019 originated from the Northern Triangle.[278]

Individuals particularly vulnerable to increasing climate change impacts include older adults, outdoor workers, and people with low income (*high confidence*). Wildfires and the related smoke are affecting a higher number of people, with strong evidence pointing to the most vulnerable populations being at greatest risk.[426] Strong evidence further connects rising particulate matter levels to higher risk in already-vulnerable populations, including individuals with low income, Indigenous Peoples, pregnant people, children, and outdoor workers.[427,428,429,430,431] It has been well documented that extreme heat disproportionately impacts the health of the most vulnerable populations in the region, including the unhoused,[227,228,229] outdoor workers, and migrant farmworkers,[230,231,232,233] as well as people with low income,[8,234] older adults,[235] and pregnant people and babies (particularly with air pollution co-exposures).[237,238,239,240]

There is *high confidence* that local, state, and federal initiatives can respond to these climatic and demographic changes by helping people and communities become healthier and more resilient. There is strong evidence that increasing adaptive capacity and resilience across communities, especially the most vulnerable, will reduce the human health impacts of climate change.[432] The relative importance of various adaptive strategies will differ across spatial and temporal scales, climatology, and social and behavioral contexts. Improving public health systems, overall health, community infrastructure, and education can reduce health risks that are being exacerbated in the Southwest due to climate change, as well as many health risks in general.[431]

Key Message 28.5

Changes in Wildfire Patterns Pose Challenges for Southwest Residents and Ecosystems

Description of Evidence Base

Changing wildfire dynamics include increases in wildfire size and severity and changing and lengthening fire seasons.[18,303,433,434] Extensive research has found that climate change is linked to increases in extreme fire weather,[18] wildfire activity,[20,303,326] wildfire severity,[17,19,21,434] and acreage burned annually.[302] Unprecedented high-severity fires have driven ecosystem conversions in many parts of the region.[294,311] Recent climate-induced aridification, including loss of snowpack, has also reduced postfire tree seedling and shrub establishment, limiting ecosystem recovery.[313,314,315]

Projections suggest that future fire activity will continue to degrade ecosystems and alter their structure and function.[294,298,319] Increased fire activity,[320,321,322] further warming and drying that stress tree seedlings, and model projections of stand-replacing fires at the forest/non-forest boundary in the western US[316] have raised the possibility of shifts in species composition or vegetation type.[294,317] These projections suggest high variability in ecosystem responses depending on interactions between vegetation type, moisture stress, disturbance regimes, and human alterations.[314,319,435,436,437,438]

Increasing wildfire risk poses threats to lives and livelihoods in the region. Wildfire and accompanying smoke have led to fatalities caused by the fires themselves,[304,327] by smoke from wildfires,[328] and by debris flows that occur when heavy rains fall on recently burned slopes.[330] Even if not fatal, wildfires have been linked to declines in physical health[265,328,439] and mental health.[268] Frontline communities, including low-income groups and populations of color, are especially vulnerable to these impacts.[231,338] Exposure of people in the Southwest to wildfire risk is also increasing due to population growth in wildland–urban interface areas near fire-prone forests, shrublands, and grasslands.[331,332,333] Economic costs to individual households come from structures burned and increased insurance and healthcare costs.[440,441] Further costs come from income lost due to fires that affect energy, agriculture, and tourism.[340,341,342,353]

Adaptation strategies include reduction in tree density and wildland fuels[299,355,358,359] that can reduce the size and severity of fires when they occur. Integration of Indigenous burning practices with contemporary forest management can mitigate wildfire risk as well.[296] Risk is expected to be reduced through public safety power shutoffs initiated by electric utilities when weather conditions suggest wildfire danger is especially high.[370]

Major Uncertainties and Research Gaps

The short-term likelihood of increasing wildfire risks and impacts is very high. What is less clear is the extent to which adaptation strategies such as increasing fuel-reduction treatments and adoption of climate-adapted silviculture will be able to mitigate those impacts. As yet, there has been no reliable way to quantify the degree to which increases in fire area and severity are due to climate change versus past management, non-native species invasions, urbanization, or other factors. To restore forest resilience (KM 7.3), the rate of thinning and fuel reduction needs to be greatly increased, and it is not known whether resources will be available to achieve such intensified management. Fire ecologists point to the need for increasing use of prescribed burning to reduce fuel loads, but it is not certain how much this increase can be achieved, considering the increasing risk of fire escape and public unease about the use of fire as a management tool.[361] Geographic factors, forest policies, and public attitudes toward forest management can constrain the rate at which risk-reduction actions can be implemented. Similarly, long-term attitudes toward public safety power shutoffs, restrictions on homebuilding in fire-prone landscapes, and other risk-reduction policies are uncertain.

Description of Confidence and Likelihood

There is *high confidence* that the Southwest region is experiencing unprecedented wildfire occurrence and that this change is linked to climate change. Contributing causes include land management policies that have led to high tree densities that increase fuel for fires,[295,318] climate-mediated events such as insect and tree disease outbreaks (Box 7.1),[319] and increased human population at the forest's edge,[331] all of which interact with climate change in ways that increase wildfire risk and occurrence.[18,21]

There is *high confidence* that fires in the region have become larger and more severe. Increased temperatures and changes to precipitation have combined to produce an increase in vapor pressure deficit.[333] This, in conjunction with episodes of climatic extremes such as droughts and heatwaves, means it is *very likely* that these trends will continue in the region's forests.[319,320,321,322] However, there is less certainty about future trends in non-forested areas because of high year-to-year variability in production of the grasses that fuel wildfires,[324] with model projections suggesting that climate impacts on plant growth will vary across the region.[325]

There is *high confidence* that severe wildfires are placing people, economies, ecosystems, and water resources at risk, and it is *very likely* that severe wildfires will continue, partially because of climate change impacts. There is consensus among studies from climate models that the Southwest will continue to warm, and there are multiple indicators that the region is becoming more arid, increasing wildfire risk. There are many indicators of costs to human lives, health, and livelihoods due to wildfire, and as the risk of catastrophic wildfire increases, so do those costs.

There is *medium confidence* that adaptation pathways will reduce wildfire risk and promote ecosystem restoration through forest management and other adaptations such as the application of Indigenous Knowledges. While the adaptation opportunities are known, it is less clear whether society will have the capacity to embrace those opportunities.

References

1. U.S. Census Bureau. 2010: State Area Measurements and Internal Point Coordinates. U.S. Department of Commerce, U.S. Census Bureau. https://www.census.gov/geographies/reference-files/2010/geo/state-area.html

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

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

4. Mote, P.W., S. Li, D.P. Lettenmaier, M. Xiao, and R. Engel, 2018: Dramatic declines in snowpack in the western US. *Npj Climate and Atmospheric Science*, **1** (1), 1–6. https://doi.org/10.1038/s41612-018-0012-1

5. Siirila-Woodburn, E.R., A.M. Rhoades, B.J. Hatchett, L.S. Huning, J. Szinai, C. Tague, P.S. Nico, D.R. Feldman, A.D. Jones, W.D. Collins, and L. Kaatz, 2021: A low-to-no snow future and its impacts on water resources in the western United States. *Nature Reviews Earth & Environment*, **2** (11), 800–819. https://doi.org/10.1038/s43017-021-00219-y

6. Uzun, S., T. Tanir, G.d.A. Coelho, A.d. Souza de Lima, F. Cassalho, and C.M. Ferreira, 2021: Changes in snowmelt runoff timing in the contiguous United States. *Hydrological Processes*, **35** (11), e14430. https://doi.org/10.1002/hyp.14430

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

8. Gabbe, C.J. and G. Pierce, 2020: Extreme heat vulnerability of subsidized housing residents in California. *Housing Policy Debate*, **30** (5), 843–860. https://doi.org/10.1080/10511482.2020.1768574

9. Knutson, T.R. and J.J. Ploshay, 2016: Detection of anthropogenic influence on a summertime heat stress index. *Climatic Change*, **138** (1), 25–39. https://doi.org/10.1007/s10584-016-1708-z

10. Li, C., X. Zhang, F. Zwiers, Y. Fang, and A.M. Michalak, 2017: Recent very hot summers in northern hemispheric land areas measured by wet bulb globe temperature will be the norm within 20 years. *Earth's Future*, **5** (12), 1203–1216. https://doi.org/10.1002/2017ef000639

11. Vicedo-Cabrera, A.M., N. Scovronick, F. Sera, D. Royé, R. Schneider, A. Tobias, C. Astrom, Y. Guo, Y. Honda, D.M. Hondula, R. Abrutzky, S. Tong, M.d.S.Z.S. Coelho, P.H.N. Saldiva, E. Lavigne, P.M. Correa, N.V. Ortega, H. Kan, S. Osorio, J. Kyselý, A. Urban, H. Orru, E. Indermitte, J.J.K. Jaakkola, N. Ryti, M. Pascal, A. Schneider, K. Katsouyanni, E. Samoli, F. Mayvaneh, A. Entezari, P. Goodman, A. Zeka, P. Michelozzi, F. de'Donato, M. Hashizume, B. Alahmad, M.H. Diaz, C.D.L.C. Valencia, A. Overcenco, D. Houthuijs, C. Ameling, S. Rao, F. Di Ruscio, G. Carrasco-Escobar, X. Seposo, S. Silva, J. Madureira, I.H. Holobaca, S. Fratianni, F. Acquaotta, H. Kim, W. Lee, C. Iniguez, B. Forsberg, M.S. Ragettli, Y.L.L. Guo, B.Y. Chen, S. Li, B. Armstrong, A. Aleman, A. Zanobetti, J. Schwartz, T.N. Dang, D.V. Dung, N. Gillett, A. Haines, M. Mengel, V. Huber, and A. Gasparrini, 2021: The burden of heat-related mortality attributable to recent human-induced climate change. *Nature Climate Change*, **11** (6), 492–500. https://doi.org/10.1038/s41558-021-01058-x

12. Miller, K., A. Milman, and M. Kiparsky, 2021: Introduction to the Special Collection: Institutional dimensions of groundwater recharge. *Case Studies in the Environment*, **5** (1). https://doi.org/10.1525/cse.2021.1245648

13. Milly, P.C.D. and K.A. Dunne, 2016: Potential evapotranspiration and continental drying. *Nature Climate Change*, **6**, 946–969. https://doi.org/10.1038/nclimate3046

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

15. Talsma, C.J., K.E. Bennett, and V.V. Vesselinov, 2022: Characterizing drought behavior in the Colorado River Basin using unsupervised machine learning. *Earth and Space Science*, **9** (5), e2021EA002086. https://doi.org/10.1029/2021ea002086

16. Xiao, M., B. Udall, and D.P. Lettenmaier, 2018: On the causes of declining Colorado River streamflows. *Water Resources Research*, **54** (9), 6739–6756. https://doi.org/10.1029/2018wr023153

17. Duane, A., M. Castellnou, and L. Brotons, 2021: Towards a comprehensive look at global drivers of novel extreme wildfire events. *Climatic Change*, **165** (3), 43. https://doi.org/10.1007/s10584-021-03066-4

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

19. Mueller, S.E., A.E. Thode, E.Q. Margolis, L.L. Yocom, J.D. Young, and J.M. Iniguez, 2020: Climate relationships with increasing wildfire in the southwestern US from 1984 to 2015. *Forest Ecology and Management*, **460**, 117861. https://doi.org/10.1016/j.foreco.2019.117861

20. Swain, D.L., 2021: A shorter, sharper rainy season amplifies California wildfire risk. *Geophysical Research Letters*, **48** (5), e2021GL092843. https://doi.org/10.1029/2021gl092843

21. Williams, A.P., J.T. Abatzoglou, A. Gershunov, J. Guzman-Morales, D.A. Bishop, J.K. Balch, and D.P. Lettenmaier, 2019: Observed impacts of anthropogenic climate change on wildfire in California. *Earth's Future*, **7** (8), 892–910. https://doi.org/10.1029/2019ef001210

22. BEA, 2022: Gross Domestic Product by State and Personal Income by State, 2nd Quarter 2022. BEA 22–48. U.S. Department of Commerce, Bureau of Economic Analysis. https://www.bea.gov/data/gdp/gdp-state

23. Bureau of Indian Affairs, 2017: Indian entities recognized and eligible to receive services from the United States Bureau of Indian Affairs. *Federal Register*, **82** (10), 4915–4920. https://www.federalregister.gov/documents/2017/01/17/2017-00912/indian-entities-recognized-and-eligible-to-receive-services-from-the-united-states-bureau-of-indian

24. CRS, 2020: Federal Land Ownership: Overview and Data. CRS Report R42346. Congressional Research Service. https://crsreports.congress.gov/product/pdf/r/r42346

25. Gonzalez, P., G.M. Garfin, D.D. Breshears, K.M. Brooks, H.E. Brown, E.H. Elias, A. Gunasekara, N. Huntly, J.K. Maldonado, N.J. Mantua, H.G. Margolis, S. McAfee, B.R. Middleton, and B.H. Udall, 2018: Ch. 25. Southwest. In: *Impacts, Risks, and Adaptation in the United States: Fourth National Climate Assessment, Volume II*. Reidmiller, D.R., C.W. Avery, D. Easterling, K. Kunkel, K.L.M. Lewis, T.K. Maycock, and B.C. Stewart, Eds. U.S. Global Change Research Program, Washington, DC, USA, 1101–1184. https://doi.org/10.7930/nca4.2018.ch25

26. Hoerling, M., J. Eischeid, X. Quan, and A. Badger, 2019: Causes for the century-long decline in Colorado River flow. *Journal of Climate*, **32** (23), 8181–8203. https://doi.org/10.1175/jcli-d-19-0207.1

27. Lukas, J.J. and E.A. Payton, 2020: Colorado River Basin Climate and Hydrology: State of the Science. Western Water Assessment. University of Colorado Boulder, Cooperative Institute for Research in Environmental Sciences, Boulder, CO. https://doi.org/10.25810/3hcv-w477

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

29. Steele, C., J. Reyes, E. Elias, S. Aney, and A. Rango, 2018: Cascading impacts of climate change on southwestern US cropland agriculture. *Climatic Change*, **148** (3), 437–450. https://doi.org/10.1007/s10584-018-2220-4

30. Ebi, K.L., C. Åström, C.J. Boyer, L.J. Harrington, J.J. Hess, Y. Honda, E. Kazura, R.F. Stuart-Smith, and F.E.L. Otto, 2020: Using detection and attribution to quantify how climate change is affecting health. *Health Affairs*, **39** (12), 2168–2174. https://doi.org/10.1377/hlthaff.2020.01004

31. Hait, A.W., 2021: Growth in the Desert Southwest Mirrors the Nation in Some Economic Sectors but Is Quite Different in Others. U.S. Census Bureau. https://www.census.gov/library/stories/2021/09/business-growth-in-desert-southwest-more-than-twice-national-average.html

32. Spencer, N. and M.-A. Urquhart, 2018: Hurricane strikes and migration: Evidence from storms in Central America and the Caribbean. *Weather, Climate, and Society*, **10** (3), 569–577. https://doi.org/10.1175/wcas-d-17-0057.1

33. Newell, J.P., B. Goldstein, and A. Foster, 2019: A 40-year review of food-energy-water nexus literature and its application to the urban scale. *Environmental Research Letters*, **14** (7). https://doi.org/10.1088/1748-9326/ab0767

34. Opejin, A.K., R.M. Aggarwal, D.D. White, J.L. Jones, R. Maciejewski, G. Mascaro, and H.S. Sarjoughian, 2020: A bibliometric analysis of food-energy-water nexus literature. *Sustainability*, **12** (3), 1112. https://doi.org/10.3390/su12031112

35. IPCC, 2022: *Climate Change 2022: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*. Pörtner, H.-O., D.C. Roberts, M. Tignor, E.S. Poloczanska, K. Mintenbeck, A. Alegría, M. Craig, S. Langsdorf, S. Löschke, V. Möller, A. Okem, and B. Rama, Eds. Cambridge University Press, Cambridge, UK and New York, NY, USA, 3056 pp. https://doi.org/10.1017/9781009325844

36. Jones, J.L. and D.D. White, 2022: Understanding barriers to collaborative governance for the food-energy-water nexus: The case of Phoenix, Arizona. *Environmental Science and Policy*, **127**, 111–119. https://doi.org/10.1016/j.envsci.2021.10.025

37. Koebele, E.A., 2020: Cross-coalition coordination in collaborative environmental governance processes. *Policy Studies Journal*, **48** (3), 727–753. https://doi.org/10.1111/psj.12306

38. Sullivan, A., D.D. White, and M. Hanemann, 2019: Designing collaborative governance: Insights from the drought contingency planning process for the lower Colorado River Basin. *Environmental Science and Policy*, **91**, 39–49. https://doi.org/10.1016/j.envsci.2018.10.011

39. The California Climate Crisis Act. Assembly Bill No. 1279, State of California, September 16, 2022. https://leginfo.legislature.ca.gov/faces/billNavClient.xhtml?bill_id=202120220AB1279

40. State of California, 2018: Executive Order B-55-18: To Achieve Carbon Neutrality. State of California, Executive Department. https://www.ca.gov/archive/gov39/wp-content/uploads/2018/09/9.10.18-Executive-Order.pdf

41. CARB, 2022: Scoping Plan for Achieving Carbon Neutrality. California Air Resources Board. https://ww2.arb.ca.gov/sites/default/files/2022-12/2022-sp.pdf

42. State of California, 2021: California Climate Commitment: Biggest Climate Investment in History. State of California, 2 pp. https://www.gov.ca.gov/wp-content/uploads/2022/06/california-climate-commitment-.pdf

43. Climate Action Plan to Reduce Pollution. HB19-1261, State of Colorado, 2019. https://leg.colorado.gov/bills/hb19-1261

44. State of New Mexico, 2019: Executive Order 2019-003: Executive Order on Addressing Climate Change and Energy Waste Prevention. State of New Mexico, Executive Office, 4 pp. https://www.governor.state.nm.us/wp-content/uploads/2019/01/EO_2019-003.pdf

45. Gangopadhyay, S., C.A. Woodhouse, G.J. McCabe, C.C. Routson, and D.M. Meko, 2022: Tree rings reveal unmatched 2nd century drought in the Colorado River Basin. *Geophysical Research Letters*, **49** (11), e2022GL098781. https://doi.org/10.1029/2022gl098781

46. Meko, D.M., C.A. Woodhouse, and A.G. Winitsky, 2022: Tree-ring perspectives on the Colorado River: Looking back and moving forward. JAWRA *Journal of the American Water Resources Association*, **58** (5), 604–621. https://doi.org/10.1111/1752-1688.12989

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

48. Lehner, F., E.R. Wahl, A.W. Wood, D.B. Blatchford, and D. Llewellyn, 2017: Assessing recent declines in Upper Rio Grande runoff efficiency from a paleoclimate perspective. *Geophysical Research Letters*, **44** (9), 4124–4133. https://doi.org/10.1002/2017gl073253

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

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

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

52. Lynn, E., A. Cuthbertson, M. He, J.P. Vasquez, M.L. Anderson, P. Coombe, J.T. Abatzoglou, and B.J. Hatchett, 2020: Technical note: Precipitation-phase partitioning at landscape scales to regional scales. *Hydrology and Earth System Sciences*, **24** (11), 5317–5328. https://doi.org/10.5194/hess-24-5317-2020

53. Skiles, S.M.K., M. Flanner, J.M. Cook, M. Dumont, and T.H. Painter, 2018: Radiative forcing by light-absorbing particles in snow. *Nature Climate Change*, **8** (11), 964–971. https://doi.org/10.1038/s41558-018-0296-5

54. Livneh, B. and A.M. Badger, 2020: Drought less predictable under declining future snowpack. *Nature Climate Change*, **10** (5), 452–458. https://doi.org/10.1038/s41558-020-0754-8

55. Walton, D.B., A. Hall, N. Berg, M. Schwartz, and F. Sun, 2017: Incorporating snow albedo feedback into downscaled temperature and snow cover projections for California's Sierra Nevada. *Journal of Climate*, **30** (4), 1417–1438. https://doi.org/10.1175/jcli-d-16-0168.1

56. Gordon, B.L., P.D. Brooks, S.A. Krogh, G.F.S. Boisrame, R.W.H. Carroll, J.P. McNamara, and A.A. Harpold, 2022: Why does snowmelt-driven streamflow response to warming vary? A data-driven review and predictive framework. *Environmental Research Letters*, **17** (5), 053004. https://doi.org/10.1088/1748-9326/ac64b4

57. Pierce, D.W., 2023: LOCA Statistical Downscaling. University of San Diego, Scripps Institution of Oceanography. https://loca.ucsd.edu/

58. Vano, J., J. Hamman, E. Gutmann, A. Wood, N. Mizukami, M. Clark, D.W. Pierce, D.R. Cayan, C. Wobus, K. Nowak, and J. Arnold, 2020: Comparing Downscaled LOCA and BCSD CMIP5 Climate and Hydrology Projections: Release of Downscaled LOCA CMIP5 Hydrology. Bureau of Reclamation, Livermore, CA, 96 pp. https://gdo-dcp.ucllnl.org/downscaled_cmip_projections/techmemo/LOCA_BCSD_hydrology_tech_memo.pdf

59. Woodhouse, C.A. and G.T. Pederson, 2018: Investigating runoff efficiency in upper Colorado River streamflow over past centuries. *Water Resources Research*, **54** (1), 286–300. https://doi.org/10.1002/2017wr021663

60. Berg, A. and J. Sheffield, 2018: Climate change and drought: The soil moisture perspective. *Current Climate Change Reports*, **4** (2), 180–191. https://doi.org/10.1007/s40641-018-0095-0

61. Null, S.E. and W.A. Wurtsbaugh, 2020: Ch. 1. Water development, consumptive water uses, and Great Salt Lake. In: *Great Salt Lake Biology: A Terminal Lake in a Time of Change*. Baxter, B.K. and J.K. Butler, Eds. Springer, Cham, Switzerland, 1–21. https://doi.org/10.1007/978-3-030-40352-2_1

62. Mankin, J.S., I. Simpson, A. Hoell, R. Fu, J. Lisonbee, A. Sheffield, and D. Barrie, 2021: NOAA Drought Task Force Report on the 2020–2021 Southwestern U.S. Drought. National Oceanic and Atmospheric Administration Drought Task Force, Modeling, Analysis, Predictions, and Projections Program, and National Integrated Drought Information System. https://www.drought.gov/documents/noaa-drought-task-force-report-2020-2021-southwestern-us-drought

63. Al Atawneh, D., N. Cartwright, and E. Bertone, 2021: Climate change and its impact on the projected values of groundwater recharge: A review. *Journal of Hydrology*, **601**, 126602. https://doi.org/10.1016/j.jhydrol.2021.126602

64. Meixner, T., A.H. Manning, D.A. Stonestrom, D.M. Allen, H. Ajami, K.W. Blasch, A.E. Brookfield, C.L. Castro, J.F. Clark, D.J. Gochis, A.L. Flint, K.L. Neff, R. Niraula, M. Rodell, B.R. Scanlon, K. Singha, and M.A. Walvoord, 2016: Implications of projected climate change for groundwater recharge in the western United States. *Journal of Hydrology*, **534**, 124–138. https://doi.org/10.1016/j.jhydrol.2015.12.027

65. Russo, T.A. and U. Lall, 2017: Depletion and response of deep groundwater to climate-induced pumping variability. *Nature Geoscience*, **10** (2), 105–108. https://doi.org/10.1038/ngeo2883

66. Sheng, Z., 2013: Impacts of groundwater pumping and climate variability on groundwater availability in the Rio Grande Basin. *Ecosphere*, **4** (1), 5. https://doi.org/10.1890/es12-00270.1

67. Lund, J., J. Medellin-Azuara, J. Durand, and K. Stone, 2018: Lessons from California's 2012–2016 drought. *Journal of Water Resources Planning and Management*, **144** (10), 04018067. https://doi.org/10.1061/(asce)wr.1943-5452.0000984

68. Davenport, F.V., J.E. Herrera-Estrada, M. Burke, and N.S. Diffenbaugh, 2020: Flood size increases nonlinearly across the western United States in response to lower snow-precipitation ratios. *Water Resources Research*, **56** (1), e2019WR025571. https://doi.org/10.1029/2019wr025571

69. Li, D., D.P. Lettenmaier, S.A. Margulis, and K. Andreadis, 2019: The role of rain-on-snow in flooding over the conterminous United States. *Water Resources Research*, **55** (11), 8492–8513. https://doi.org/10.1029/2019wr024950

70. Huang, H., M.R. Fischella, Y. Liu, Z. Ban, J.v. Fayne, D. Li, K.C. Cavanaugh, and D.P. Lettenmaier, 2022: Changes in mechanisms and characteristics of western U.S. floods over the last sixty years. *Geophysical Research Letters*, **49** (3). https://doi.org/10.1029/2021gl097022

71. Albano, C.M., M.D. Dettinger, and A.A. Harpold, 2020: Patterns and drivers of atmospheric river precipitation and hydrologic impacts across the western United States. *Journal of Hydrometeorology*, **21** (1), 143–159. https://doi.org/10.1175/jhm-d-19-0119.1

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

73. Pierce, D.W., J.F. Kalansky, and D.R. Cayan, 2018: Climate, Drought, and Sea Level Rise Scenarios for the Fourth California Climate Assessment. California's Fourth Climate Change Assessment. Publication Number: CNRA-CEC-2018-006. California Energy Commission. https://www.energy.ca.gov/sites/default/files/2019-11/projections_ccca4-cec-2018-006_ada.pdf

74. Wang, J., H. Yin, E. Reyes, T. Smith, and F. Chung, 2018: Mean and Extreme Climate Change Impacts on the State Water Project. California's Fourth Climate Change Assessment. Publication Number: CCCA4-EXT-2018-004. California Energy Commission. https://www.energy.ca.gov/sites/default/files/2019-12/water_ccca4-ext-2018-004_ada.pdf

75. Hatcher, S.M., C. Agnew-Brune, M. Anderson, L.D. Zambrano, C.E. Rose, M.A. Jim, A. Baugher, G.S. Liu, S.v. Patel, M.E. Evans, T. Pindyck, C.L. Dubray, J.J. Rainey, J. Chen, C. Sadowski, K. Winglee, A. Penman-Aguilar, A. Dixit, E. Claw, and J. McCollum, 2020: COVID-19 among American Indian and Alaska Native persons—23 states, January 31–July 3, 2020. *Morbidity and Mortality Weekly Report*, **69** (34). https://doi.org/10.15585/mmwr.mm6934e1

76. ASCE, 2017: The Economic Benefits of Investing in Water Infrastructure: How a Failure to Act Would Affect the US Economic Recovery. American Society of Civil Engineers. www.downstreamstrategies.com

77. Tanana, H., J. Combs, and A. Hoss, 2021: Water is life: Law, systemic racism, and water security in Indian Country. *Health Security*, **19** (1), 78–82. https://doi.org/10.1089/hs.2021.0034

78. Yang, Y.C.E., K. Son, F. Hung, and V. Tidwell, 2020: Impact of climate change on adaptive management decisions in the face of water scarcity. *Journal of Hydrology*, **588**, 125015. https://doi.org/10.1016/j.jhydrol.2020.125015

79. Sanders, B.F., J.E. Schubert, D.T. Kahl, K.J. Mach, D. Brady, A. AghaKouchak, F. Forman, R.A. Matthew, N. Ulibarri, and S.J. Davis, 2023: Large and inequitable flood risks in Los Angeles, California. *Nature Sustainability*, **6** (1), 47–57. https://doi.org/10.1038/s41893-022-00977-7

80. Schaider, L.A., L. Swetschinski, C. Campbell, and R.A. Rudel, 2019: Environmental justice and drinking water quality: Are there socioeconomic disparities in nitrate levels in U.S. drinking water? *Environmental Health*, **18** (1), 3. https://doi.org/10.1186/s12940-018-0442-6

81. Dobbin, K.B. and M. Lubell, 2021: Collaborative governance and environmental justice: Disadvantaged community representation in California sustainable groundwater management. *Policy Studies Journal*, **49** (2), 562–590. https://doi.org/10.1111/psj.12375

82. Conrad, E., T. Moran, M.E. DuPraw, D. Ceppos, J. Martinez, and W. Blomquist, 2018: Diverse stakeholders create collaborative, multilevel basin governance for groundwater sustainability. *California Agriculture*, **72** (1), 44–53. https://doi.org/10.3733/ca.2018a0002

83. Gilson, G.G. and D.E. Garrick, 2021: Can philanthropy enable collective action to conserve rivers? Insights from a decade of collaboration in the Colorado River Basin. *Conservation and Society*, **19** (3), 190–194. https://doi.org/10.4103/cs.cs_225_20

84. Garcia, M., E. Koebele, A. Deslatte, K. Ernst, K.F. Manago, and G. Treuer, 2019: Towards urban water sustainability: Analyzing management transitions in Miami, Las Vegas, and Los Angeles. *Global Environmental Change*, **58**, 101967. https://doi.org/10.1016/j.gloenvcha.2019.101967

85. Perry, M.D. and S.J. Praskievicz, 2017: A new era of big infrastructure? (Re)developing water storage in the U.S. West in the context of climate change and environmental regulation. *Water Alternatives*, **10** (2), 437–454. https://www.water-alternatives.org/index.php/alldoc/articles/vol10/v10issue2/363-a10-2-13/file

86. Quay, R., F. Sternlieb, E. Rauh, R. Andrade, A. Bartholomew, D. White, J. Holway, Z. Sugg, and E. Rugland, 2022: Evaluating the effectiveness of land and water integrative practices for achieving water sustainability within the Colorado River Basin: Perceptions and indicators. *Water International*, **47** (2), 257–277. https://doi.org/10.1080/02508060.2022.2041281

87. Sterle, K. and L. Singletary, 2017: Adapting to variable water supply in the Truckee-Carson River system, western USA. *Water*, **9** (10), 768. https://doi.org/10.3390/w9100768

88. White, D.D., E.K. Rauh, A. Sullivan, K.L. Larson, A. Wutich, D. Linthicum, V. Horvath, and K.L. Lawless, 2019: Public attitudes toward urban water sustainability transitions: A multi-city survey in the western United States. *Sustainability Science*, **14** (6), 1469–1483. https://doi.org/10.1007/s11625-019-00658-z

89. Obringer, R. and D.D. White, 2023: Leveraging unsupervised learning to develop a typology of residential water users' attitudes towards conservation. *Water Resources Management*, **37** (1), 37–53. https://doi.org/10.1007/s11269-022-03354-3

90. USBR, 2021: Reclamation Announces 2022 Operating Conditions for Lake Powell and Lake Mead. U.S. Bureau of Reclamation. https://www.usbr.gov/newsroom/news-release/3950

91. Black & Veatch, 2020: Binational Study of Water Desalination Opportunities in the Sea of Cortez. TM1: Water Supply Availability and Demand Analysis. Prepared for Minute 323 Desalination Work Group. B&V Project No. 400584. Black & Veatch. https://www.ibwc.gov/wp-content/uploads/2023/04/TMs_All_Portfolio.pdf

92. OCM, 2023: California. National Oceanic and Atmospheric Administration, National Ocean Service, Office for Coastal Management, accessed July 19, 2023. https://coast.noaa.gov/states/california.html

93. OCM, 2015: The National Significance of California's Ocean Economy. National Oceanic and Atmospheric Administration, National Ocean Service, Office for Coastal Management. https://coast.noaa.gov/digitalcoast/training/california-ocean-economy.html

94. CalEPA, 2018: Coastal Ocean Temperature: Ocean Waters Along California's Coast Are Warming. California Environmental Protection Agency, Office of Environmental Health Hazard Assessment, 2 pp. https://oehha.ca.gov/media/epic/downloads/15coastoceantemp_19dec2018.pdf

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

96. Pozo Buil, M., M.G. Jacox, J. Fiechter, M.A. Alexander, S.J. Bograd, E.N. Curchitser, C.A. Edwards, R.R. Rykaczewski, and C.A. Stock, 2021: A dynamically downscaled ensemble of future projections for the California Current System. *Frontiers in Marine Science*, **8**, 612874. https://doi.org/10.3389/fmars.2021.612874

97. Di Lorenzo, E. and N. Mantua, 2016: Multi-year persistence of the 2014/15 North Pacific marine heatwave. *Nature Climate Change*, **6**, 1042–1047. https://doi.org/10.1038/nclimate3082

98. Fumo, J.T., M.L. Carter, R.E. Flick, L.L. Rasmussen, D.L. Rudnick, and S.F. Iacobellis, 2020: Contextualizing marine heatwaves in the Southern California Bight under anthropogenic climate change. *Journal of Geophysical Research: Oceans*, **125** (5), e2019JC015674. https://doi.org/10.1029/2019jc015674

99. Oliver, E.C.J., M.G. Donat, M.T. Burrows, P.J. Moore, D.A. Smale, L.V. Alexander, J.A. Benthuysen, M. Feng, A. Sen Gupta, A.J. Hobday, N.J. Holbrook, S.E. Perkins-Kirkpatrick, H.A. Scannell, S.C. Straub, and T. Wernberg, 2018: Longer and more frequent marine heatwaves over the past century. *Nature Communications*, **9** (1), 1324. https://doi.org/10.1038/s41467-018-03732-9

100. Shi, H., M. García-Reyes, M.G. Jacox, R.R. Rykaczewski, B.A. Black, S.J. Bograd, and W.J. Sydeman, 2021: Co-occurrence of California drought and northeast Pacific marine heatwaves under climate change. *Geophysical Research Letters*, **48** (17), e2021GL092765. https://doi.org/10.1029/2021gl092765

101. Nielsen, J.M., L.A. Rogers, R.D. Brodeur, A.R. Thompson, T.D. Auth, A.L. Deary, J.T. Duffy-Anderson, M. Galbraith, J.A. Koslow, and R.I. Perry, 2021: Responses of ichthyoplankton assemblages to the recent marine heatwave and previous climate fluctuations in several Northeast Pacific marine ecosystems. *Global Change Biology*, **27** (3), 506–520. https://doi.org/10.1111/gcb.15415

102. Koenigstein, S., M.G. Jacox, M. Pozo Buil, J. Fiechter, B.A. Muhling, S. Brodie, P.T. Kuriyama, T.D. Auth, E.L. Hazen, S.J. Bograd, and D. Tommasi, 2022: Population projections of Pacific sardine driven by ocean warming and changing food availability in the California Current. *ICES Journal of Marine Science*, **79** (9), 2510–2523. https://doi.org/10.1093/icesjms/fsac191

103. von Biela, V.R., M.L. Arimitsu, J.F. Piatt, B. Heflin, S.K.T.J.L. Schoen, and C.M. Clawson, 2019: Extreme reduction in nutritional value of a key forage fish during the Pacific marine heatwave of 2014–2016. *Marine Ecology Progress Series*, **613**, 171–182. https://doi.org/10.3354/meps12891

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

105. Piatt, J.F., J.K. Parrish, H.M. Renner, S.K. Schoen, T.T. Jones, M.L. Arimitsu, K.J. Kuletz, B. Bodenstein, M. García-Reyes, R.S. Duerr, R.M. Corcoran, R.S.A. Kaler, G.J. McChesney, R.T. Golightly, H.A. Coletti, R.M. Suryan, H.K. Burgess, J. Lindsey, K. Lindquist, P.M. Warzybok, J. Jahncke, J. Roletto, and W.J. Sydeman, 2020: Extreme mortality and reproductive failure of common murres resulting from the northeast Pacific marine heatwave of 2014–2016. *PLoS ONE*, **15** (1), e0226087. https://doi.org/10.1371/journal.pone.0226087

106. Tolowa Dee-ni' Nation, InterTribal Sinkyone Wilderness Council, Cher-Ae Heights Indian Community of the Trinidad Rancheria, and Wiyot Tribe, 2017: Informing the North Coast MPA Baseline: Traditional Ecological Knowledge of Keystone Marine Species and Ecosystems. University of California, San Diego. https://caseagrant.ucsd.edu/sites/default/files/39-Rocha-Final.pdf

107. Cheung, W.W.L. and T.L. Frölicher, 2020: Marine heatwaves exacerbate climate change impacts for fisheries in the northeast Pacific. *Scientific Reports*, **10** (1), 6678. https://doi.org/10.1038/s41598-020-63650-z

108. Fisher, M.C., S.K. Moore, S.L. Jardine, J.R. Watson, and J.F. Samhouri, 2021: Climate shock effects and mediation in fisheries. *Proceedings of the National Academy of Sciences of the United States of America*, **118** (2), e2014379117. https://doi.org/10.1073/pnas.2014379117

109. Smith, J.A., M. Pozo Buil, B. Muhling, D. Tommasi, S. Brodie, T.H. Frawley, J. Fiechter, S. Koenigstein, A. Himes-Cornell, M.A. Alexander, S.J. Bograd, N. Cordero Quirós, L.B. Crowder, E. Curchitser, S.J. Green, N.A. Hardy, A.C. Haynie, E.L. Hazen, K. Holsman, G. Le Fol, N. Lezama-Ochoa, R.R. Rykaczewski, C.A. Stock, S. Stohs, J. Sweeney, H. Welch, and M.G. Jacox, 2023: Projecting climate change impacts from physics to fisheries: A view from three California Current fisheries. *Progress in Oceanography*, **211**, 102973. https://doi.org/10.1016/j.pocean.2023.102973

110. CalEPA, 2022: Indicators of Climate Change in California: Impacts on Tribes. California Environmental Protection Agency, Office of Environmental Health Hazard Assessment. https://oehha.ca.gov/media/tribalsection2022.pdf

111. Wei, X., K.-Y. Li, T. Kilpatrick, M. Wang, and S.-P. Xie, 2021: Large-scale conditions for the record-setting Southern California marine heatwave of August 2018. *Geophysical Research Letters*, **48** (7), e2020GL091803. https://doi.org/10.1029/2020gl091803

112. Chen, Z., J. Shi, Q. Liu, H. Chen, and C. Li, 2021: A persistent and intense marine heatwave in the Northeast Pacific during 2019–2020. *Geophysical Research Letters*, **48** (13), e2021GL093239. https://doi.org/10.1029/2021gl093239

113. McCabe, R.M., B.M. Hickey, R.M. Kudela, K.A. Lefebvre, N.G. Adams, B.D. Bill, F.M.D. Gulland, R.E. Thomson, W.P. Cochlan, and V.L. Trainer, 2016: An unprecedented coastwide toxic algal bloom linked to anomalous ocean conditions. *Geophysical Research Letters*, **43** (19), 10366–10376. https://doi.org/10.1002/2016gl070023

114. Holland, D.S. and J. Leonard, 2020: Is a delay a disaster? Economic impacts of the delay of the california Dungeness crab fishery due to a harmful algal bloom. *Harmful Algae*, **98**, 101904. https://doi.org/10.1016/j.hal.2020.101904

115. Samhouri, J.F., B.E. Feist, M.C. Fisher, O. Liu, S.M. Woodman, B. Abrahms, K.A. Forney, E.L. Hazen, D. Lawson, J. Redfern, and L.E. Saez, 2021: Marine heatwave challenges solutions to human-wildlife conflict. *Proceedings of the Royal Society B: Biological Sciences*, **288** (1964), 20211607. https://doi.org/10.1098/rspb.2021.1607

116. Santora, J.A., N.J. Mantua, I.D. Schroeder, J.C. Field, E.L. Hazen, S.J. Bograd, W.J. Sydeman, B.K. Wells, J. Calambokidis, L. Saez, D. Lawson, and K.A. Forney, 2020: Habitat compression and ecosystem shifts as potential links between marine heatwave and record whale entanglements. *Nature Communications*, **11** (1), 536. https://doi.org/10.1038/s41467-019-14215-w

117. Rogers-Bennett, L. and C.A. Catton, 2019: Marine heat wave and multiple stressors tip bull kelp forest to sea urchin barrens. *Scientific Reports*, **9** (1), 15050. https://doi.org/10.1038/s41598-019-51114-y

118. Rogers-Bennett, L., R. Klamt, and C.A. Catton, 2021: Survivors of climate driven abalone mass mortality exhibit declines in health and reproduction following kelp forest collapse. *Frontiers in Marine Science*, **8**, 725134. https://doi.org/10.3389/fmars.2021.725134

119. Jardine, S.L., M.C. Fisher, S.K. Moore, and J.F. Samhouri, 2020: Inequality in the economic impacts from climate shocks in fisheries: The case of harmful algal blooms. *Ecological Economics*, **176**, 106691. https://doi.org/10.1016/j.ecolecon.2020.106691

120. Freedman, R.M., J.A. Brown, C. Caldow, and J.E. Caselle, 2020: Marine protected areas do not prevent marine heatwave-induced fish community structure changes in a temperate transition zone. *Scientific Reports*, **10** (1), 21081. https://doi.org/10.1038/s41598-020-77885-3

121. Kawana, S.K., C.A. Catton, J.K.K. Hofmeister, C.I. Juhasz, I.K. Taniguchi, D.M. Stein, and L. Rogers-Bennett, 2019: Warm water shifts abalone recruitment and sea urchin diversity in Southern California: Implications for climate-ready abalone restoration planning. *Journal of Shellfish Research*, **38** (2), 475–484. https://doi.org/10.2983/035.038.0231

122. Munsch, S.H., C.M. Greene, N.J. Mantua, and W.H. Satterthwaite, 2022: One hundred-seventy years of stressors erode salmon fishery climate resilience in California's warming landscape. *Global Change Biology*, **28** (7), 2183–2201. https://doi.org/10.1111/gcb.16029

123. Holsman, K.K., A.C. Haynie, A.B. Hollowed, J.C.P. Reum, K. Aydin, A.J. Hermann, W. Cheng, A. Faig, J.N. Ianelli, K.A. Kearney, and A.E. Punt, 2020: Ecosystem-based fisheries management forestalls climate-driven collapse. *Nature Communications*, **11** (1), 4579. https://doi.org/10.1038/s41467-020-18300-3

124. Ekstrom, J.A., S.K. Moore, and T. Klinger, 2020: Examining harmful algal blooms through a disaster risk management lens: A case study of the 2015 U.S. West Coast domoic acid event. *Harmful Algae*, **94**, 101740. https://doi.org/10.1016/j.hal.2020.101740

125. Hartog, J.R., C.M. Spillman, G. Smith, and A.J. Hobday, 2023: Forecasts of marine heatwaves for marine industries: Reducing risk, building resilience and enhancing management responses. *Deep Sea Research Part II: Topical Studies in Oceanography*, **209**, 105276. https://doi.org/10.1016/j.dsr2.2023.105276

126. Fiechter, J., M. Pozo Buil, M.G. Jacox, M.A. Alexander, and K.A. Rose, 2021: Projected shifts in 21st century sardine distribution and catch in the California Current. *Frontiers in Marine Science*, **8**, 685241. https://doi.org/10.3389/fmars.2021.685241

127. Clements, J.C. and T. Chopin, 2017: Ocean acidification and marine aquaculture in North America: Potential impacts and mitigation strategies. *Reviews in Aquaculture*, **9** (4), 326–341. https://doi.org/10.1111/raq.12140

128. Klinger, T., E.A. Chornesky, E.A. Whiteman, F. Chan, J.L. Largier, and W.W. Wakefield, 2017: Using integrated, ecosystem-level management to address intensifying ocean acidification and hypoxia in the California Current large marine ecosystem. *Elementa: Science of the Anthropocene*, **5**, 16. https://doi.org/10.1525/elementa.198

129. Beheshti, K.M., S.L. Williams, K.E. Boyer, C. Endris, A. Clemons, T. Grimes, K. Wasson, and B.B. Hughes, 2022: Rapid enhancement of multiple ecosystem services following the restoration of a coastal foundation species. *Ecological Applications*, **32** (1), e02466. https://doi.org/10.1002/eap.2466

130. Hirsh, H.K., K.J. Nickols, Y. Takeshita, S.B. Traiger, D.A. Mucciarone, S. Monismith, and R.B. Dunbar, 2020: Drivers of biogeochemical variability in a central California kelp forest: Implications for local amelioration of ocean acidification. *Journal of Geophysical Research: Oceans*, **125** (11), e2020JC016320. https://doi.org/10.1029/2020jc016320

131. Chavez, F.P., C. Costello, D. Aseltine-Neilson, H. Doremus, J.C. Field, S.D. Gaines, M. Hall-Arber, N.J. Mantua, B. McCovey, C. Pomeroy, L. Sievanen, W. Sydeman, and S.A. Wheeler, 2017: Readying California Fisheries for Climate Change. California Ocean Science Trust, Oakland, CA. https://www.oceansciencetrust.org/wp-content/uploads/2016/06/Climate-and-Fisheries_GuidanceDoc.pdf

132. Alleway, H.K., C.L. Gillies, M.J. Bishop, R.R. Gentry, S.J. Theuerkauf, and R. Jones, 2019: The ecosystem services of marine aquaculture: Valuing benefits to people and nature. *BioScience*, **69** (1), 59–68. https://doi.org/10.1093/biosci/biy137

133. Froehlich, H.E., J.C. Afflerbach, M. Frazier, and B.S. Halpern, 2019: Blue growth potential to mitigate climate change through seaweed offsetting. *Current Biology*, **29** (18), 3087–3093. https://doi.org/10.1016/j.cub.2019.07.041

134. Froehlich, H.E., R.R. Gentry, and B.S. Halpern, 2017: Conservation aquaculture: Shifting the narrative and paradigm of aquaculture's role in resource management. *Biological Conservation*, **215**, 162–168. https://doi.org/10.1016/j.biocon.2017.09.012

135. Theuerkauf, S.J., B.J. Puckett, and D.B. Eggleston, 2021: Metapopulation dynamics of oysters: Sources, sinks, and implications for conservation and restoration. *Ecosphere*, **12** (7), e03573. https://doi.org/10.1002/ecs2.3573

136. Kübler, J.E., S.R. Dudgeon, and D. Bush, 2021: Climate change challenges and opportunities for seaweed aquaculture in California, the United States. *Journal of the World Aquaculture Society*, **52** (5), 1069–1080. https://doi.org/10.1111/jwas.12794

137. Titus, J.G., 2023: Population in floodplains or close to sea level increased in US but declined in some counties—Especially among black residents. *Environmental Research Letters*, **18** (3), 034001. https://doi.org/10.1088/1748-9326/acadf5

138. Befus, K.M., P.L. Barnard, D.J. Hoover, J.A. Finzi Hart, and C.I. Voss, 2020: Increasing threat of coastal groundwater hazards from sea-level rise in California. *Nature Climate Change*, **10** (10), 946–952. https://doi.org/10.1038/s41558-020-0874-1

139. Bruzgul, J., R. Kay, A. Petrow, T. Hendrickson, B. Rodehorst, D. Revell, M. Bruguera, D. Moreno, and K. Collison, 2018: Rising Seas and Electricity Infrastructure: Potential Impacts and Adaptation Actions for San Diego Gas & Electric. California's Fourth Climate Change Assessment. Publication Number: CCCA4-CEC-2018-004. California Energy Commission. https://www.energy.ca.gov/sites/default/files/2019-11/energy_ccca4-cec-2018-004_ada.pdf

140. Buchanan, M.K., S. Kulp, L. Cushing, R. Morello-Frosch, T. Nedwick, and B. Strauss, 2020: Sea level rise and coastal flooding threaten affordable housing. *Environmental Research Letters*, **15** (12), 124020. https://doi.org/10.1088/1748-9326/abb266

141. Hoover, D.J., K.O. Odigie, P.W. Swarzenski, and P. Barnard, 2017: Sea-level rise and coastal groundwater inundation and shoaling at select sites in California, USA. *Journal of Hydrology: Regional Studies*, **11**, 234–249. https://doi.org/10.1016/j.ejrh.2015.12.055

142. Nicholls, R.J., D. Lincke, J. Hinkel, S. Brown, A.T. Vafeidis, B. Meyssignac, S.E. Hanson, J.-L. Merkens, and J. Fang, 2021: A global analysis of subsidence, relative sea-level change and coastal flood exposure. *Nature Climate Change*, **11** (4), 338–342. https://doi.org/10.1038/s41558-021-00993-z

143. Radke, J.D., G.S. Biging, K. Roberts, M. Schmidt-Poolman, H. Foster, E. Roe, Y. Ju, S. Lindbergh, T. Beach, L. Maier, Y. He, M. Ashenfarb, P. Norton, M. Wray, A. Alruheili, S. Yi, R. Rau, J. Collins, D. Radke, M. Coufal, S. Marx, A. Gohar, D. Moanga, V. Ulyashin, and A. Dalal, 2018: Assessing Extreme Weather-Related Vulnerability and Identifying Resilience Options for California's Interdependent Transportation Fuel Sector. California's Fourth Climate Change Assessment. Publication Number: CCCA4-CEC-2018-012. California Energy Commission. https://www.energy.ca.gov/sites/default/files/2019-11/energy_ccca4-cec-2018-012_ada.pdf

144. Caltrans, 2022: Sea Level Rise and the Transportation System in the Coastal Zone. California Department of Transportation. https://dot.ca.gov/programs/environmental-analysis/coastal-program/coastal-act-policy-resource-information/coastal-hazards/sea-level-rise

145. Martinich, J., J. Neumann, L. Ludwig, and L. Jantarasami, 2013: Risks of sea level rise to disadvantaged communities in the United States. *Mitigation and Adaptation Strategies for Global Change*, **18** (2), 169–185. https://doi.org/10.1007/s11027-011-9356-0

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

147. Tebaldi, C., B.H. Strauss, and C.E. Zervas, 2012: Modelling sea level rise impacts on storm surges along US coasts. *Environmental Research Letters*, **7** (1), 014032. https://doi.org/10.1088/1748-9326/7/1/014032

148. Morello-Frosch, R., 2020: Toxic Tides: Sea Level Rise, Hazardous Sites, and Environmental Justice in California. University of California, Berkeley. https://sites.google.com/berkeley.edu/toxictides/home

149. OEHHA, 2021: CalEnviroScreen 4.0. California Office of Environmental Health Hazard Assessment. https://oehha.ca.gov/calenviroscreen/report/calenviroscreen-40

150. Keenan, J.M., T. Hill, and A. Gumber, 2018: Climate gentrification: From theory to empiricism in Miami-Dade County, Florida. *Environmental Research Letters*, **13** (5), 054001. https://doi.org/10.1088/1748-9326/aabb32

151. Blackwell, E., M. Shirzaei, C. Ojha, and S. Werth, 2020: Tracking California's sinking coast from space: Implications for relative sea-level rise. *Science Advances*, **6** (31), 4551. https://doi.org/10.1126/sciadv.aba4551

152. Fu, X., 2020: Measuring local sea-level rise adaptation and adaptive capacity: A national survey in the United States. *Cities*, **102**, 102717. https://doi.org/10.1016/j.cities.2020.102717

153. Moser, S.C., J.A. Finzi Hart, A.G. Newton Mann, N. Sadrpour, and P.M. Grifman, 2018: Growing Effort, Growing Challenge: Findings from the 2016 CA Coastal Adaptation Needs Assessment Survey. California's Fourth Climate Change Assessment. CCCA4-EXT-2018-009. California Natural Resources Agency. https://www.energy.ca.gov/sites/default/files/2019-12/Oceans_CCCA4-EXT-2018-009_ada.pdf

154. An Act to Amend Section 65302 of the Government Code, Relating to Land Use. Senate Bill No. 379, Chapter 608, State of California, October 8, 2015. https://leginfo.legislature.ca.gov/faces/billTextClient.xhtml?bill_id=201520160SB379

155. CAL OES, 2020: California Adaptation Planning Guide. California Governor's Office of Emergency Services, Mather, CA. https://www.caloes.ca.gov/ca-adaptation-planning-guide-final-june-2020-accessible/

156. State of California, 2015: Executive Order B-30-15: Governor Brown Establishes Most Ambitious Greenhouse Gas Reduction Target in North America. State of California, Office of the Governor, Sacramento, CA. https://www.ca.gov/archive/gov39/2015/04/29/news18938/index.html

157. State of California, 2019: Executive Order N-19-19: To Require the Redoubling of the State's "Efforts to Reduce Greenhouse Gas Emissions and Mitigate the Impacts of Climate Change While Building a Sustainable, Inclusive Economy". State of California, Office of the Governor. https://www.adaptationclearinghouse.org/resources/state-of-california-executive-order-n-19-19.html

158. California Coastal Commission, 2021: Critical Infrastructure at Risk: Sea Level Rise Planning Guidance for California's Coastal Zone. California Coastal Commission, San Francisco, CA. https://www.coastal.ca.gov/climate/slr/vulnerability-adaptation/infrastructure/

159. California Ocean Protection Council, 2018: State of California Sea-Level Rise Guidance 2018 Update. State of California, 84 pp. https://www.adaptationclearinghouse.org/resources/california-sea-level-rise-guidance-2018-update.html

160. Governor's Office of Planning and Research, 2022: The ResilientCA Adaptation Planning Map (RAP-Map). State of California, Governor's Office of Planning and Research. https://resilientca.org/rap-map/

161. Moser, S.C., J.A. Ekstrom, J. Kim, and S. Heitsch, 2018: Adaptation Finance Challenges: Characteristic Patterns Facing California Local Governments and Ways to Overcome Them. California's Fourth Climate Change Assessment. Publication Number: CCCA4-CNRA2018-007. California Natural Resources Agency. https://www.energy.ca.gov/sites/default/files/2019-12/governance_ccca4-cnra-2018-007_ada.pdf

162. Matthews, S.N., L.R. Iverson, M.P. Peters, and A.M. Prasad, 2018: Assessing Potential Climate Change Pressures Across the Conterminous United States: Mapping Plant Hardiness Zones, Heat Zones, Growing Degree Days, and Cumulative Drought Severity Throughout This Century. RMAP-NRS-9. U.S. Department of Agriculture, Forest Service, Northern Research Station, Newtown Square, PA, 31 pp. https://doi.org/10.2737/nrs-rmap-9

163. Marklein, A., E. Elias, P. Nico, and K. Steenwerth, 2020: Projected temperature increases may require shifts in the growing season of cool-season crops and the growing locations of warm-season crops. *Science of The Total Environment*, **746**, 140918. https://doi.org/10.1016/j.scitotenv.2020.140918

164. Jin, Y., B. Chen, B.D. Lampinen, and P.H. Brown, 2020: Advancing agricultural production with machine learning analytics: Yield determinants for California's almond orchards. *Frontiers in Plant Science*, **11**, 290. https://doi.org/10.3389/fpls.2020.00290

165. Parker, L.E., N. Zhang, J.T. Abatzoglou, S.M. Ostoja, and T.B. Pathak, 2022: Observed changes in agroclimate metrics relevant for specialty crop production in California. *Agronomy*, **12** (1), 205. https://doi.org/10.3390/agronomy12010205

166. Kral-O'Brien, K.C., P.L. O'Brien, and J.P. Harmon, 2019: Need for false spring research in the northern Great Plains, USA. *Agricultural & Environmental Letters*, **4** (1), 190025. https://doi.org/10.2134/ael2019.07.0025

167. Guirguis, K., A. Gershunov, D.R. Cayan, and D.W. Pierce, 2018: Heat wave probability in the changing climate of the Southwest US. *Climate Dynamics*, **50** (9–10), 3853–3864. https://doi.org/10.1007/s00382-017-3850-3

168. Ayankojo, I.T., K.R. Thorp, K. Morgan, K. Kothari, and S. Ale, 2020: Assessing the impacts of future climate on cotton production in the Arizona low desert. *Transactions of the* ASABE, **63** (4), 1087–1098. https://doi.org/10.13031/trans.13731

169. Pathak, T.B., M.L. Maskey, J.A. Dahlberg, F. Kearns, K.M. Bali, and D. Zaccaria, 2018: Climate change trends and impacts on California agriculture: A detailed review. *Agronomy*, **8** (3), 25. https://doi.org/10.3390/agronomy8030025

170. Conrad, L.M., A.G. Fernald, S.J. Guldan, and C.G. Ochoa, 2022: A water balancing act: Water balances highlight the benefits of community-based adaptive management in northern New Mexico, USA. *Hydrology*, **9** (4), 64. https://doi.org/10.3390/hydrology9040064

171. Duniway, M.C., A.A. Pfennigwerth, S.E. Fick, T.W. Nauman, J. Belnap, and N.N. Barger, 2019: Wind erosion and dust from US drylands: A review of causes, consequences, and solutions in a changing world. *Ecosphere*, **10** (3), e02650. https://doi.org/10.1002/ecs2.2650

172. Finger-Higgens, R., M.C. Duniway, S. Fick, E.L. Geiger, D.L. Hoover, A.A. Pfennigwerth, M.W. Van Scoyoc, and J. Belnap, 2022: Decline in biological soil crust N-fixing lichens linked to increasing summertime temperatures. *Proceedings of the National Academy of Sciences of the United States of America*, **119** (16), e2120975119. https://doi.org/10.1073/pnas.2120975119

173. Fassnacht, S.R., C.R. Duncan, A.K.D. Pfohl, R.W. Webb, J.E. Derry, W.E. Sanford, D.C. Reimanis, and L.G. Doskocil, 2022: Drivers of dust-enhanced snowpack melt-out and streamflow timing. *Hydrology*, **9** (3), 47. https://doi.org/10.3390/hydrology9030047

174. ERS, 2020: Ag and Food Statistics: Charting the Essentials. U.S. Department of Agriculture, Economic Research Service. https://www.ers.usda.gov/data-products/ag-and-food-statistics-charting-the-essentials/

175. CDFA, 2022: California Agricultural Production Statistics. California Department of Food and Agriculture. https://www.cdfa.ca.gov/statistics/

176. NASS, 2022: Data and Statistics, October 2022. U.S. Department of Agriculture, National Agricultural Statistics Service. https://www.nass.usda.gov/data_and_statistics/index.php

177. Parajuli, R., G. Thoma, and M.D. Matlock, 2019: Environmental sustainability of fruit and vegetable production supply chains in the face of climate change: A review. *Science of The Total Environment*, **650**, 2863–2879. https://doi.org/10.1016/j.scitotenv.2018.10.019

178. Davis, K.F., S. Downs, and J.A. Gephart, 2021: Towards food supply chain resilience to environmental shocks. *Nature Food*, **2** (1), 54–65. https://doi.org/10.1038/s43016-020-00196-3

179. Medellín-Azuara, J., A. Escriva-Bou, J.A. Abatzoglou, J.H. Viers, S.A. Cole, J.M. Rodríguez-Flores, and D.A. Sumner, 2022: Economic Impacts of the 2021 Drought on California Agriculture: Preliminary Report. University of California, Merced. https://wsm.ucmerced.edu/wp-content/uploads/2022/02/2021-Drought-Impact-Assessment_20210224.pdf

180. Monteverde, C. and F. De Sales, 2020: Impacts of global warming on southern California's winegrape climate suitability. *Advances in Climate Change Research*, **11** (3), 279–293. https://doi.org/10.1016/j.accre.2020.08.002

181. Parker, L.E., A.J. McElrone, S.M. Ostoja, and E.J. Forrestel, 2020: Extreme heat effects on perennial crops and strategies for sustaining future production. *Plant Science*, **295**, 110397. https://doi.org/10.1016/j.plantsci.2019.110397

182. Hanak, E., A. Escriva-Bou, B. Gray, S. Green, T. Harter, J. Jezdimirovic, J. Lund, J. Medellín-Azuara, P. Moyle, and N. Seavy, 2019: Water and the Future of the San Joaquin Valley. Public Policy Institute of California, 100 pp. https://www.ppic.org/publication/water-and-the-future-of-the-san-joaquin-valley/

183. Morris, J.L., S. Cottrell, C.J. Fettig, R.J. DeRose, K.M. Mattor, V.A. Carter, J. Clear, J. Clement, W.D. Hansen, J.A. Hicke, P.E. Higuera, A.W. Seddon, H. Seppä, R.L. Sherriff, J.D. Stednick, and S.J. Seybold, 2018: Bark beetles as agents of change in social–ecological systems. *Frontiers in Ecology and the Environment*, **16** (S1), S34–S43. https://doi.org/10.1002/fee.1754

184. Standiford, R., S.L. Evans, and J. Henderson, 2020: Economic Contribution of California's Forestry and Forest-Products Sectors. Publication Number: 8670. University of California, Agriculture and Natural Resources, 17 pp. https://anrcatalog.ucanr.edu/details.aspx?itemno=8670

185. Ortiz-Bobea, A., E. Knippenberg, and R.G. Chambers, 2018: Growing climatic sensitivity of U.S. agriculture linked to technological change and regional specialization. *Science Advances*, **4** (12), 4343. https://doi.org/10.1126/sciadv.aat4343

186. Bae, J. and S. Dall'erba, 2018: Crop production, export of virtual water and water-saving strategies in Arizona. *Ecological Economics*, **146**, 148–156. https://doi.org/10.1016/j.ecolecon.2017.10.018

187. York, A.M., H. Eakin, J.C. Bausch, S. Smith-Heisters, J.M. Anderies, R. Aggarwal, B. Leonard, and K. Wright, 2020: Agricultural water governance in the desert: Shifting risks in central Arizona. *Water Alternatives*, **13** (2), 418–445. https://www.water-alternatives.org/index.php/alldoc/articles/vol13/v13issue2/582-a13-2-11/file

188. Abbott, B.W., B.K. Baxter, K. Busche, L.d. Freitas, R. Frei, T. Gomez, M.A. Karren, R.L. Buck, J. Price, S. Frutos, R.B. Sowby, J. Brahney, B.G. Hopkins, M.F. Bekker, J.S. Bekker, R. Rader, B. Brown, M. Proteau, G.T. Carling, L. Conner, P.A. Cox, E. McQuhae, C. Oscarson, D.T. Nelson, R.J. Davis, D. Horns, H. Dove, T. Bishop, A. Johnson, K. Nelson, J. Bennion, and P. Belmont, 2023: Emergency Measures Needed to Rescue Great Salt Lake from Ongoing Collapse. Brigham Young University, College of Life Sciences, Plant and Wildlife Sciences, 34 pp. https://pws.byu.edu/great-salt-lake

189. Reyes, J.J. and E. Elias, 2019: Spatio-temporal variation of crop loss in the United States from 2001 to 2016. *Environmental Research Letters*, **14** (7), 074017. https://doi.org/10.1088/1748-9326/ab1ac9

190. Johnson, K.M. and D.T. Lichter, 2019: Rural depopulation: Growth and decline processes over the past century. *Rural Sociology*, **84** (1), 3–27. https://doi.org/10.1111/ruso.12266

191. Lichter, D.T., D.L. Brown, and D. Parisi, 2021: The rural–urban interface: Rural and small town growth at the metropolitan fringe. *Population, Space and Place*, **27** (3), e2415. https://doi.org/10.1002/psp.2415

192. Ahmed, S. and D. Jackson-Smith, 2019: Impacts of spatial patterns of rural and exurban residential development on agricultural trends in the Intermountain West. *SAGE Open*, **9** (3). https://doi.org/10.1177/2158244019871037

193. Park, S. and S. Deller, 2021: Effect of farm structure on rural community well-being. *Journal of Rural Studies*, **87**, 300–313. https://doi.org/10.1016/j.jrurstud.2021.09.014

194. Stahle, D.W., 2020: Anthropogenic megadrought. *Science*, **368** (6488), 238–239. https://doi.org/10.1126/science.abb6902

195. Havstad, K.M., J.R. Brown, R. Estell, E. Elias, A. Rango, and C. Steele, 2018: Vulnerabilities of southwestern U.S. rangeland-based animal agriculture to climate change. *Climatic Change*, **148** (3), 371–386. https://doi.org/10.1007/s10584-016-1834-7

196. Holechek, J.L., H.M.E. Geli, A.F. Cibils, and M.N. Sawalhah, 2020: Climate change, rangelands, and sustainability of ranching in the western United States. *Sustainability*, **12** (12), 4942. https://doi.org/10.3390/su12124942

197. Brice, E.M., B.A. Miller, H. Zhang, K. Goldstein, S.N. Zimmer, G.J. Grosklos, P. Belmont, C.G. Flint, J.E. Givens, P.B. Adler, M.W. Brunson, and J.W. Smith, 2020: Impacts of climate change on multiple use management of Bureau of Land Management land in the Intermountain West, USA. *Ecosphere*, **11** (11), e03286. https://doi.org/10.1002/ecs2.3286

198. Godde, C.M., D. Mason-D'Croz, D.E. Mayberry, P.K. Thornton, and M. Herrero, 2021: Impacts of climate change on the livestock food supply chain; a review of the evidence. *Global Food Security*, **28**, 100488. https://doi.org/10.1016/j.gfs.2020.100488

199. Dinan, M., P.B. Adler, J. Bradford, M. Brunson, E. Elias, A. Felton, C. Greene, J. James, K. Suding, and E. Thacker, 2021: Making research relevant: Sharing climate change research with rangeland advisors to transform results into drought resilience. *Rangelands*, **43** (5), 185–193. https://doi.org/10.1016/j.rala.2021.08.004

200. Flörke, M., C. Schneider, and R.I. McDonald, 2018: Water competition between cities and agriculture driven by climate change and urban growth. *Nature Sustainability*, **1** (1), 51–58. https://doi.org/10.1038/s41893-017-0006-8

201. Bray, L.A., 2022: Water justice across the rural-urban interface: The making of hydrosocial territories in New Mexico's Rio Grande Valley. *Society & Natural Resources*, **35** (3), 320–337. https://doi.org/10.1080/08941920.2022.2032893

202. Dilling, L., J. Berggren, J. Henderson, and D. Kenney, 2019: Savior of rural landscapes or Solomon's choice? Colorado's experiment with alternative transfer methods for water (ATMs). *Water Security*, **6**, 100027. https://doi.org/10.1016/j.wasec.2019.100027

203. Fulton, J., M. Norton, and F. Shilling, 2019: Water-indexed benefits and impacts of California almonds. *Ecological Indicators*, **96**, 711–717. https://doi.org/10.1016/j.ecolind.2017.12.063

204. Reisman, E., 2019: The great almond debate: A subtle double movement in California water. *Geoforum*, **104**, 137–146. https://doi.org/10.1016/j.geoforum.2019.04.021

205. Morgan, B., K. Spangler, J. Stuivenvolt Allen, C.N. Morrisett, M.W. Brunson, S.-Y.S. Wang, and N. Huntly, 2021: Water availability for cannabis in Northern California: Intersections of climate, policy, and public discourse. *Water*, **13** (1), 5. https://doi.org/10.3390/w13010005

206. Carney, M.A. and K.C. Krause, 2020: Immigration/migration and healthy publics: The threat of food insecurity. *Palgrave Communications*, **6** (1), 93. https://doi.org/10.1057/s41599-020-0461-0

207. Glazebrook, T., S. Noll, and E. Opoku, 2020: Gender matters: Climate change, gender bias, and women's farming in the global South and North. *Agriculture*, **10** (7), 267. https://doi.org/10.3390/agriculture10070267

208. Greene, C., 2018: Broadening understandings of drought—The climate vulnerability of farmworkers and rural communities in California (USA). *Environmental Science & Policy*, **89**, 283–291. https://doi.org/10.1016/j.envsci.2018.08.002

209. Howard, M., S. Ahmed, P. Lachapelle, and M.B. Schure, 2020: Farmer and rancher perceptions of climate change and their relationships with mental health. *Journal of Rural Mental Health*, **44** (2), 87–95. https://doi.org/10.1037/rmh0000131

210. Munden-Dixon, K., K. Tate, B. Cutts, and L. Roche, 2019: An uncertain future: Climate resilience of first-generation ranchers. *The Rangeland Journal*, **41**, 189–196. https://doi.org/10.1071/rj18023

211. Siegner, A., J. Sowerwine, and C. Acey, 2018: Does urban agriculture improve food security? Examining the nexus of food access and distribution of urban produced foods in the United States: A systematic review. *Sustainability*, **10** (9), 2988. https://doi.org/10.3390/su10092988

212. Adger, W.N., J. Barnett, K. Brown, N. Marshall, and K. O'Brien, 2013: Cultural dimensions of climate change impacts and adaptation. *Nature Climate Change*, **3** (2), 112–117. https://doi.org/10.1038/nclimate1666

213. Hepler, M. and E.A. Kronk Warner, 2019: Learning from tribal innovations: Lessons in climate change adaptation. *Environmental Law Reporter*, **49** (11130). https://doi.org/10.2139/ssrn.3444403

214. Nabhan, G.P., E.C. Riordan, L. Monti, A.M. Rea, B.T. Wilder, E. Ezcurra, J.B. Mabry, J. Aronson, G.A. Barron-Gafford, J.M. García, A. Búrquez, T.E. Crews, P. Mirocha, and W.C. Hodgson, 2020: An Aridamerican model for agriculture in a hotter, water scarce world. *Plants, People, Planet*, **2** (6), 627–639. https://doi.org/10.1002/ppp3.10129

215. Sowerwine, J., D. Sarna-Wojcicki, M. Mucioki, L. Hillman, F. Lake, and E. Friedman, 2019: Enhancing food sovereignty: A five-year collaborative Tribal-University research and extension project in California and Oregon. *Journal of Agriculture, Food Systems, and Community Development*, **9** (B), 167–190. https://doi.org/10.5304/jafscd.2019.09b.013

216. Gosnell, H., S. Charnley, and P. Stanley, 2020: Climate change mitigation as a co-benefit of regenerative ranching: Insights from Australia and the United States. *Interface Focus*, **10** (5), 20200027. https://doi.org/10.1098/rsfs.2020.0027

217. Shrum, T.R., W.R. Travis, T.M. Williams, and E. Lih, 2018: Managing climate risks on the ranch with limited drought information. *Climate Risk Management*, **20**, 11–26. https://doi.org/10.1016/j.crm.2018.01.002

218. Mitchell, J.P., D.C. Reicosky, E.A. Kueneman, J. Fisher, and D. Beck, 2019: Conservation agriculture systems. *CABI Reviews*, **2019**, 1–25. https://doi.org/10.1079/pavsnnr201914001

219. Mpanga, I.K., G. Neumann, U.K. Schuch, and J. Schalau, 2020: Sustainable agriculture practices as a driver for increased harvested cropland among large-scale growers in Arizona: A paradox for small-scale growers. *Advanced Sustainable Systems*, **4** (4), 1900143. https://doi.org/10.1002/adsu.201900143

220. Kelly, C., S.J. Fonte, A. Shrestha, K.M. Daane, and J.P. Mitchell, 2021: Winter cover crops and no-till promote soil macrofauna communities in irrigated, Mediterranean cropland in California, USA. *Applied Soil Ecology*, **166**, 104068. https://doi.org/10.1016/j.apsoil.2021.104068

221. Paye, W.S., R. Ghimire, P. Acharya, A. Nilahyane, A.O. Mesbah, and M.A. Marsalis, 2022: Cover crop water use and corn silage production in semi-arid irrigated conditions. *Agricultural Water Management*, **260**, 107275. https://doi.org/10.1016/j.agwat.2021.107275

222. Thapa, V.R., R. Ghimire, D. VanLeeuwen, V. Acosta-Martínez, and M. Shukla, 2022: Response of soil organic matter to cover cropping in water-limited environments. *Geoderma*, **406**, 115497. https://doi.org/10.1016/j.geoderma.2021.115497

223. Babin, N., C. Klier, and A. Singh, 2022: Understanding and promoting adoption of irrigation efficiency practices in Paso Robles, California vineyards: The importance of farm typology and grower sustainability networks. *Current Research in Environmental Sustainability*, **4**, 100143. https://doi.org/10.1016/j.crsust.2022.100143

224. Douglass-Gallagher, E. and D. Stuart, 2019: Crop growers' adaptive capacity to climate change: A situated study of agriculture in Arizona's Verde Valley. *Environmental Management*, **63** (1), 94–109. https://doi.org/10.1007/s00267-018-1114-6

225. Johnson, M.K., A.M. Lien, N.R. Sherman, and L. López-Hoffman, 2018: Barriers to PES programs in Indigenous communities: A lesson in land tenure insecurity from the Hopi Indian reservation. *Ecosystem Services*, **32**, 62–69. https://doi.org/10.1016/j.ecoser.2018.05.009

226. Johnson, M.K., M.J. Rowe, A. Lien, and L. López-Hoffman, 2021: Enhancing integration of indigenous agricultural knowledge into USDA Natural Resources Conservation Service cost-share initiatives. *Journal of Soil and Water Conservation*, **76** (6), 487. https://doi.org/10.2489/jswc.2021.00179

227. MCDPH, 2021: Heat Reports. Maricopa County Department of Public Health, accessed August 15, 2022. https://www.maricopa.gov/1858/heat-surveillance

228. Putnam, H., D.M. Hondula, A. Urban, V. Berisha, P. Iñiguez, and M. Roach, 2018: It's not the heat, it's the vulnerability: Attribution of the 2016 spike in heat-associated deaths in Maricopa County, Arizona. *Environmental Research Letters*, **13** (9), 094022. https://doi.org/10.1088/1748-9326/aadb44

229. Schwarz, L., E.M. Castillo, T.C. Chan, J.J. Brennan, E.S. Sbiroli, G. Carrasco-Escobar, A. Nguyen, R.E.S. Clemesha, A. Gershunov, and T. Benmarhnia, 2022: Heat waves and emergency department visits among the homeless, San Diego, 2012–2019. *American Journal of Public Health*, **112** (1), 98–106. https://doi.org/10.2105/ajph.2021.306557

230. López-Carr, D., J. Vanos, A. Sánchez-Vargas, R. Vargas, and F. Castillo, 2022: Extreme heat and COVID-19: A dual burden for farmworkers. *Frontiers in Public Health*, **10**, 884152. https://doi.org/10.3389/fpubh.2022.884152

231. Méndez, M., G. Flores-Haro, and L. Zucker, 2020: The (in)visible victims of disaster: Understanding the vulnerability of undocumented Latino/a and Indigenous immigrants. *Geoforum*, **116**, 50–62. https://doi.org/10.1016/j.geoforum.2020.07.007

232. Mitchell, D.C., J. Castro, T.L. Armitage, A.J. Vega-Arroyo, S.C. Moyce, D.J. Tancredi, D.H. Bennett, J.H. Jones, T. Kjellstrom, and M.B. Schenker, 2017: Recruitment, methods, and descriptive results of a physiologic assessment of Latino farmworkers: The California heat illness prevention study. *Journal of Occupational and Environmental Medicine*, **59** (7). https://doi.org/10.1097/jom.0000000000000988

233. Taylor, E.V., A. Vaidyanathan, W.D. Flanders, M. Murphy, M. Spencer, and R.S. Noe, 2018: Differences in heat-related mortality by citizenship status: United States, 2005–2014. *American Journal of Public Health*, **108** (S2), S131–S136. https://doi.org/10.2105/ajph.2017.304006

234. Guardaro, M., D.M. Hondula, J. Ortiz, and C.L. Redman, 2022: Adaptive capacity to extreme urban heat: The dynamics of differing narratives. *Climate Risk Management*, **35**, 100415. https://doi.org/10.1016/j.crm.2022.100415

235. Jay, O., A. Capon, P. Berry, C. Broderick, R. de Dear, G. Havenith, Y. Honda, R.S. Kovats, W. Ma, A. Malik, N.B. Morris, L. Nybo, S.I. Seneviratne, J. Vanos, and K.L. Ebi, 2021: Reducing the health effects of hot weather and heat extremes: From personal cooling strategies to green cities. *The Lancet*, **398** (10301), 709–724. https://doi.org/10.1016/s0140-6736(21)01209-5

236. CDC, 2022: National Environmental Public Health Tracking Network. Centers for Disease Control and Prevention, accessed August 20, 2022. https://ephtracking.cdc.gov/dataexplorer/

237. Avalos, L.A., H. Chen, D.-K. Li, and R. Basu, 2017: The impact of high apparent temperature on spontaneous preterm delivery: A case-crossover study. *Environmental Health*, **16** (1), 5. https://doi.org/10.1186/s12940-017-0209-5

238. Barreca, A. and J. Schaller, 2020: The impact of high ambient temperatures on delivery timing and gestational lengths. *Nature Climate Change*, **10** (1), 77–82. https://doi.org/10.1038/s41558-019-0632-4

239. Ilango, S.D., M. Weaver, P. Sheridan, L. Schwarz, R.E.S. Clemesha, T. Bruckner, R. Basu, A. Gershunov, and T. Benmarhnia, 2020: Extreme heat episodes and risk of preterm birth in California, 2005–2013. *Environment International*, **137**, 105541. https://doi.org/10.1016/j.envint.2020.105541

240. Lu, C., Y. Zhang, B. Li, Z. Zhao, C. Huang, X. Zhang, H. Qian, J. Wang, W. Liu, Y. Sun, D. Norbäck, and Q. Deng, 2022: Interaction effect of prenatal and postnatal exposure to ambient air pollution and temperature on childhood asthma. *Environment International*, **167**, 107456. https://doi.org/10.1016/j.envint.2022.107456

241. Gershunov, A. and K. Guirguis, 2012: California heat waves in the present and future. *Geophysical Research Letters*, **39** (18). https://doi.org/10.1029/2012gl052979

242. EPA, 2021: Climate Change Indicators: Health and Society. U.S. Environmental Protection Agency. https://www.epa.gov/climate-indicators/health-society

243. Prein, A.F., G.J. Holland, R.M. Rasmussen, M.P. Clark, and M.R. Tye, 2016: Running dry: The U.S. Southwest's drift into a drier climate state. *Geophysical Research Letters*, **43** (3), 1272–1279. https://doi.org/10.1002/2015gl066727

244. Achakulwisut, P., S.C. Anenberg, J.E. Neumann, S.L. Penn, N. Weiss, A. Crimmins, N. Fann, J. Martinich, H. Roman, and L.J. Mickley, 2019: Effects of increasing aridity on ambient dust and public health in the U.S. Southwest under climate change. *GeoHealth*, **3** (5), 127–144. https://doi.org/10.1029/2019gh000187

245. McCotter, O.Z., K. Benedict, D.M. Engelthaler, K. Komatsu, K.D. Lucas, J.C. Mohle-Boetani, H. Oltean, D. Vugia, T.M. Chiller, G.L. Sondermeyer Cooksey, A. Nguyen, C.C. Roe, C. Wheeler, and R. Sunenshine, 2019: Update on the Epidemiology of coccidioidomycosis in the United States. *Medical Mycology*, **57** (Supplement_1), S30–S40. https://doi.org/10.1093/mmy/myy095

246. Gorris, M.E., L.A. Cat, C.S. Zender, K.K. Treseder, and J.T. Randerson, 2018: Coccidioidomycosis dynamics in relation to climate in the southwestern United States. *GeoHealth*, **2** (1), 6–24. https://doi.org/10.1002/2017gh000095

247. Head, J.R., G. Sondermeyer-Cooksey, A.K. Heaney, A.T. Yu, I. Jones, A. Bhattachan, S.K. Campo, R. Wagner, W. Mgbara, S. Phillips, N. Keeney, J. Taylor, E. Eisen, D.P. Lettenmaier, A. Hubbard, G.S. Okin, D.J. Vugia, S. Jain, and J.V. Remais, 2022: Effects of precipitation, heat, and drought on incidence and expansion of coccidioidomycosis in western USA: A longitudinal surveillance study. *The Lancet Planetary Health*, **6** (10), e793–e803. https://doi.org/10.1016/s2542-5196(22)00202-9

248. Gorris, M.E., J.E. Neumann, P.L. Kinney, M. Sheahan, and M.C. Sarofim, 2021: Economic valuation of coccidioidomycosis (Valley fever) projections in the United States in response to climate change. *Weather, Climate, and Society*, **13** (1), 107–123. https://doi.org/10.1175/wcas-d-20-0036.1

249. Graff Zivin, J. and M. Neidell, 2014: Temperature and the allocation of time: Implications for climate change. *Journal of Labor Economics*, **32** (1), 1–26. https://doi.org/10.1086/671766

250. Vanos, J., S. Moyce, B. Lemke, and T. Kjellstrom, 2021: Ch. 10. Extreme heat exposure and occupational health in a changing climate. In: *Extreme Events and Climate Change: A Multidisciplinary Approach*. Castillo, F., M. Wehner, and D.A. Stone, Eds. Wiley, 147–166. https://doi.org/10.1002/9781119413738.ch10

251. Zhang, Y. and D.T. Shindell, 2021: Costs from labor losses due to extreme heat in the USA attributable to climate change. *Climatic Change*, **164** (3), 35. https://doi.org/10.1007/s10584-021-03014-2

252. Castillo, F., A.M. Mora, G.L. Kayser, J. Vanos, C. Hyland, A.R. Yang, and B. Eskenazi, 2021: Environmental health threats to Latino migrant farmworkers. *Annual Review of Public Health*, **42** (1), 257–276. https://doi.org/10.1146/annurev-publhealth-012420-105014

253. Stevens, A.W., 2017: Temperature, Wages, and Agricultural Labor Productivity. University of California, Berkeley. https://www.econ.iastate.edu/files/events/files/stevens_jmp_jan16.pdf

254. Moyce, S., J. Joseph, D. Tancredi, D. Mitchell, and M. Schenker, 2016: Cumulative incidence of acute kidney injury in California's agricultural workers. *Journal of Occupational and Environmental Medicine*, **58** (4). https://doi.org/10.1097/jom.0000000000000668

255. Wesseling, C., J. Glaser, J. Rodríguez-Guzmán, I. Weiss, R. Lucas, S. Peraza, A. Soares da Silva, E. Hansson, R.J. Johnson, C. Hogstedt, D.H. Wegman, and K. Jakobsson, 2020: Chronic kidney disease of non-traditional origin in Mesoamerica: A disease primarily driven by occupational heat stress. *Pan American Journal of Public Health*, **44**, 15. https://doi.org/10.26633/rpsp.2020.15

256. Foster, J., J.W. Smallcombe, S. Hodder, O. Jay, A.D. Flouris, and G. Havenith, 2022: Quantifying the impact of heat on human physical work capacity; Part II: The observed interaction of air velocity with temperature, humidity, sweat rate, and clothing is not captured by most heat stress indices. *International Journal of Biometeorology*, **66** (3), 507–520. https://doi.org/10.1007/s00484-021-02212-y

257. Foster, J., J.W. Smallcombe, S. Hodder, O. Jay, A.D. Flouris, L. Nybo, and G. Havenith, 2021: An advanced empirical model for quantifying the impact of heat and climate change on human physical work capacity. *International Journal of Biometeorology*, **65** (7), 1215–1229. https://doi.org/10.1007/s00484-021-02105-0

258. Foster, J., J.W. Smallcombe, S. Hodder, O. Jay, A.D. Flouris, L. Nybo, and G. Havenith, 2022: Quantifying the impact of heat on human physical work capacity; Part III: The impact of solar radiation varies with air temperature, humidity, and clothing coverage. *International Journal of Biometeorology*, **66** (1), 175–188. https://doi.org/10.1007/s00484-021-02205-x

259. Smallcombe, J.W., J. Foster, S.G. Hodder, O. Jay, A.D. Flouris, and G. Havenith, 2022: Quantifying the impact of heat on human physical work capacity; part IV: Interactions between work duration and heat stress severity. *International Journal of Biometeorology*, **66** (12), 2463–2476. https://doi.org/10.1007/s00484-022-02370-7

260. Colmer, J., I. Hardman, J. Shimshack, and J. Voorheis, 2020: Disparities in $PM_{2.5}$ air pollution in the United States. *Science*, **369** (6503), 575–578. https://doi.org/10.1126/science.aaz9353

261. Liang, Y., D. Sengupta, M.J. Campmier, D.M. Lunderberg, J.S. Apte, and A.H. Goldstein, 2021: Wildfire smoke impacts on indoor air quality assessed using crowdsourced data in California. *Proceedings of the National Academy of Sciences of the United States of America*, **118** (36), e2106478118. https://doi.org/10.1073/pnas.2106478118

262. Navarro, K.M., R. Cisneros, D. Schweizer, P. Chowdhary, E.M. Noth, J.R. Balmes, and S.K. Hammond, 2019: Incident command post exposure to polycyclic aromatic hydrocarbons and particulate matter during a wildfire. *Journal of Occupational and Environmental Hygiene*, **16** (11), 735–744. https://doi.org/10.1080/15459624.2019.1657579

263. Fann, N., B. Alman, R.A. Broome, G.G. Morgan, F.H. Johnston, G. Pouliot, and A.G. Rappold, 2018: The health impacts and economic value of wildland fire episodes in the U.S.: 2008–2012. *Science of The Total Environment*, **610–611**, 802–809. https://doi.org/10.1016/j.scitotenv.2017.08.024

264. Yang, X., Y. Yu, S. Shirowzhan, S. sepasgozar, and H. Li, 2020: Automated PPE-tool pair check system for construction safety using smart IoT. *Journal of Building Engineering*, **32**, 101721. https://doi.org/10.1016/j.jobe.2020.101721

265. Aguilera, R., T. Corringham, A. Gershunov, and T. Benmarhnia, 2021: Wildfire smoke impacts respiratory health more than fine particles from other sources: Observational evidence from Southern California. *Nature Communications*, **12** (1), 1493. https://doi.org/10.1038/s41467-021-21708-0

266. Jaffe, D.A., S.M. O'Neill, N.K. Larkin, A.L. Holder, D.L. Peterson, J.E. Halofsky, and A.G. Rappold, 2020: Wildfire and prescribed burning impacts on air quality in the United States. *Journal of the Air & Waste Management Association*, **70** (6), 583–615. https://doi.org/10.1080/10962247.2020.1749731

267. Grant, E. and J.D. Runkle, 2022: Long-term health effects of wildfire exposure: A scoping review. *The Journal of Climate Change and Health*, **6**, 100110. https://doi.org/10.1016/j.joclim.2021.100110

268. Silveira, S., M. Kornbluh, M.C. Withers, G. Grennan, V. Ramanathan, and J. Mishra, 2021: Chronic mental health sequelae of climate change extremes: A case study of the deadliest Californian wildfire. *International Journal of Environmental Research and Public Health*, **18** (4), 1487. https://doi.org/10.3390/ijerph18041487

269. Proctor, C.R., J. Lee, D. Yu, A.D. Shah, and A.J. Whelton, 2020: Wildfire caused widespread drinking water distribution network contamination. AWWA *Water Science*, **2** (4), e1183. https://doi.org/10.1002/aws2.1183

270. National Academies of Sciences, Engineering, and Medicine, 2020: *Implications of the California Wildfires for Health, Communities, and Preparedness: Proceedings of a Workshop*. The National Academies Press, Washington, DC. https://doi.org/10.17226/25622

271. Dong, L., L.R. Leung, J. Lu, and Y. Gao, 2019: Contributions of extreme and non-extreme precipitation to California precipitation seasonality changes under warming. *Geophysical Research Letters*, **46** (22), 13470–13478. https://doi.org/10.1029/2019gl084225

272. Huang, X. and D.L. Swain, 2022: Climate change is increasing the risk of a California megaflood. *Science Advances*, **8** (32), 0995. https://doi.org/10.1126/sciadv.abq0995

273. Semenza, J.C., J. Rocklöv, and K.L. Ebi, 2022: Climate change and cascading risks from infectious disease. *Infectious Diseases and Therapy*, **11** (4), 1371–1390. https://doi.org/10.1007/s40121-022-00647-3

274. NCEZID, 2023: 2022 Provisional Human Data. Centers for Disease Control and Prevention, National Center for Emerging and Zoonotic Infectious Diseases, accessed April 3, 2023. https://wwwn.cdc.gov/arbonet/maps/adb_diseases_map/index.html

275. CA DWR, 2022: Central Valley Flood Protection Plan Update 2022. State of California, Natural Resources Agency, Department of Water Resources. https://water.ca.gov/-/media/dwr-website/web-pages/programs/flood-management/flood-planning-and-studies/central-valley-flood-protection-plan/files/cvfpp-updates/2022/central_valley_flood_protection_plan_update_2022_adopted.pdf

276. Gorris, M.E., A.W. Bartlow, S.D. Temple, D. Romero-Alvarez, D.P. Shutt, J.M. Fair, K.A. Kaufeld, S.Y. Del Valle, and C.A. Manore, 2021: Updated distribution maps of predominant *Culex* mosquitoes across the Americas. *Parasites & Vectors*, **14** (1), 547. https://doi.org/10.1186/s13071-021-05051-3

277. Méndez, M., 2022: Behind the bougainvillea curtain: Wildfires and inequality. *Issues in Science and Technology*, **38** (2), 84–90. https://www.preventionweb.net/publication/behind-bougainvillea-curtain-wildfires-and-inequality

278. CBP, 2020: Southwest Border Migration FY 2020. U.S. Customs and Border Protection. https://www.cbp.gov/newsroom/stats/sw-border-migration-fy2020

279. WFP, 2017: Food Security and Emigration: Why People Flee and the Impact on Family Members Left Behind in El Salvador, Guatemala, and Honduras. United Nations World Food Programme. https://docs.wfp.org/api/documents/wfp-0000019632/download/

280. Bradatan, C., J.A. Dennis, N. Flores-Yeffal, and S. Swain, 2020: Child health, household environment, temperature and rainfall anomalies in Honduras: A socio-climate data linked analysis. *Environmental Health*, **19** (1), 10. https://doi.org/10.1186/s12940-020-0560-9

281. U.S. Census Bureau, 2021: Community Resilience Estimates: Thematic Risk Factor (RF). U.S. Department of Commerce, U.S. Census Bureau. https://experience.arcgis.com/experience/b0341fa9b237456c9a9f1758c15cde8d/

282. U.S. Census Bureau, 2023: Selected Population Profile in the United States—2021: ACS 1-Year Estimates Selected Population Profiles. U.S. Department of Commerce, U.S. Census Bureau, accessed April 3, 2023. https://data.census.gov/table?q=united+states&t=716:720:721:722&g=040xx00us04,06,08,32,35,49&y=2021

283. Schwerdtle, P., K. Bowen, and C. McMichael, 2018: The health impacts of climate-related migration. *BMC Medicine*, **16** (1), 1. https://doi.org/10.1186/s12916-017-0981-7

284. White-Newsome, J., S. McCormick, N. Sampson, M. Buxton, M. O'Neill, C. Gronlund, L. Catalano, K. Conlon, and E. Parker, 2014: Strategies to reduce the harmful effects of extreme heat events: A four-city study. *International Journal of Environmental Research and Public Health*, **11** (2), 1960–1988. https://doi.org/10.3390/ijerph110201960

285. NCEH, 2015: CDC's Building Resilience Against Climate Effects (BRACE) Framework. Centers for Disease Control and Prevention, National Center for Environmental Health. https://www.cdc.gov/climateandhealth/brace.htm

286. Shortridge, A., W. Walker Vi, D.D. White, M.M. Guardaro, D.M. Hondula, and J.K. Vanos, 2022: HeatReady schools: A novel approach to enhance adaptive capacity to heat through school community experiences, risks, and perceptions. *Climate Risk Management*, **36**, 100437. https://doi.org/10.1016/j.crm.2022.100437

287. ADHS, 2021: Managing Extreme Heat Recommendations for Schools: Pilot Version. Arizona Department of Health Services, Phoenix, AZ. https://www.azdhs.gov/documents/preparedness/epidemiology-disease-control/extreme-weather/heat/managing-extreme-heat-recommendations-for-schools.pdf

288. NCEH, 2020: Preparing for the Regional Health Impacts of Climate Change in the United States: A Summary of Health Effects, Resources, and Adaptation Examples from Health Departments Funded by CDC's Climate and Health Program. Centers for Disease Control and Prevention, National Center for Environmental Health. https://stacks.cdc.gov/view/cdc/99147

289. Rosenthal, N., T. Benmarhnia, R. Ahmadov, E. James, and M.E. Marlier, 2022: Population co-exposure to extreme heat and wildfire smoke pollution in California during 2020. *Environmental Research: Climate*, **1** (2), 025004. https://doi.org/10.1088/2752-5295/ac860e

290. Stowell, J.D., C.-E. Yang, J.S. Fu, N.C. Scovronick, M.J. Strickland, and Y. Liu, 2022: Asthma exacerbation due to climate change-induced wildfire smoke in the western US. *Environmental Research Letters*, **17** (1), 014023. https://doi.org/10.1088/1748-9326/ac4138

291. The World Bank, 2021: Enabling Private Investment in Climate Adaptation & Resilience. World Bank Group. https://openknowledge.worldbank.org/server/api/core/bitstreams/127de8c7-d367-59ac-9e54-27ee52c744aa/content

292. CDI, 2023: Climate Risk Carbon Initiative. California Department of Insurance. https://www.insurance.ca.gov/0250-insurers/0300-insurers/0100-applications/ci/

293. Margolis, E.Q., C.H. Guiterman, R.D. Chavardès, J.D. Coop, K. Copes-Gerbitz, D.A. Dawe, D.A. Falk, J.D. Johnston, E. Larson, H. Li, J.M. Marschall, C.E. Naficy, A.T. Naito, M.-A. Parisien, S.A. Parks, J. Portier, H.M. Poulos, K.M. Robertson, J.H. Speer, M. Stambaugh, T.W. Swetnam, A.J. Tepley, I. Thapa, C.D. Allen, Y. Bergeron, L.D. Daniels, P.Z. Fulé, D. Gervais, M.P. Girardin, G.L. Harley, J.E. Harvey, K.M. Hoffman, J.M. Huffman, M.D. Hurteau, L.B. Johnson, C.W. Lafon, M.K. Lopez, R.S. Maxwell, J. Meunier, M. North, M.T. Rother, M.R. Schmidt, R.L. Sherriff, L.A. Stachowiak, A. Taylor, E.J. Taylor, V. Trouet, M.L. Villarreal, L.L. Yocom, K.B. Arabas, A.H. Arizpe, D. Arseneault, A.A. Tarancón, C. Baisan, E. Bigio, F. Biondi, G.D. Cahalan, A. Caprio, J. Cerano-Paredes, B.M. Collins, D.C. Dey, I. Drobyshev, C. Farris, M.A. Fenwick, W. Flatley, M.L. Floyd, Z.e. Gedalof, A. Holz, L.F. Howard, D.W. Huffman, J. Iniguez, K.F. Kipfmueller, S.G. Kitchen, K. Lombardo, D. McKenzie, A.G. Merschel, K.L. Metlen, J. Minor, C.D. O'Connor, L. Platt, W.J. Platt, T. Saladyga, A.B. Stan, S. Stephens, C. Sutheimer, R. Touchan, and P.J. Weisberg, 2022: The North American tree-ring fire-scar network. *Ecosphere*, **13** (7), e4159. https://doi.org/10.1002/ecs2.4159

294. Guiterman, C.H., R.M. Gregg, L.A.E. Marshall, J.J. Beckmann, P.J. van Mantgem, D.A. Falk, J.E. Keeley, A.C. Caprio, J.D. Coop, P.J. Fornwalt, C. Haffey, R.K. Hagmann, S.T. Jackson, A.M. Lynch, E.Q. Margolis, C. Marks, M.D. Meyer, H. Safford, A.D. Syphard, A. Taylor, C. Wilcox, D. Carril, C.A.F. Enquist, D. Huffman, J. Iniguez, N.A. Molinari, C. Restaino, and J.T. Stevens, 2022: Vegetation type conversion in the US Southwest: Frontline observations and management responses. *Fire Ecology*, **18** (1), 6. https://doi.org/10.1186/s42408-022-00131-w

295. Hagmann, R.K., P.F. Hessburg, S.J. Prichard, N.A. Povak, P.M. Brown, P.Z. Fulé, R.E. Keane, E.E. Knapp, J.M. Lydersen, K.L. Metlen, M.J. Reilly, A.J. Sánchez Meador, S.L. Stephens, J.T. Stevens, A.H. Taylor, L.L. Yocom, M.A. Battaglia, D.J. Churchill, L.D. Daniels, D.A. Falk, P. Henson, J.D. Johnston, M.A. Krawchuk, C.R. Levine, G.W. Meigs, A.G. Merschel, M.P. North, H.D. Safford, T.W. Swetnam, and A.E.M. Waltz, 2021: Evidence for widespread changes in the structure, composition, and fire regimes of western North American forests. *Ecological Applications*, **31** (8), e02431. https://doi.org/10.1002/eap.2431

296. Lake, F.K., J. Parrotta, C.P. Giardina, I. Davidson-Hunt, and Y. Uprety, 2018: Ch. 12. Integration of Traditional and Western knowledge in forest landscape restoration. In: *Forest Landscape Restoration: Integrated Approaches to Support Effective Implementation*. Mansourian, S. and J. Parrotta, Eds. Routledge, New York, 198–226. https://www.fs.usda.gov/treesearch/pubs/57158

297. Collins, L., H. Clarke, M.F. Clarke, S.C. McColl Gausden, R.H. Nolan, T. Penman, and R. Bradstock, 2022: Warmer and drier conditions have increased the potential for large and severe fire seasons across south-eastern Australia. *Global Ecology and Biogeography*, **31** (10), 1933–1948. https://doi.org/10.1111/geb.13514

298. Coop, J.D., S.A. Parks, C.S. Stevens-Rumann, S.D. Crausbay, P.E. Higuera, M.D. Hurteau, A. Tepley, E. Whitman, T. Assal, B.M. Collins, K.T. Davis, S. Dobrowski, D.A. Falk, P.J. Fornwalt, P.Z. Fulé, B.J. Harvey, V.R. Kane, C.E. Littlefield, E.Q. Margolis, M. North, M.-A. Parisien, S. Prichard, and K.C. Rodman, 2020: Wildfire-driven forest conversion in western North American landscapes. *BioScience*, **70** (8), 659–673. https://doi.org/10.1093/biosci/biaa061

299. North, M.P., R.E. Tompkins, A.A. Bernal, B.M. Collins, S.L. Stephens, and R.A. York, 2022: Operational resilience in western US frequent-fire forests. *Forest Ecology and Management*, **507**, 120004. https://doi.org/10.1016/j.foreco.2021.120004

300. Prichard, S.J., P.F. Hessburg, R.K. Hagmann, N.A. Povak, S.Z. Dobrowski, M.D. Hurteau, V.R. Kane, R.E. Keane, L.N. Kobziar, C.A. Kolden, M. North, S.A. Parks, H.D. Safford, J.T. Stevens, L.L. Yocom, D.J. Churchill, R.W. Gray, D.W. Huffman, F.K. Lake, and P. Khatri-Chhetri, 2021: Adapting western North American forests to climate change and wildfires: 10 common questions. *Ecological Applications*, **31** (8), e02433. https://doi.org/10.1002/eap.2433

301. MacDonald, G., T. Wall, C.A.F. Enquist, S.R. LeRoy, J.B. Bradford, D.D. Breshears, T. Brown, D. Cayan, C. Dong, D.A. Falk, E. Fleishman, A. Gershunov, M. Hunter, R.A. Loehman, P.J. van Mantgem, B.R. Middleton, H.D. Safford, M.W. Schwartz, and V. Trouet, 2023: Drivers of California's changing wildfires: A state-of-the-knowledge synthesis. *International Journal of Wildland Fire*, **32** (7), 1039–1058. https://doi.org/10.1071/WF22155

302. Westerling, A.L., 2016: Increasing western US forest wildfire activity: Sensitivity to changes in the timing of spring. *Philosophical Transactions of the Royal Society B: Biological Sciences*, **371** (1696), 20150178. https://doi.org/10.1098/rstb.2015.0178

303. Westerling, A.L., H.G. Hidalgo, D.R. Cayan, and T.W. Swetnam, 2006: Warming and earlier spring increase western U.S. forest wildfire activity. *Science*, **313** (5789), 940–943. https://doi.org/10.1126/science.1128834

304. CalFire, 2021: Top 20 Deadliest California Wildfires. California Department of Forestry and Fire Protection. https://www.fire.ca.gov/our-impact/statistics

305. NICC, 2021: Wildland Fire Summary and Statistics Annual Report 2020. National Interagency Coordination Center. https://www.predictiveservices.nifc.gov/intelligence/intelligence.htm

306. NICC, 2022: Wildland Fire Summary and Statistics Annual Report 2021. National Interagency Coordination Center. https://www.predictiveservices.nifc.gov/intelligence/intelligence.htm

307. Stinnesbeck, J., 2020: Wildfires in Nevada: An Overview. Legislative Counsel Bureau, Research Division, 5 pp. https://www.leg.state.nv.us/division/research/documents/wildfires-in-nevada-2020-final.pdf

308. Li, Z., J.P. Angerer, and X.B. Wu, 2021: Temporal patterns of large wildfires and their burn severity in rangelands of western United States. *Geophysical Research Letters*, **48** (7), e2020GL091636. https://doi.org/10.1029/2020GL091636

309. Archer, D., D. Toledo, D.M. Blumenthal, J. Derner, C. Boyd, K. Davies, E. Hamerlynck, R. Sheley, P. Clark, S. Hardegree, F. Pierson, C. Clements, B. Newingham, B. Rector, J. Gaskin, C.L. Wonkka, K. Jensen, T. Monaco, L.T. Vermeire, and S.L. Young, 2023: Invasive annual grasses—Reenvisioning approaches in a changing climate. *Journal of Soil and Water Conservation*, **78** (2), 95–103. https://doi.org/10.2489/jswc.2023.00074

310. Singleton, M.P., A.E. Thode, A.J. Sánchez Meador, and J.M. Iniguez, 2019: Increasing trends in high-severity fire in the southwestern USA from 1984 to 2015. *Forest Ecology and Management*, **433**, 709–719. https://doi.org/10.1016/j.foreco.2018.11.039

311. Haffey, C., T.D. Sisk, C.D. Allen, A.E. Thode, and E.Q. Margolis, 2018: Limits to ponderosa pine regeneration following large high-severity forest fires in the United States Southwest. *Fire Ecology*, **14** (1), 143–163. https://doi.org/10.4996/fireecology.140114316

312. Webb, A.D., D.A. Falk, and D.M. Finch, 2019: Fire Ecology and Management in Lowland Riparian Ecosystems of the Southwestern United States and Northern Mexico. Gen. Tech. Rep. RMRS-GTR-401. U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station, Fort Collins, CO, 132 pp. https://www.fs.usda.gov/research/treesearch/59156

313. Davis, K.T., S.Z. Dobrowski, P.E. Higuera, Z.A. Holden, T.T. Veblen, M.T. Rother, S.A. Parks, A. Sala, and M.P. Maneta, 2019: Wildfires and climate change push low-elevation forests across a critical climate threshold for tree regeneration. *Proceedings of the National Academy of Sciences of the United States of America*, **116** (13), 6193–6198. https://doi.org/10.1073/pnas.1815107116

314. O'Connor, R.C., M.J. Germino, D.M. Barnard, C.M. Andrews, J.B. Bradford, D.S. Pilliod, R.S. Arkle, and R.K. Shriver, 2020: Small-scale water deficits after wildfires create long-lasting ecological impacts. *Environmental Research Letters*, **15** (4), 044001. https://doi.org/10.1088/1748-9326/ab79e4

315. Rodman, K.C., T.T. Veblen, M.A. Battaglia, M.E. Chambers, P.J. Fornwalt, Z.A. Holden, T.E. Kolb, J.R. Ouzts, and M.T. Rother, 2020: A changing climate is snuffing out post-fire recovery in montane forests. *Global Ecology and Biogeography*, **29** (11), 2039–2051. https://doi.org/10.1111/geb.13174

316. Parks, S.A., S.Z. Dobrowski, J.D. Shaw, and C. Miller, 2019: Living on the edge: Trailing edge forests at risk of fire-facilitated conversion to non-forest. *Ecosphere*, **10** (3), e02651. https://doi.org/10.1002/ecs2.2651

317. Halofsky, J.E., D.L. Peterson, and B.J. Harvey, 2020: Changing wildfire, changing forests: The effects of climate change on fire regimes and vegetation in the Pacific Northwest, USA. *Fire Ecology*, **16** (1), 4. https://doi.org/10.1186/s42408-019-0062-8

318. Keeley, J.E. and A.D. Syphard, 2019: Twenty-first century California, USA, wildfires: Fuel-dominated vs. wind-dominated fires. *Fire Ecology*, **15** (1), 24. https://doi.org/10.1186/s42408-019-0041-0

319. Loehman, R.A., R.E. Keane, and L.M. Holsinger, 2020: Simulation modeling of complex climate, wildfire, and vegetation dynamics to address wicked problems in land management. *Frontiers in Forests and Global Change*, **3**, 3. https://doi.org/10.3389/ffgc.2020.00003

320. Stevens-Rumann, C.S., K.B. Kemp, P.E. Higuera, B.J. Harvey, M.T. Rother, D.C. Donato, P. Morgan, and T.T. Veblen, 2018: Evidence for declining forest resilience to wildfires under climate change. *Ecology Letters*, **21** (2), 243–252. https://doi.org/10.1111/ele.12889

321. Stevens-Rumann, C.S. and P. Morgan, 2019: Tree regeneration following wildfires in the western US: A review. *Fire Ecology*, **15** (1), 15. https://doi.org/10.1186/s42408-019-0032-1

322. Turner, M.G., K.H. Braziunas, W.D. Hansen, and B.J. Harvey, 2019: Short-interval severe fire erodes the resilience of subalpine lodgepole pine forests. *Proceedings of the National Academy of Sciences of the United States of America*, **116** (23), 11319–11328. https://doi.org/10.1073/pnas.1902841116

323. Doherty, K., D.M. Theobald, J.B. Bradford, L.A. Wiechman, G. Bedrosian, C.S. Boyd, M. Cahill, P.S. Coates, M.K. Creutzburg, M.R. Crist, S.P. Finn, A.V. Kumar, C.E. Littlefield, J.D. Maestas, K.L. Prentice, B.G. Prochazka, T.E. Remington, W.D. Sparklin, J.C. Tull, Z. Wurtzebach, and K.A. Zeller, 2022: A Sagebrush Conservation Design to Proactively Restore America's Sagebrush Biome. Open-File Report 2022–1081. U.S. Geological Survey. https://www.usgs.gov/publications/a-sagebrush-conservation-design-proactively-restore-americas-sagebrush-biome

324. Shinneman, D.J., E.K. Strand, M. Pellant, J.T. Abatzoglou, M.W. Brunson, N.F. Glenn, J.A. Heinrichs, M. Sadegh, and N.M. Vaillant, 2023: Future direction of fuels management in sagebrush rangelands. *Rangeland Ecology & Management*, **86**, 50–63. https://doi.org/10.1016/j.rama.2022.10.009

325. Felton, A.J., R.K. Shriver, M. Stemkovski, J.B. Bradford, K.N. Suding, and P.B. Adler, 2022: Climate disequilibrium dominates uncertainty in long-term projections of primary productivity. *Ecology Letters*, **25** (12), 2688–2698. https://doi.org/10.1111/ele.14132

326. Ellis, T.M., D.M.J.S. Bowman, P. Jain, M.D. Flannigan, and G.J. Williamson, 2022: Global increase in wildfire risk due to climate-driven declines in fuel moisture. *Global Change Biology*, **28** (4), 1544–1559. https://doi.org/10.1111/gcb.16006

327. Haynes, K., K. Short, G. Xanthopoulos, D. Viegas, L.M. Ribeiro, and R. Blanchi, 2020: Wildfires and WUI fire fatalities. In: *Encyclopedia of Wildfires and Wildland-Urban Interface (WUI) Fires*. Manzello, S.L., Ed. Springer, Cham, Switzerland, 1–16. https://doi.org/10.1007/978-3-319-51727-8_92-1

328. Schwarz, L., A. Dimitrova, R. Aguilera, R. Basu, A. Gershunov, and T. Benmarhnia, 2022: Smoke and COVID-19 case fatality ratios during California wildfires. *Environmental Research Letters*, **17** (1), 014054. https://doi.org/10.1088/1748-9326/ac4538

329. Tiwari, B., B. Ajmera, A. Gonzalez, and H. Sonbol, 2020: Impact of wildfire on triggering mudslides—A case study of 2018 Montecito debris flows. In: *Geo-Congress 2020: Engineering, Monitoring, and Management of Geotechnical Infrastructure*. Hambleton, J.P., R. Makhnenko, and A.S. Budge, Eds. American Society of Civil Engineers, Reston, VA, 40–49. https://doi.org/10.1061/9780784482797.005

330. Murray, A.T., L. Carvalho, R.L. Church, C. Jones, D. Roberts, J. Xu, K. Zigner, and D. Nash, 2021: Coastal vulnerability under extreme weather. *Applied Spatial Analysis and Policy*, **14** (3), 497–523. https://doi.org/10.1007/s12061-020-09357-0

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

332. Rao, K., A.P. Williams, N.S. Diffenbaugh, M. Yebra, and A.G. Konings, 2022: Plant-water sensitivity regulates wildfire vulnerability. *Nature Ecology & Evolution*, **6** (3), 332–339. https://doi.org/10.1038/s41559-021-01654-2

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

334. Winkler, R.L. and M.D. Rouleau, 2021: Amenities or disamenities? Estimating the impacts of extreme heat and wildfire on domestic US migration. *Population and Environment*, **42** (4), 622–648. https://doi.org/10.1007/s11111-020-00364-4

335. Sharygin, E., 2021: Ch. 3. Estimating migration impacts of wildfire: California's 2017 North Bay fires. In: *The Demography of Disasters: Impacts for Population and Place*. Karácsonyi, D., A. Taylor, and D. Bird, Eds. Springer, Cham, Switzerland, 49–70. https://doi.org/10.1007/978-3-030-49920-4_3

336. Baijnath-Rodino, J.A., M. Kumar, M. Rivera, K.D. Tran, and T. Banerjee, 2021: How vulnerable are American states to wildfires? A livelihood vulnerability assessment. *Fire*, **4** (3), 54. https://doi.org/10.3390/fire4030054

337. Goldsmith, L., V. Raditz, and M. Méndez, 2022: Queer and present danger: Understanding the disparate impacts of disasters on LGBTQ+ communities. *Disasters*, **46** (4), 946–973. https://doi.org/10.1111/disa.12509

338. Davies, I.P., R.D. Haugo, J.C. Robertson, and P.S. Levin, 2018: The unequal vulnerability of communities of color to wildfire. *PLoS ONE*, **13** (11), 0205825. https://doi.org/10.1371/journal.pone.0205825

339. Engelman, A., L. Craig, and A. Iles, 2022: Global disability justice in climate disasters: Mobilizing people with disabilities as change agents. *Health Affairs*, **41** (10), 1496–1504. https://doi.org/10.1377/hlthaff.2022.00474

340. Madhusoodanan, J., 2021: Wildfires pose a burning problem for wines and winemakers. *Proceedings of the National Academy of Sciences of the United States of America*, **118** (34), e2113327118. https://doi.org/10.1073/pnas.2113327118

341. Cartier, E.A. and L.L. Taylor, 2020: Living in a wildfire: The relationship between crisis management and community resilience in a tourism-based destination. *Tourism Management Perspectives*, **34**, 100635. https://doi.org/10.1016/j.tmp.2020.100635

342. Kim, M.-K. and P.M. Jakus, 2019: Wildfire, national park visitation, and changes in regional economic activity. *Journal of Outdoor Recreation and Tourism*, **26**, 34–42. https://doi.org/10.1016/j.jort.2019.03.007

343. Dillis, C., V. Butsic, D. Moanga, P. Parker-Shames, A. Wartenberg, and T.E. Grantham, 2022: The threat of wildfire is unique to cannabis among agricultural sectors in California. *Ecosphere*, **13** (9), e4205. https://doi.org/10.1002/ecs2.4205

344. Crews, P., P. Dorenbach, G. Amberchan, R.F. Keiffer, I. Lizama-Chamu, T.C. Ruthenburg, E.P. McCauley, and G. McGourty, 2022: Natural product phenolic diglycosides created from wildfires, defining their impact on California and Oregon grapes and wines. *Journal of Natural Products*, **85** (3), 547–561. https://doi.org/10.1021/acs.jnatprod.2c00028

345. Rhoades, C.C., J.P. Nunes, U. Silins, and S.H. Doerr, 2019: The influence of wildfire on water quality and watershed processes: New insights and remaining challenges. *International Journal of Wildland Fire*, **28** (10), 721–725. https://doi.org/10.1071/wfv28n10_fo

346. Carbone, L.M., J. Tavella, J.G. Pausas, and R. Aguilar, 2019: A global synthesis of fire effects on pollinators. *Global Ecology and Biogeography*, **28** (10), 1487–1498. https://doi.org/10.1111/geb.12939

347. O'Hara, K.C., J. Ranches, L.M. Roche, T.K. Schohr, R.C. Busch, and G.U. Maier, 2021: Impacts from wildfires on livestock health and production: Producer perspectives. *Animals*, **11** (11), 3230. https://doi.org/10.3390/ani11113230

348. Gellman, J., M. Walls, and M. Wibbenmeyer, 2022: Wildfire, smoke, and outdoor recreation in the western United States. *Forest Policy and Economics*, **134**, 102619. https://doi.org/10.1016/j.forpol.2021.102619

349. Vukomanovic, J. and T. Steelman, 2019: A systematic review of relationships between mountain wildfire and ecosystem services. *Landscape Ecology*, **34** (5), 1179–1194. https://doi.org/10.1007/s10980-019-00832-9

350. Hohner, A.K., C.C. Rhoades, P. Wilkerson, and F.L. Rosario-Ortiz, 2019: Wildfires alter forest watersheds and threaten drinking water quality. *Accounts of Chemical Research*, **52** (5), 1234–1244. https://doi.org/10.1021/acs.accounts.8b00670

351. Schulze, S.S., E.C. Fischer, S. Hamideh, and H. Mahmoud, 2020: Wildfire impacts on schools and hospitals following the 2018 California Camp Fire. *Natural Hazards*, **104** (1), 901–925. https://doi.org/10.1007/s11069-020-04197-0

352. Robinne, F.-N., D.W. Hallema, K.D. Bladon, M.D. Flannigan, G. Boisramé, C.M. Bréthaut, S.H. Doerr, G. Di Baldassarre, L.A. Gallagher, A.K. Hohner, S.J. Khan, A.M. Kinoshita, R. Mordecai, J.P. Nunes, P. Nyman, C. Santín, G. Sheridan, C.R. Stoof, M.P. Thompson, J.M. Waddington, and Y. Wei, 2021: Scientists' warning on extreme wildfire risks to water supply. *Hydrological Processes*, **35** (5), e14086. https://doi.org/10.1002/hyp.14086

353. Juliano, T.W., P.A. Jiménez, B. Kosović, T. Eidhammer, G. Thompson, L.K. Berg, J. Fast, A. Motley, and A. Polidori, 2022: Smoke from 2020 United States wildfires responsible for substantial solar energy forecast errors. *Environmental Research Letters*, **17** (3), 034010. https://doi.org/10.1088/1748-9326/ac5143

354. Pereira, P., I. Bogunovic, W. Zhao, and D. Barcelo, 2021: Short-term effect of wildfires and prescribed fires on ecosystem services. *Current Opinion in Environmental Science & Health*, **22**, 100266. https://doi.org/10.1016/j.coesh.2021.100266

355. van Mantgem, P.J., A.C. Caprio, N.L. Stephenson, and A.J. Das, 2021: Forest resistance to extended drought enhanced by prescribed fire in low elevation forests of the Sierra Nevada. *Forests*, **12** (9), 1248. https://doi.org/10.3390/f12091248

356. Hunter, M.E. and M.D. Robles, 2020: Tamm review: The effects of prescribed fire on wildfire regimes and impacts: A framework for comparison. *Forest Ecology and Management*, **475**, 118435. https://doi.org/10.1016/j.foreco.2020.118435

357. Long, J.W., F.K. Lake, R.W. Goode, and B.M. Burnette, 2020: How traditional tribal perspectives influence ecosystem restoration. *Ecopsychology*, **12** (2). https://doi.org/10.1089/eco.2019.0055

358. Banerjee, T., 2020: Impacts of forest thinning on wildland fire behavior. *Forests*, **11** (9), 918. https://doi.org/10.3390/f11090918

359. Goodwin, M.J., M.P. North, H.S.J. Zald, and M.D. Hurteau, 2020: Changing climate reallocates the carbon debt of frequent-fire forests. *Global Change Biology*, **26** (11), 6180–6189. https://doi.org/10.1111/gcb.15318

360. Stephens, S.L., M.A. Battaglia, D.J. Churchill, B.M. Collins, M. Coppoletta, C.M. Hoffman, J.M. Lydersen, M.P. North, R.A. Parsons, S.M. Ritter, and J.T. Stevens, 2021: Forest restoration and fuels reduction: Convergent or divergent? *BioScience*, **71** (1), 85–101. https://doi.org/10.1093/biosci/biaa134

361. Striplin, R., S.A. McAfee, H.D. Safford, and M.J. Papa, 2020: Retrospective analysis of burn windows for fire and fuels management: An example from the Lake Tahoe Basin, California, USA. *Fire Ecology*, **16** (1), 13. https://doi.org/10.1186/s42408-020-00071-3

362. Sleeter, B.M., D.C. Marvin, D.R. Cameron, P.C. Selmants, A.L. Westerling, J. Kreitler, C.J. Daniel, J. Liu, and T.S. Wilson, 2019: Effects of 21st-century climate, land use, and disturbances on ecosystem carbon balance in California. *Global Change Biology*, **25** (10), 3334–3353. https://doi.org/10.1111/gcb.14677

363. Xu, X., A. Huang, E. Belle, P. De Frenne, and G. Jia, 2022: Protected areas provide thermal buffer against climate change. *Science Advances*, **8** (44), 0119. https://doi.org/10.1126/sciadv.abo0119

364. Anderegg, W.R.L., A.T. Trugman, G. Badgley, C.M. Anderson, A. Bartuska, P. Ciais, D. Cullenward, C.B. Field, J. Freeman, S.J. Goetz, J.A. Hicke, D. Huntzinger, R.B. Jackson, J. Nickerson, S. Pacala, and J.T. Randerson, 2020: Climate-driven risks to the climate mitigation potential of forests. *Science*, **368** (6497), 7005. https://doi.org/10.1126/science.aaz7005

365. Ontl, T.A., M.K. Janowiak, C.W. Swanston, J. Daley, S. Handler, M. Cornett, S. Hagenbuch, C. Handrick, L. McCarthy, and N. Patch, 2020: Forest management for carbon sequestration and climate adaptation. *Journal of Forestry*, **118** (1), 86–101. https://doi.org/10.1093/jofore/fvz062

366. Krofcheck, D.J., C.C. Remy, A.R. Keyser, and M.D. Hurteau, 2019: Optimizing forest management stabilizes carbon under projected climate and wildfires. *Journal of Geophysical Research: Biogeosciences*, **124** (10), 3075–3087. https://doi.org/10.1029/2019jg005206

367. North, M.P., J.T. Stevens, D.F. Greene, M. Coppoletta, E.E. Knapp, A.M. Latimer, C.M. Restaino, R.E. Tompkins, K.R. Welch, R.A. York, D.J.N. Young, J.N. Axelson, T.N. Buckley, B.L. Estes, R.N. Hager, J.W. Long, M.D. Meyer, S.M. Ostoja, H.D. Safford, K.L. Shive, C.L. Tubbesing, H. Vice, D. Walsh, C.M. Werner, and P. Wyrsch, 2019: Tamm review: Reforestation for resilience in dry western U.S. forests. *Forest Ecology and Management*, **432**, 209–224. https://doi.org/10.1016/j.foreco.2018.09.007

368. Holl, K.D. and P.H.S. Brancalion, 2020: Tree planting is not a simple solution. *Science*, **368** (6491), 580–581. https://doi.org/10.1126/science.aba8232

369. Anderson, R., P.E. Bayer, and D. Edwards, 2020: Climate change and the need for agricultural adaptation. *Current Opinion in Plant Biology*, **56**, 197–202. https://doi.org/10.1016/j.pbi.2019.12.006

370. Meyer, M.D., B.L. Estes, A. Wuenschel, B. Bulaon, A. Stucy, D.F. Smith, and A.C. Caprio, 2019: Structure, diversity and health of Sierra Nevada red fir forests with reestablished fire regimes. *International Journal of Wildland Fire*, **28** (5), 386–396. https://doi.org/10.1071/wf18114

371. Mildenberger, M., P.D. Howe, S. Trachtman, L.C. Stokes, and M. Lubell, 2022: The effect of public safety power shut-offs on climate change attitudes and behavioural intentions. *Nature Energy*, **7** (8), 736–743. https://doi.org/10.1038/s41560-022-01071-0

372. Zanocco, C., J. Flora, R. Rajagopal, and H. Boudet, 2021: When the lights go out: Californians' experience with wildfire-related public safety power shutoffs increases intention to adopt solar and storage. *Energy Research & Social Science*, **79**, 102183. https://doi.org/10.1016/j.erss.2021.102183

373. Mildenberger, M., S. Trachtman, P. Howe, L. Stokes, and M. Lubell, 2021: Wildfire-mitigating power shut-offs promote household-level adaptation but not climate policy support. *Nature Portfolio*. https://doi.org/10.21203/rs.3.rs-631250/v1

374. Wong-Parodi, G., 2020: When climate change adaptation becomes a "looming threat" to society: Exploring views and responses to California wildfires and public safety power shutoffs. *Energy Research & Social Science*, **70**, 101757. https://doi.org/10.1016/j.erss.2020.101757

375. Martin, J.T., G.T. Pederson, C.A. Woodhouse, E.R. Cook, G.J. McCabe, K.J. Anchukaitis, E.K. Wise, P.J. Erger, L. Dolan, M. McGuire, S. Gangopadhyay, K.J. Chase, J.S. Littell, S.T. Gray, S. St. George, J.M. Friedman, D.J. Sauchyn, J.-M. St-Jacques, and J. King, 2020: Increased drought severity tracks warming in the United States' largest river basin. *Proceedings of the National Academy of Sciences of the United States of America*, **117** (21), 11328–11336. https://doi.org/10.1073/pnas.1916208117

376. Luo, X., S. Dee, S. Stevenson, Y. Okumura, N. Steiger, and L. Parsons, 2022: Last millennium ENSO diversity and North American teleconnections: New insights from paleoclimate data assimilation. *Paleoceanography and Paleoclimatology*, **37** (3), e2021PA004283. https://doi.org/10.1029/2021pa004283

377. Patricola, C.M., J.P. O'Brien, M.D. Risser, A.M. Rhoades, T.A. O'Brien, P.A. Ullrich, D.A. Stone, and W.D. Collins, 2020: Maximizing ENSO as a source of western US hydroclimate predictability. *Climate Dynamics*, **54** (1), 351–372. https://doi.org/10.1007/s00382-019-05004-8

378. Brown, T.C., V. Mahat, and J.A. Ramirez, 2019: Adaptation to future water shortages in the United States caused by population growth and climate change. *Earth's Future*, **7** (3), 219–234. https://doi.org/10.1029/2018ef001091

379. Di Baldassarre, G., N. Wanders, A. AghaKouchak, L. Kuil, S. Rangecroft, T.I.E. Veldkamp, M. Garcia, P.R. van Oel, K. Breinl, and A.F. Van Loon, 2018: Water shortages worsened by reservoir effects. *Nature Sustainability*, **1** (11), 617–622. https://doi.org/10.1038/s41893-018-0159-0

380. Elias, E., J. Reyes, C. Steele, and A. Rango, 2018: Diverse landscapes, diverse risks: Synthesis of the special issue on climate change and adaptive capacity in a hotter, drier Southwestern United States. *Climatic Change*, **148** (3), 339–353. https://doi.org/10.1007/s10584-018-2219-x

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

382. du Bray, M.V., B. Quimby, J.C. Bausch, A. Wutich, W.M. Eaton, K.J. Brasier, A. Brewis, and C. Williams, 2022: Red, white, and blue: Environmental distress among water stakeholders in a U.S. farming community. *Weather, Climate, and Society*, **14** (2), 585–595. https://doi.org/10.1175/wcas-d-21-0103.1

383. Wilson, N.J., T. Montoya, R. Arseneault, and A. Curley, 2021: Governing water insecurity: Navigating Indigenous water rights and regulatory politics in settler colonial states. *Water International*, **46** (6), 783–801. https://doi.org/10.1080/02508060.2021.1928972

384. Wutich, A., W. Jepson, C. Velasco, A. Roque, Z. Gu, M. Hanemann, M.J. Hossain, L. Landes, R. Larson, W.W. Li, O. Morales-Pate, N. Patwoary, S. Porter, Y.-s. Tsai, M. Zheng, and P. Westerhoff, 2022: Water insecurity in the Global North: A review of experiences in U.S. colonias communities along the Mexico border. *WIREs Water*, **9** (4), e1595. https://doi.org/10.1002/wat2.1595

385. Laufkötter, C., J. Zscheischler, and T.L. Frölicher, 2020: High-impact marine heatwaves attributable to human-induced global warming. *Science*, **369** (6511), 1621–1625. https://doi.org/10.1126/science.aba0690

386. Orr, J.A., R.D. Vinebrooke, M.C. Jackson, K.J. Kroeker, R.L. Kordas, C. Mantyka-Pringle, P.J. Van den Brink, F. De Laender, R. Stoks, M. Holmstrup, C.D. Matthaei, W.A. Monk, M.R. Penk, S. Leuzinger, R.B. Schäfer, and J.J. Piggott, 2020: Towards a unified study of multiple stressors: Divisions and common goals across research disciplines. *Proceedings of the Royal Society B: Biological Sciences*, **287** (1926), 20200421. https://doi.org/10.1098/rspb.2020.0421

387. Sunday, J.M., E. Howard, S. Siedlecki, D.J. Pilcher, C. Deutsch, P. MacCready, J. Newton, and T. Klinger, 2022: Biological sensitivities to high-resolution climate change projections in the California Current Marine Ecosystem. *Global Change Biology*, **28** (19), 5726–5740. https://doi.org/10.1111/gcb.16317

388. National Academies of Sciences, Engineering, and Medicine, 2022: *A Research Strategy for Ocean-based Carbon Dioxide Removal and Sequestration*. The National Academies Press, Washington, DC, 322 pp. https://doi.org/10.17226/26278

389. DeAngelo, J., B.T. Saenz, I.B. Arzeno-Soltero, C.A. Frieder, M.C. Long, J. Hamman, K.A. Davis, and S.J. Davis, 2023: Economic and biophysical limits to seaweed farming for climate change mitigation. *Nature Plants*, **9** (1), 45–57. https://doi.org/10.1038/s41477-022-01305-9

390. Levin, L.A., J.M. Alfaro-Lucas, A. Colaço, E.E. Cordes, N. Craik, R. Danovaro, H.-J. Hoving, J. Ingels, N.C. Mestre, S. Seabrook, A.R. Thurber, C. Vivian, and M. Yasuhara, 2023: Deep-sea impacts of climate interventions. *Science*, **379** (6636), 978–981. https://doi.org/10.1126/science.ade7521

391. Spillias, S., R. Kelly, R.S. Cottrell, K.R. O'Brien, R.-Y. Im, J.Y. Kim, C. Lei, R.W.S. Leung, M. Matsuba, J.A. Reis, Y. Sato, K. Sempert, and E. McDonald-Madden, 2023: The empirical evidence for the social-ecological impacts of seaweed farming. *PLOS Sustainability and Transformation*, **2** (2), e0000042. https://doi.org/10.1371/journal.pstr.0000042

392. Gobler, C.J., 2020: Climate change and harmful algal blooms: Insights and perspective. *Harmful Algae*, **91**, 101731. https://doi.org/10.1016/j.hal.2019.101731

393. Sea-Level Rise Leadership Team, 2022: State Agency Sea-Level Rise Action Plan for California. State of California, Ocean Protection Council. https://www.opc.ca.gov/webmaster/_media_library/2022/02/Item-7_Exhibit-A_SLR-Action-Plan-Final.pdf

394. State of California, 2022: Protecting Californians from Extreme Heat: A State Action Plan to Build Community Resilience. State of California. https://resources.ca.gov/-/media/CNRA-Website/Files/Initiatives/Climate-Resilience/2022-Final-Extreme-Heat-Action-Plan.pdf

395. State of California, 2021: California Climate Adaptation Strategy. State of California. https://climateresilience.ca.gov/

396. Governor's Office of Planning and Research, 2022: Climate Adaptation Planning Grant Program. State of California, Governor's Office of Planning and Research. https://opr.ca.gov/climate/icarp/grants/adaptation-planning-grant.html#:~:text=The%20Adaptation%20Planning%20Grant%20Program,infrastructure%20projects%20across%20the%20state

397. Caltrans, 2022: Climate Adaptation Planning—Sustainable Transportation Planning Grant Program. California Department of Transportation. https://www.grants.ca.gov/grants/climate-adaptation-planning-sustainable-transportation-planning-grant-program/

398. California Transportation Commission, 2022: Local Transportation Climate Adaptation Program (LTCAP). State of California, California Transportation Commission. https://catc.ca.gov/programs/local-transportation-climate-adaptation-program

399. Governor's Office of Planning and Research, 2022: Regional Resilience Planning and Implementation Grant Program. State of California, Governor's Office of Planning and Research. https://opr.ca.gov/climate/icarp/grants/regional-resilience-grant.html

400. Lester, S.E., R.R. Gentry, H.R. Lemoine, H.E. Froehlich, L.D. Gardner, M. Rennick, E.O. Ruff, and K.D. Thompson, 2022: Diverse state-level marine aquaculture policy in the United States: Opportunities and barriers for industry development. *Reviews in Aquaculture*, **14** (2), 890–906. https://doi.org/10.1111/raq.12631

401. Froehlich, H.E., J.Z. Koehn, K.K. Holsman, and B.S. Halpern, 2022: Emerging trends in science and news of climate change threats to and adaptation of aquaculture. *Aquaculture*, **549**, 737812. https://doi.org/10.1016/j.aquaculture.2021.737812

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

403. Dannenberg, M.P., D. Yan, M.L. Barnes, W.K. Smith, M.R. Johnston, R.L. Scott, J.A. Biederman, J.F. Knowles, X. Wang, T. Duman, M.E. Litvak, J.S. Kimball, A.P. Williams, and Y. Zhang, 2022: Exceptional heat and atmospheric dryness amplified losses of primary production during the 2020 U.S. Southwest hot drought. *Global Change Biology*, **28** (16), 4794–4806. https://doi.org/10.1111/gcb.16214

404. Robertson, A.D., Y. Zhang, L.A. Sherrod, S.T. Rosenzweig, L. Ma, L. Ahuja, and M.E. Schipanski, 2018: Climate change impacts on yields and soil carbon in row crop dryland agriculture. *Journal of Environmental Quality*, **47** (4), 684–694. https://doi.org/10.2134/jeq2017.08.0309

405. Collier, R.J., L.H. Baumgard, R.B. Zimbelman, and Y. Xiao, 2018: Heat stress: Physiology of acclimation and adaptation. *Animal Frontiers*, **9** (1), 12–19. https://doi.org/10.1093/af/vfy031

406. Klemm, T. and D.D. Briske, 2021: Retrospective assessment of beef cow numbers to climate variability throughout the U.S. Great Plains. *Rangeland Ecology & Management*, **78**, 273–280. https://doi.org/10.1016/j.rama.2019.07.004

407. Schwarz, L., K. Hansen, A. Alari, S.D. Ilango, N. Bernal, R. Basu, A. Gershunov, and T. Benmarhnia, 2021: Spatial variation in the joint effect of extreme heat events and ozone on respiratory hospitalizations in California. *Proceedings of the National Academy of Sciences of the United States of America*, **118** (22), e2023078118. https://doi.org/10.1073/pnas.2023078118

408. Georgescu, M., P.E. Morefield, B.G. Bierwagen, and C.P. Weaver, 2014: Urban adaptation can roll back warming of emerging megapolitan regions. *Proceedings of the National Academy of Sciences of the United States of America*, **111** (8), 2909–2914. https://doi.org/10.1073/pnas.1322280111

409. Hondula, D.M., M. Georgescu, and R.C. Balling, 2014: Challenges associated with projecting urbanization-induced heat-related mortality. *Science of The Total Environment*, **490**, 538–544. https://doi.org/10.1016/j.scitotenv.2014.04.130

410. Burke, M., A. Driscoll, S. Heft-Neal, J. Xue, J. Burney, and M. Wara, 2021: The changing risk and burden of wildfire in the United States. *Proceedings of the National Academy of Sciences of the United States of America*, **118** (2), e2011048118. https://doi.org/10.1073/pnas.2011048118

411. Magzamen, S., R.W. Gan, J. Liu, K. O'Dell, B. Ford, K. Berg, K. Bol, A. Wilson, E.V. Fischer, and J.R. Pierce, 2021: Differential cardiopulmonary health impacts of local and long-range transport of wildfire smoke. *GeoHealth*, **5** (3), 2020GH000330. https://doi.org/10.1029/2020gh000330

412. Hondula, D.M., J.L. Sabo, R. Quay, M. Chester, M. Georgescu, N.B. Grimm, S.L. Harlan, A. Middel, S. Porter, C.L. Redman, B. Rittmann, B.L. Ruddell, and D.D. White, 2019: Cities of the Southwest are testbeds for urban resilience. *Frontiers in Ecology and the Environment*, **17** (2), 79–80. https://doi.org/10.1002/fee.2005

413. Keith, L. and S. Meerow, 2022: Planning for Urban Heat Resilience. PAS Report 600. American Planning Association, 99 pp. https://www.planning.org/publications/report/9245695/

414. Keith, L., S. Meerow, D.M. Hondula, V.K. Turner, and J.C. Arnott, 2021: Deploy heat officers, policies and metrics. *Nature*, **598** (7879), 29–31. https://doi.org/10.1038/d41586-021-02677-2

415. Schramm, P.J., A.L.A. Janabi, L.W. Campbell, J.L. Donatuto, and S.C. Gaughen, 2020: How Indigenous communities are adapting to climate change: Insights from the Climate-Ready Tribes Initiative. *Health Affairs*, **39** (12), 2153–2159. https://doi.org/10.1377/hlthaff.2020.00997

416. OPHDST, 2023: National Notifiable Disease Surveillance System: Notifiable Infectious Disease Tables. Centers for Disease Control and Prevention, Office of Public Health Data, Surveillance, and Technology. https://www.cdc.gov/nndss/data-statistics/infectious-tables/index.html

417. Rochlin, I., A. Faraji, K. Healy, and T.G. Andreadis, 2019: West Nile virus mosquito vectors in North America. *Journal of Medical Entomology*, **56** (6), 1475–1490. https://doi.org/10.1093/jme/tjz146

418. Reisen, W.K., 2012: The contrasting bionomics of *Culex* mosquitoes in western North America. *Journal of the American Mosquito Control Association*, **28** (4s), 82–91. https://doi.org/10.2987/8756-971x-28.4.82

419. Harrigan, R.J., H.A. Thomassen, W. Buermann, and T.B. Smith, 2014: A continental risk assessment of West Nile virus under climate change. *Global Change Biology*, **20** (8), 2417–2425. https://doi.org/10.1111/gcb.12534

420. Habeeb, D., J. Vargo, and B. Stone, 2015: Rising heat wave trends in large US cities. *Natural Hazards*, **76** (3), 1651–1665. https://doi.org/10.1007/s11069-014-1563-z

421. Ebi, K.L., A. Capon, P. Berry, C. Broderick, R. de Dear, G. Havenith, Y. Honda, R.S. Kovats, W. Ma, A. Malik, N.B. Morris, L. Nybo, S.I. Seneviratne, J. Vanos, and O. Jay, 2021: Hot weather and heat extremes: Health risks. *The Lancet*, **398** (10301), 698–708. https://doi.org/10.1016/s0140-6736(21)01208-3

422. Crooks, J.L., W.E. Cascio, M.S. Percy, J. Reyes, L.M. Neas, and E.D. Hilborn, 2016: The association between dust storms and daily non-accidental mortality in the United States, 1993–2005. *Environmental Health Perspectives*, **124** (11), 1735–1743. https://doi.org/10.1289/ehp216

423. Reid, C.E., E.M. Considine, G.L. Watson, D. Telesca, G.G. Pfister, and M. Jerrett, 2019: Associations between respiratory health and ozone and fine particulate matter during a wildfire event. *Environment International*, **129**, 291–298. https://doi.org/10.1016/j.envint.2019.04.033

424. Borlina, C.S. and N.O. Rennó, 2017: The impact of a severe drought on dust lifting in California's Owens Lake area. *Scientific Reports*, **7** (1), 1784. https://doi.org/10.1038/s41598-017-01829-7

425. U.S. Census Bureau, 2022: Foreign Born. U.S. Department of Commerce, U.S. Census Bureau. https://www.census.gov/topics/population/foreign-born.html

426. Reid, C.E. and M.M. Maestas, 2019: Wildfire smoke exposure under climate change: Impact on respiratory health of affected communities. *Current Opinion in Pulmonary Medicine*, **25** (2). https://doi.org/10.1097/mcp.0000000000000552

427. Bekkar, B., S. Pacheco, R. Basu, and N. DeNicola, 2020: Association of air pollution and heat exposure with preterm birth, low birth weight, and stillbirth in the US: A systematic review. *JAMA Network Open*, **3** (6), e208243. https://doi.org/10.1001/jamanetworkopen.2020.8243

428. Benmarhnia, T., J. Huang, R. Basu, J. Wu, and T.A. Bruckner, 2017: Decomposition analysis of Black–White disparities in birth outcomes: The relative contribution of air pollution and social factors in California. *Environmental Health Perspectives*, **125** (10), 107003. https://doi.org/10.1289/ehp490

429. Lowe, A.A., B. Bender, A.H. Liu, T. Solomon, A. Kobernick, W. Morgan, and L.B. Gerald, 2018: Environmental concerns for children with asthma on the Navajo Nation. *Annals of the American Thoracic Society*, **15** (6), 745–753. https://doi.org/10.1513/annalsats.201708-674ps

430. Sun, Y., S.D. Ilango, L. Schwarz, Q. Wang, J.-C. Chen, J.M. Lawrence, J. Wu, and T. Benmarhnia, 2020: Examining the joint effects of heatwaves, air pollution, and green space on the risk of preterm birth in California. *Environmental Research Letters*, **15** (10), 104099. https://doi.org/10.1088/1748-9326/abb8a3

431. USGCRP, 2016: *The Impacts of Climate Change on Human Health in the United States: A Scientific Assessment*. Crimmins, A., J. Balbus, J.L. Gamble, C.B. Beard, J.E. Bell, D. Dodgen, R.J. Eisen, N. Fann, M.D. Hawkins, S.C. Herring, L. Jantarasami, D.M. Mills, S. Saha, M.C. Sarofim, J. Trtanj, and L. Ziska, Eds. U.S. Global Change Research Program, Washington, DC, 312 pp. https://doi.org/10.7930/j0r49nqx

432. Ebi, K.L., J. Vanos, J.W. Baldwin, J.E. Bell, D.M. Hondula, N.A. Errett, K. Hayes, C.E. Reid, S. Saha, J. Spector, and P. Berry, 2021: Extreme weather and climate change: Population health and health system implications. *Annual Review of Public Health*, **42** (1), 293–315. https://doi.org/10.1146/annurev-publhealth-012420-105026

433. Dennison, P.E., S.C. Brewer, J.D. Arnold, and M.A. Moritz, 2014: Large wildfire trends in the western United States, 1984–2011. *Geophysical Research Letters*, **41** (8), 2928–2933. https://doi.org/10.1002/2014gl059576

434. Parks, S.A. and J.T. Abatzoglou, 2020: Warmer and drier fire seasons contribute to increases in area burned at high severity in western US forests from 1985 to 2017. *Geophysical Research Letters*, **47** (22), e2020GL089858. https://doi.org/10.1029/2020gl089858

435. Kitzberger, T., D.A. Falk, A.L. Westerling, and T.W. Swetnam, 2017: Direct and indirect climate controls predict heterogeneous early-mid 21st century wildfire burned area across western and boreal North America. *PLoS ONE*, **12** (12), e0188486. https://doi.org/10.1371/journal.pone.0188486

436. Hurteau, M. and M. North, 2008: Mixed-conifer understory response to climate change, nitrogen, and fire. *Global Change Biology*, **14** (7), 1543–1552. https://doi.org/10.1111/j.1365-2486.2008.01584.x

437. Hurteau, M.D., S. Liang, A.L. Westerling, and C. Wiedinmyer, 2019: Vegetation-fire feedback reduces projected area burned under climate change. *Scientific Reports*, **9** (1), 2838. https://doi.org/10.1038/s41598-019-39284-1

438. Littell, J.S., 2018: Drought and fire in the western USA: Is climate attribution enough? *Current Climate Change Reports*, **4** (4), 396–406. https://doi.org/10.1007/s40641-018-0109-y

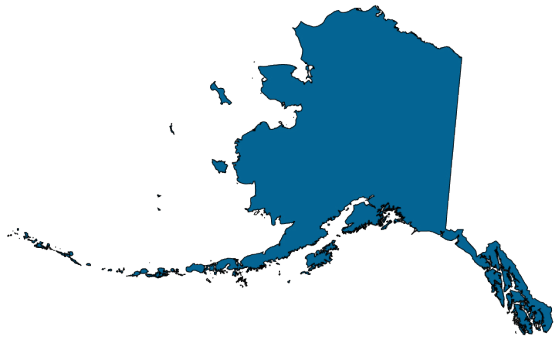
439. Stowell, J.D., G. Geng, E. Saikawa, H.H. Chang, J. Fu, C.-E. Yang, Q. Zhu, Y. Liu, and M.J. Strickland, 2019: Associations of wildfire smoke $PM_{2.5}$ exposure with cardiorespiratory events in Colorado 2011–2014. *Environment International*, **133**, 105151. https://doi.org/10.1016/j.envint.2019.105151

440. Dixon, L., F. Tsang, and G. Fitts, 2018: The Impact of Changing Wildfire Risk on California's Residential Insurance Market. California's Fourth Climate Change Assessment. CCCA4-CNRA-2018-008. California Natural Resources Agency. https://www.energy.ca.gov/sites/default/files/2019-12/Forests_CCCA4-CNRA-2018-008_ada.pdf

441. Wang, D., D. Guan, S. Zhu, M.M. Kinnon, G. Geng, Q. Zhang, H. Zheng, T. Lei, S. Shao, P. Gong, and S.J. Davis, 2021: Economic footprint of California wildfires in 2018. *Nature Sustainability*, **4** (3), 252–260. https://doi.org/10.1038/s41893-020-00646-7

Fifth National Climate Assessment: Chapter 29

Alaska



Chapter 29. Alaska

Authors and Contributors

Federal Coordinating Lead Author

Colleen Strawhacker, National Science Foundation

Chapter Lead Author

Henry P. Huntington, Ocean Conservancy

Agency Chapter Lead Authors

Jeffrey Falke, US Geological Survey, Alaska Cooperative Fish and Wildlife Research Unit

Ellen M. Ward, National Oceanic and Atmospheric Administration

Chapter Authors

Linda Behnken, Alaska Longline Fishermen's Association

Tracie N. Curry, Northern Social-Environmental Research

Adelheid C. Herrmann, University of Alaska Fairbanks, Alaska Center for Climate Assessment and Policy

Cana Uluak Itchuaqiyaq, Virginia Tech

Jeremy S. Littell, US Geological Survey, Alaska Climate Adaptation Science Center

Elizabeth A. Logerwell, NOAA Fisheries, Alaska Fisheries Science Center

Danielle Meeker, University of Alaska Fairbanks, Alaska Center for Climate Assessment and Policy

Jacquelyn R. Overbeck, State of Alaska Division of Geological & Geophysical Surveys (through July 2022)

Darcy L. Peter, Alaska Conservation Foundation

Rebecca Pincus, Woodrow Wilson Center, Polar Institute

Alyssa A. Quintyne, The Alaska Center

Sarah F. Trainor, University of Alaska Fairbanks, Alaska Center for Climate Assessment and Policy

Sarah A. Yoder, Alaska Department of Health

Technical Contributors

Patricia Chambers, Ocean Conservancy

Willow M. Hetrick, Chugach Regional Resources Commission

Michelle Michaels, US Army Corps of Engineers, Cold Regions Research and Engineering Laboratory

Patricia E. Nelsen, US Army Corps of Engineers, Cold Regions Research and Engineering Laboratory

Erin Shew, Chugach Regional Resources Commission

Elena B. Sparrow, University of Alaska Fairbanks, International Arctic Research Center

Richard L. Thoman Jr., University of Alaska Fairbanks

Mark F. Turgeon, Department of Defense, Climate Action Team

Vanessa R. von Biela, US Geological Survey, Alaska Science Center

Review Editor

Micah B. Hahn, University of Alaska Anchorage

Cover Art

Tami Phelps

Recommended Citation

Huntington, H.P., C. Strawhacker, J. Falke, E.M. Ward, L. Behnken, T.N. Curry, A.C. Herrmann, C.U. Itchuaqiyaq, J.S. Littell, E.A. Logerwell, D. Meeker, J.R. Overbeck, D.L. Peter, R. Pincus, A.A. Quintyne, S.F. Trainor, and S.A. Yoder, 2023: Ch. 29. Alaska. In: *Fifth National Climate Assessment*. Crimmins, A.R., C.W. Avery, D.R. Easterling, K.E. Kunkel, B.C. Stewart, and T.K. Maycock, Eds. U.S. Global Change Research Program, Washington, DC, USA. https://doi.org/10.7930/NCA5.2023.CH29

Table of Contents

Introduction 5

Key Message 29.1
Our Health and Healthcare Are at Risk 10
Box 29.1. "I've Been Called to Pray" 14

Key Message 29.2
Our Communities Are Navigating Compounding Stressors 15
Box 29.2. "We Had to Dig In and Out of Our House" 18

Key Message 29.3
Our Livelihoods Are Vulnerable Without Diversification 19
Box 29.3. What It Means to Lose Salmon 22

Key Message 29.4
Our Built Environment Will Become More Costly 23
Box 29.4. The Cost of Thawing Ground for Alaska Industries 25

Key Message 29.5
Our Natural Environment Is Transforming Rapidly 26
Box 29.5. A New Era for Pacific Salmon Research in Alaska 29

Key Message 29.6
Our Security Faces Greater Threats 30
Box 29.6. Tribal Perspectives on "Security" 33

Key Message 29.7
Our Just and Prosperous Future Starts with Adaptation 34
Box 29.7. Tribal Adaptation to Climate Change 38

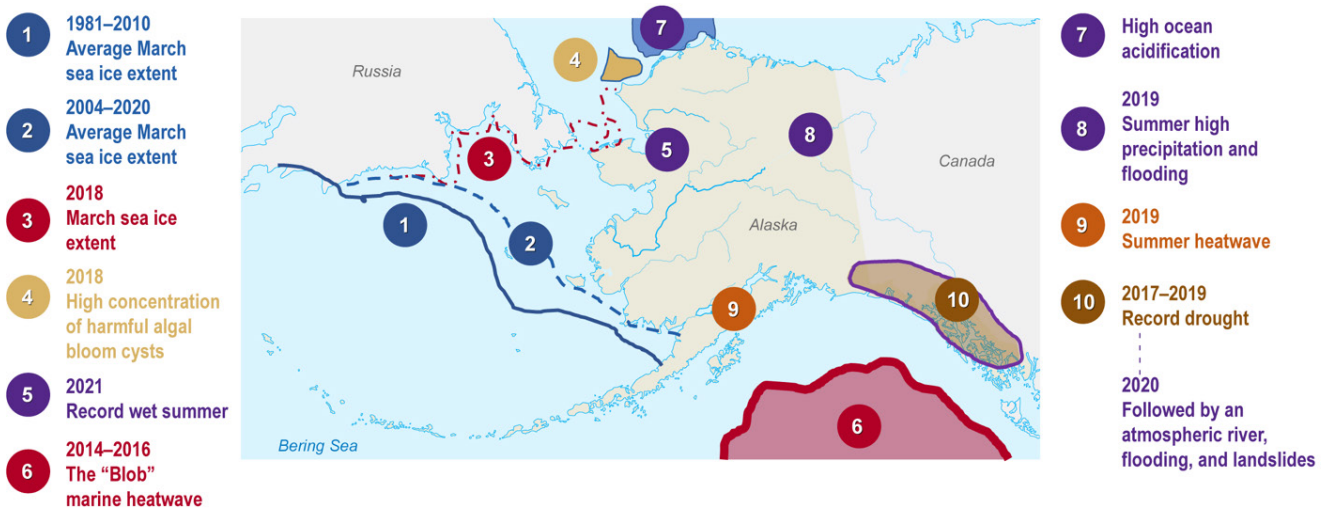
Traceable Accounts 39
Process Description 39
Key Message 29.1 39
Key Message 29.2 40
Key Message 29.3 41
Key Message 29.4 42
Key Message 29.5 42
Key Message 29.6 44
Key Message 29.7 44

References 46

Introduction

Alaska is warming two to three times faster than the global average.[1,2] The physical and ecological effects of warming are evident around the state (Figures 29.1, 29.11). Glaciers are shrinking, permafrost is thawing, and sea ice is diminishing. The growing season is longer, and fish, mammals, birds, and insects have increased in numbers in some areas and dropped sharply in others. This combination of environmental effects has far-reaching consequences for people statewide. Following a brief description of distinctive characteristics of Alaska and an overview of recent climatology in this Introduction, the chapter emphasizes the societal implications of climate change for Alaska to a greater degree than in the corresponding chapters of previous National Climate Assessments (NCAs), with illustrative examples and recurring themes, such as salmon, governance, and adaptation.

Recent Climate-Driven Extremes and Notable Events



Climate-driven extreme events continue throughout Alaska.

Figure 29.1. Climate-driven extremes and notable events have recently affected different regions of Alaska. These events have redefined expectations of regional extremes and challenged preparedness (Focus on Compound Events). March sea ice extent in 2018 was far below recent low averages (Figure A4.6).[3] High concentrations of harmful algal bloom cysts were discovered in the Chukchi Sea (KM 29.1).[4] A record wet summer occurred in northwest Alaska in 2021, and 2019 brought uncharacteristic precipitation and flooding on the North Slope. The effects of the 2014–2016 North Pacific marine heatwave (the "Blob")[5] have become clear (Figures 29.11, A4.11; Box 10.1). Ongoing ocean acidification in Arctic Alaska has contributed to fundamental changes in marine water quality (KM 3.4).[6] In summer 2019, a record and persistent heatwave occurred in southern Alaska. A multiyear drought (2017–2019)[7,8] in Southeast Alaska's rainforest was followed by intense rain and destructive landslides.[9] Figure credit: USGS, NOAA Fisheries, and Ocean Conservancy.

Climatologically, Alaska is notable for frozen water in the forms of permafrost, sea ice, land ice, and snow. Culturally, Alaska is home to 21 distinct Indigenous Peoples, comprising about one-fifth of the population. Alaska's lands and communities are governed by a complex system of federal, state, and local agencies and 229 Tribal governments, as well as Alaska Native regional and village corporations. More than 200 communities are located off the road system. Most of these have year-round access by only small aircraft and summer access by ferry, cargo barge, or river vessel. Economically, Alaska is dominated by the public sector and by natural resource industries, with fisheries being the largest private-sector industry in terms of employment and oil and gas the largest in terms of revenue.[10] These characteristics shape the ways that climate change affects society in Alaska (see also KM 29.2).

Responses to climate change in Alaska's communities occur in the context of the governance systems divided among federal, state, regional, local, and Tribal agencies, with various and often overlapping responsibilities. About two-thirds of Alaska's land is under federal jurisdiction, with another quarter owned by the State of Alaska and a tenth owned by Alaska Native corporations. Tribal governments, with few exceptions, do not have geographical jurisdiction but are responsible for many programs affecting Tribal members. Because climate change affects society in many ways, fragmented governance can frustrate a coordinated response or the ability of communities to address climate change in a holistic fashion (Figure 29.16). Some precedents, such as the Denali Commission (an independent federal agency designed to provide Alaska with critical utilities, infrastructure, and economic support), demonstrate the potential for greater coordination of government support to better address community needs, if adequate resources and direction are provided.

Since NCA4 was published in 2018, Alaska has continued to experience rapid, widespread, and extreme climate-related changes in the form of ocean warming, record low sea ice,[3,11,12] the world's highest rates of ocean acidification,[6,13] an increasing frequency of extreme events such as marine heatwaves (KM 10.1),[5,12,14,15] and extreme snow and rain storms in winter (App. 4.2; Box 29.2).[16,17] These changes have reduced biological productivity, shifted seasonal timing of productivity, altered food web dynamics, and caused steep declines in prey.[18,19,20,21] In many freshwater environments, these changes result in a combination of reduced summer streamflows, increased summer water temperatures, hypoxia, and decreased prey abundance, which are lethal to many aquatic species.[7,19,22,23] There is no indication that these trends will slow or reverse in the near future (KM 2.2).[19,24,25,26,27,28,29]

Climate change in Alaska is driven by global trends (KM 2.1), but regional impacts are evident. The state is experiencing warming air temperatures,[1] record-breaking droughts,[7] reduced snowpack,[1] shrinking glaciers,[30,31] continued permafrost thaw,[32] relative sea level change,[33] record numbers of pollen outbreaks, increasingly destructive wildfires,[34] changing snowfall amounts and seasons,[1] and changing patterns of windstorms.[35] Although year-to-year variability is and will be a feature of Alaska's climate,[36] it is apparent that detectable warming trends started in the 1970s.[1,2] Annual average temperatures have increased across the state since 1971, with increases ranging from 2.4°F in Southeast Alaska to 6.2°F in northern Alaska,[1] up to 2.6 times the rate of change in the Lower 48. Of the annual average Alaska warming for 1950–2017, 75% is explained by greenhouse gas warming.[37] Heatwaves are increasing in the Arctic.[38] A 2019 summer heatwave brought record-high temperatures to southern and Interior Alaska,[39] with daily high temperatures exceeding normal by more than 20°F. This event had important community impacts such as wildfire smoke and fish kills, as well as uncharacteristically severe and expensive disturbances such as the Swan Lake Fire on the Kenai Peninsula.[40] Alaska's statewide annual average surface air temperature is projected to increase by 8.1°F (4.5°C) by the end of the century under an intermediate scenario (SSP2-4.5) and 14.2°F (7.9°C) under a very high scenario (SSP5-8.5), for 2081–2100 relative to 1981–2010.[41,42] This projection is 2.5°F (1.4°C) greater than comparable regional projections in NCA4.[43]

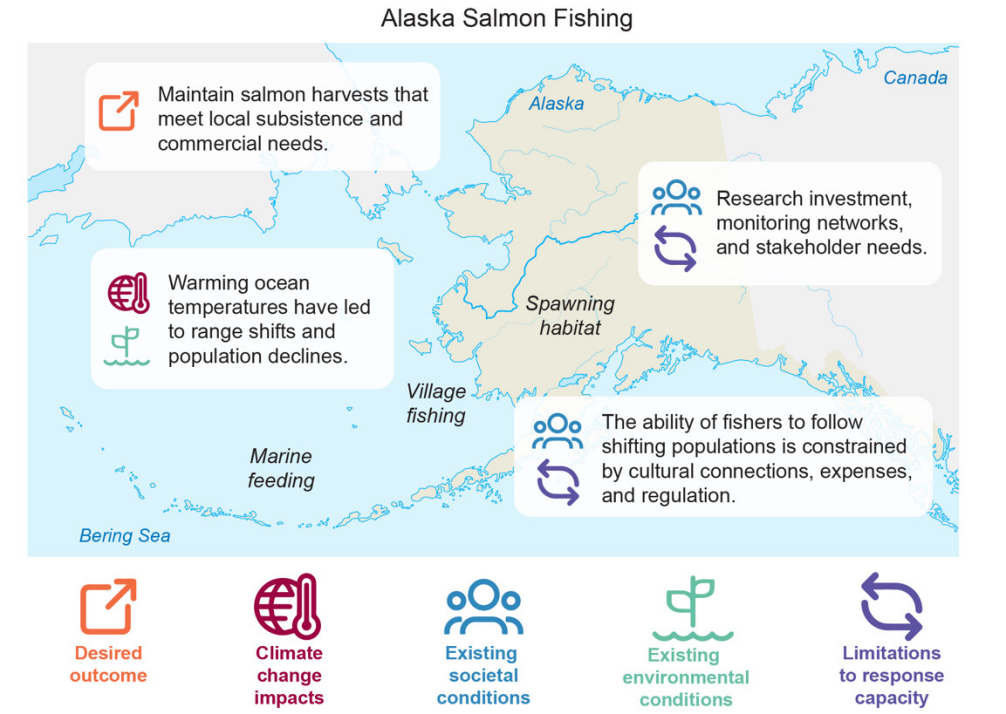
Annual and seasonal precipitation totals are generally increasing, but the size and significance of the changes vary with dataset and location,[1,44] with the most consistent increasing trends in northern Alaska, particularly on the North Slope (over 2.5% per decade).[1] One- and five-day maximum precipitation is increasing in most Alaska climate divisions, but changes are statistically significant since 1957 on the North Slope (over 2% per decade) and in the southeastern part of the Interior (over 1.4% per decade). Recent unprecedented extreme rainfall and seasonal precipitation events have presented challenges in multiple parts of Alaska. For example, an atmospheric river (an atmospheric flow that causes extreme precipitation) in December 2020 broke all-time extreme 24-hour precipitation records in 11 Southeast Alaska communities and caused two fatalities and more than $33.5 million (in 2022 dollars) in public property damage due to rain-on-snow and storm runoff as well as wind and landslides. Alaska's statewide average annual total precipitation is projected to increase by 20.6% by the end of the century under an intermediate scenario

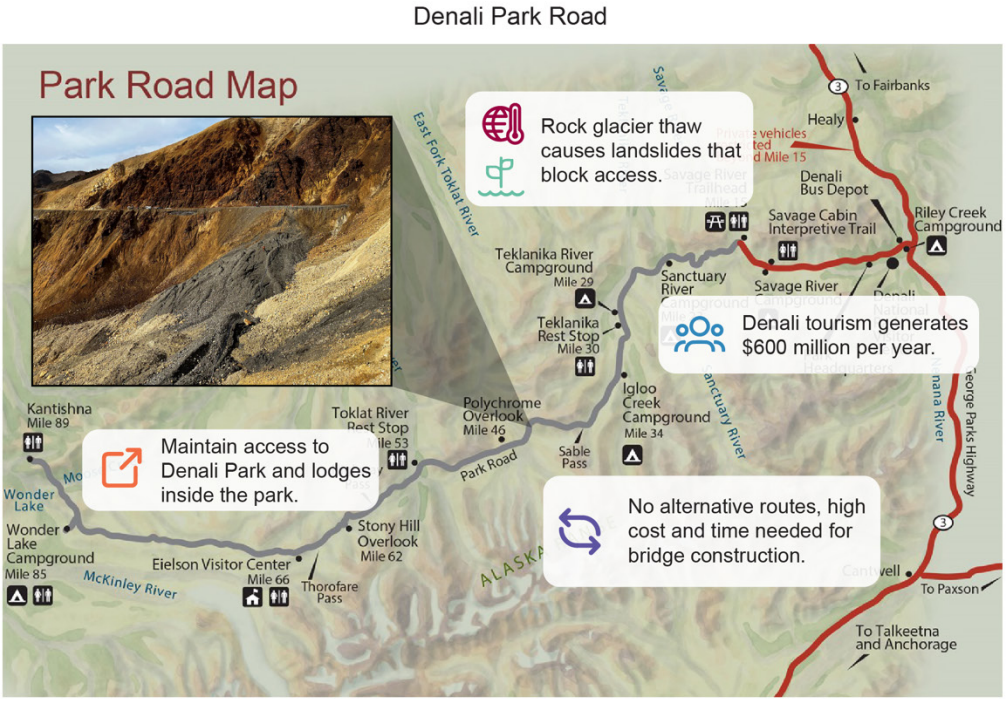
(SSP2-4.5) and 35.8% by the end of the century under a very high scenario (SSP5-8.5), for 2081–2100 relative to 1981–2010.[41,42]

Some of the most direct impacts of rising temperatures are on the cryosphere—snow, ice, and permafrost (KM 3.4),[45] with substantial, consequential impacts on hydrology, ecosystem function, infrastructure, and human health and livelihoods. Across the Arctic, temperature increases are driving a shortened snow cover season, melting glaciers, thawing permafrost, and less predictable sea ice extent (App. 4.3).[1,45] Snowfall has decreased in autumn and spring but increased in parts of Alaska in the midwinter snow season.[1] The Alaska snowfall season is projected to decrease across the state,[46,47] and water entrained in snowpack is projected to decrease between 20% and 60% by the 2050s (2040–2069, moderate emissions) and between 40% and 90% by the 2080s (2070–2099, higher emissions) in most of the southern and western parts of the state. The highest elevations and coldest parts of Alaska, however, could see no net loss or even increases up to 35% (such as in the Brooks Range) in snowfall during the midwinter snow season.[46] For March, historically the month of maximum sea ice extent, the Bering Sea ice extent has decreased by about 20,000 square miles per decade since 1957,[1] and record minimums in 2018 and 2019 were associated with warm ocean temperatures.[48] For September, historically the month of minimum sea ice extent, the Chukchi and Beaufort ice extents have decreased by about 27,000 square miles per decade and 31,000 square miles per decade, respectively.[1] These sea ice losses accelerated in the mid-1990s. Permafrost degradation and thaw described in previous NCAs continues and may be accelerating due to recent warm winters and, for 2018, increased snow cover (e.g., Douglas et al. 2021[49]), which insulates the surface from cold air above.[50] Previously reported projections of permafrost degradation may underestimate permafrost thaw rates.[51]

These extensive changes affect Alaska's society in many ways—in the context of Alaska's existing geography, governance, economics, demographics, cultures, and social services (Figure 29.2 provides two examples). By disrupting familiar patterns and conditions, climate change exacerbates existing tensions and conflicts across the state. As coastlines and riverbanks erode, and as fish and wildlife distributions shift, potential responses include relocating communities or using new areas for hunting, fishing, and other uses. However, current societal systems can constrain the options available for responding to change (KM 20.2). Land and resource management policies and practices, for example, may prevent or restrict the movements of people and their activities.[52] At the same time, the strong ties that Alaska Native Peoples have to their lands and waters are a vital consideration in any equitable responses to change.

The Context of Climate Change Response





The response to climate change depends on the desired societal outcome and is shaped by existing societal and environmental conditions.

Figure 29.2. Two examples illustrate the interactions between climate change and societal and environmental factors for an activity important throughout much of the state and for a place that attracts many residents and visitors alike. Successful salmon fishing in rural Alaska villages is threatened by ecological changes affecting salmon spawning and survival (top; Boxes 29.3, 29.5). The $600 million annual tourism economy of Denali National Park is threatened by a thawing rock glacier that has damaged the access road (bottom; Box 29.4). Figure credit: (top) Ocean Conservancy; (bottom) adapted from NPS. Photo credit: NPS

Although Alaskans cannot stop global warming alone, they can choose to take actions that contribute to global efforts to limit climate change and be leaders in effective planning and adaptation (KM 31.3). From Alaska Native culture camps teaching climate and cultural resilience to courses on residential solar installation for homeowners and workers, Alaskans working together can accomplish a great deal. The effectiveness of cooperation, together with careful preparation and planning, was seen in the rapid and effective response to the November 2018 earthquake in Southcentral Alaska.[53] If Alaska's response to climate change remains fragmented, climate change will be intertwined with nearly all of the other persistent problems facing Alaska. If Alaska's society pulls together, much can be done to create lasting benefits for today and for future generations, contributing to a prosperous and just society in the state (Table 29.1).

Table 29.1. The Intersection of Climate Change and Societal Context

Climate change exacerbates existing societal tensions, but responding effectively to climate change can yield many societal benefits, as shown in the examples here for each of the chapter's Key Messages.

Key Message	Examples of Challenges That Intersect with Climate Change	Examples of Opportunities for Climate Responses with Multiple Benefits
29.1 Our Health and Healthcare Are at Risk	Inequitable access to basic nutrition and physical and mental healthcare services	Strong public health services
29.2 Our Communities Are Navigating Compounding Stressors	Food insecurity	Increasing community capacity and agency
29.3 Our Livelihoods Are Vulnerable Without Diversification	High prices and scarce jobs, especially in rural Alaska	Renewable energy and value-added industries
29.4 Our Built Environment Will Become More Costly	High needs, high costs, and barriers to implementation	Cross-community learning, priority setting by communities themselves
29.5 Our Natural Environment Is Transforming Rapidly	Allocation conflicts and cumulative effects of human activities	Ecosystem-based management and equitable participation
29.6 Our Security Faces Greater Threats	Conflict at many scales and competition for limited resources	Recognizing and supporting widespread contributions to security
29.7 Our Just and Prosperous Future Starts with Adaptation	The societal needs listed above present challenges to climate change adaptation	Cross-scale learning and cooperation to improve justice and equity

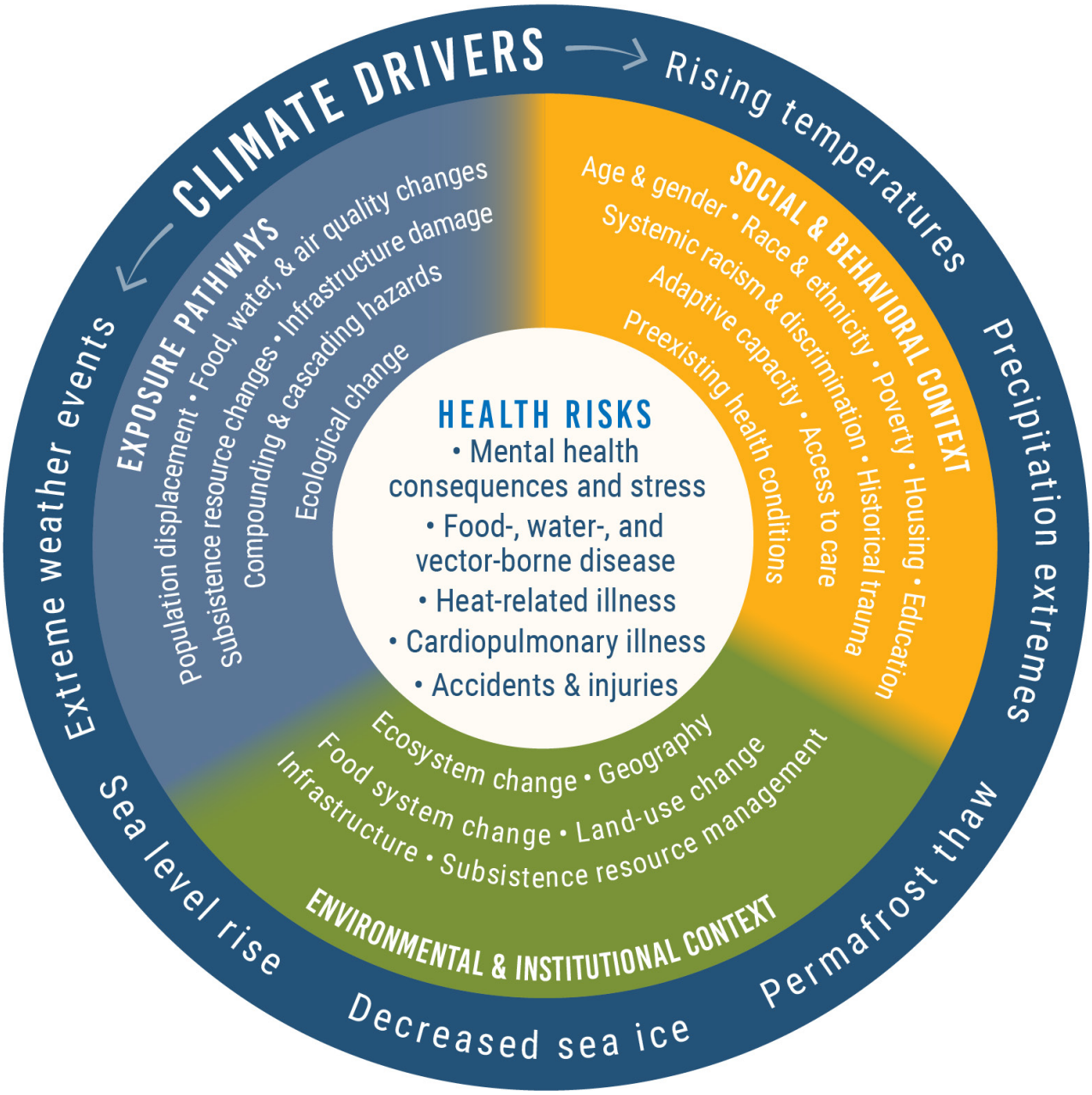
Key Message 29.1

Our Health and Healthcare Are at Risk

Health disparities in Alaska, including access to healthcare and health outcomes, are exacerbated by climate change (*high confidence*). The well-being of Alaska residents will be further challenged by climate-driven threats and by emerging diseases (*medium confidence*). Improving health surveillance and healthcare access statewide can increase resilience to events that threaten public health (*medium confidence*).

Many Alaskans, particularly Alaska Native Peoples, have a distinct connection to and understanding of the natural environment (KM 29.5) and depend on the land, sea, and natural resources for their economic activities, food security, health, culture, and overall well-being. This close connection to local ecosystems, combined with the geographical isolation of many communities and their resulting distance from healthcare and other services, creates a population particularly vulnerable to health impacts from the local effects of a changing climate (Figure 29.3) yet also fosters self-reliance and resilience.

Climate, Health, and Well-Being in Communities



The impacts of climate change on health and well-being depend on many social and environmental factors.

Figure 29.3. Well-being includes physical, mental, and spiritual health outcomes, all of which are shaped by many contextual factors, including environmental change and governance, social and behavioral characteristics and systems, and the exposure pathways that connect the changing environment to human health. All of these contextual factors are affected by climate change and occur simultaneously. Adapted from Balbus et al. 2016.[54]

Climate change in Alaska highlights existing inequities confronting many racial and ethnic groups, including discrimination, lack of access to healthcare, lack of indoor plumbing, and poverty.[55,56,57] In rural Alaska especially, underserved communities often face food and water insecurity, inadequate sanitation, overcrowding in homes, limited transportation options, limited medical access, and significant geographical isolation.[58,59,60] People living in such settings are disproportionately impacted by climate change (KMs 15.2, 20.1),[61] and have limited options to respond to additional disturbances.

The lack of basic household sanitation facilities (Figure 4.16) contributes to health disparities, especially in rural Alaska. The lack of indoor plumbing was a key factor contributing to the high incidence of COVID-19 cases among Tribal communities (Focus on COVID-19 and Climate Change).[62,63,64] More than 3,300 households in more than 30 Alaska communities lack in-home piped water and sewer services.[65,66] In Alaska, the lack of water and sewer services is associated with multiple adverse health outcomes.[67,68,69] Environmental factors such as permafrost thaw, river erosion, and flooding exacerbate inequitable health-related infrastructure, and climate change has created new challenges to building and supporting sanitation systems. The Portable Arctic Sanitation System, developed by the Alaska Native Tribal Health Consortium and tested in five communities to date, provides households with treated water for drinking and a handwashing sink, in addition to a waterless toilet system. These systems allow households to meet basic water and sanitation needs in situations such as damage to existing water and sewer infrastructure or community relocation.[66] While not a replacement for a piped water system, these systems are a successful example of responding to climate hazards in Alaska (KM 16.3).

Climate change in Alaska is related to a range of environmental catastrophes, which can directly impact health in significant ways that may not be well known (KM 15.1). Flooding, for example, negatively impacts physical and mental well-being, with special and persistent implications for certain populations, such as pregnant people and children.[70,71] In Alaska, these effects are compounded by preexisting disparities, such as limited access to healthcare (e.g., pregnant people in rural Alaska typically travel to urban areas for childbirth) and the lack of alternative housing options. In the aftermath of ex-Typhoon Merbok in September 2022, which resulted in widespread flooding of a thousand miles of Alaska's coastline, people experienced loss of air travel service, multiday power outages, and damaged housing (often resulting in a subsequent need to move to a different community).[72]

Environmental disruption due to climate change can lead to increased rates of suicidality, among other negative mental health effects (KM 15.1).[73] These effects, including a profound loss of connection to a landscape altered by climate change, can increase instances of mental illness and spiritual grief in affected populations and subsequent generations.[74,75,76] Forced displacement inland due to rising sea levels, coastal erosion, flooding, and permafrost thaw disrupt social networks and increase instances of homelessness.[77,78,79] Alaska Native populations already experience significantly elevated rates of suicide, especially among youth.[80] Based on research with Inuit in Labrador, Canada, Alaska Native populations whose ways of life and culture depend on subsistence activities may be particularly vulnerable to negative mental health impacts related to climate change because of their deep connection to the land, exacerbated by existing disparities in mental health services (KM 16.1).[81]

Various health concerns connected to climate change have been raised by Alaska residents and public health officials (KM 15.1). For example, wildfire smoke exposure is associated with an increased risk of adverse health outcomes among Alaska Natives and rural residents.[82] This increased risk is thought to be due, in part, to underlying differences in rates of chronic disease, as well as access to healthcare and resources for exposure reduction (e.g., air filters).[82] Common exposure-reduction strategies may not be an option for many households. For example, few homes in Alaska have air-conditioning. During a wildfire smoke event that occurs at the same time as a heatwave, people must weigh the risks of opening a window to decrease the heat versus keeping windows closed to minimize smoke exposure. When developing adaptation strategies for climate hazards, it is critical to consider existing health disparities within communities, the relative capacity of individuals to adapt, and the potential to exacerbate existing inequities (KMs 15.3, 20.3).

The expanding geographic ranges of tick species and the potential implications for human health are another concern (KM 8.2). The blacklegged tick and western blacklegged tick, carriers of the bacteria that cause Lyme disease, are not established in Alaska, although the western blacklegged tick has been found on humans and domestic animals that have not reported recent travel out of the state.[83,84] Current conditions in

Southeast Alaska and some portions of Southcentral Alaska are suitable for the establishment of the western blacklegged tick, and models predict an increase in the suitability of tick habitat in many areas.[84] While there have been no known locally acquired human cases of Lyme disease in Alaska, the risk of occurrence is expected to increase, especially for those who spend a lot of time outdoors.[57]

Rabies is another disease that can be transmitted from animals to people, with potential connections to changing climate conditions due to shifting ranges of host species. In Alaska, rabies is found in populations of Arctic and red fox populations along the northern and western coasts. During the 2020/21 winter, there was a widespread outbreak of rabies in western Alaska, with more than 35 confirmed cases in animals, compared with an average of four to five cases each year. Changes in sea ice and prey availability may have played a role by increasing exposure of red foxes to rabid Arctic foxes and thus spreading rabies to inland areas as well as along the coast.[85,86]

Climate change is also affecting the ability to dry and store food in traditional ways[87] and increasing the potential for adverse health effects from processing and consuming fish and wildlife.[57] Wetter weather inhibits drying of fish and meat, and permafrost thaw and flooding damage ice cellars.[88] Additionally, human, marine mammal, and seabird health are increasingly threatened by harmful algal blooms (HABs), which produce a toxin that can cause severe illness or death when consumed (KM 10.1).[89,90,91,92] The largest bed of resting cysts of HAB species in the world has been discovered in the Chukchi Sea.[4] Warming ocean temperatures make these cysts more apt to hatch into massive and recurring toxic blooms.[4]

In general, there are limited conventional disease surveillance systems in Alaska for identifying, detecting, and monitoring climate-related hazards and conditions, as well as limited information on broader health impacts, such as the degree to which climate-related factors have impacted mental health. The development and sustainability of robust surveillance systems is hampered by many factors, including the state's small population and large geographic scale, limited in-state locations with adequate laboratory and diagnostic testing, and other healthcare limitations, such as access to healthcare and disconnected health databases. To fill these gaps, several local and Tribal programs have been implemented, such the Local Environmental Observer Network, Southeast Alaska Tribal Ocean Research, and Indigenous Sentinels Network, which facilitate integration of community observations.

In addition to limited health surveillance systems for climate-related risks, there are also large disparities in healthcare access and services in Alaska. The COVID-19 pandemic highlighted some of these gaps,[93,94] although some responses to the pandemic created or strengthened health partnerships and surveillance, which may support longer-term action to improve healthcare and health outcomes around the state. Because more immediate crises, such as a disease outbreak, can reduce the capacity for responding to longer-term healthcare challenges, such as those posed by climate change, continued investment in these types of improvements in the healthcare system statewide may increase resilience to climate-driven health impacts.

Box 29.1. "I've Been Called to Pray"

Tragedies related to climate change, such as deaths associated with changing ice conditions, impact more than just those who are directly affected. Alaska Native communities, although often geographically spread out, remain intimately connected via cultural and family ties, social media, and other networks, such as churches (KM 16.2).

Iñupiaq Elder Gladys I'yiiqpak Pungowiyi, of Kotzebue, a predominantly Inupiaq town in northwestern Alaska, states:

> *I've been called to pray.*
>
> *On Facebook, there are mothers, grandmothers requesting prayer for their lost loved ones who fall through the ice and their families who are going through a hard time. Especially when they're not found.*
>
> *I've been called to pray for people that are affected mentally. What's happened over the years is that a number of skilled hunters were lost when they went out hunting. Either they fall through the ice or just disappear. It seems like every springtime people start saying "Our men are going out hunting. Please pray for them." It's hard.*[95]

Gladys I'yiiqpak Pungowiyi

Strong connections between individuals and communities are vital in rural Alaska.

Figure 29.4. Iñupiaq Elder Gladys I'yiiqpak Pungowiyi is shown here using a laptop computer in Kotzebue, Alaska, August 19, 2022. Photo credit: ©Cana Uluaq Itchuaqiyaq.

Key Message 29.2

Our Communities Are Navigating Compounding Stressors

Climate change amplifies the social and economic challenges facing Alaska communities (*high confidence*). Resource shifts, coastal and riverbank erosion, and disproportionate access to services will continue to threaten the physical and social integrity of these communities (*high confidence*). Increased adaptation capacity and equitable support have the potential to help rural and urban communities address Alaska's regionally varied climate-driven threats (*high confidence*).

Climate change affects all Alaska communities but in regionally distinct ways for urban areas compared with rural, predominantly Alaska Native, places. Lacking road connections, Alaska's rural areas are more remote than rural areas in the Lower 48. About 79% of Alaskans live in urban areas.[96] This concentration creates challenges for the development and maintenance of infrastructure in rural areas where economies of scale do not exist (KM 12.2). For example, there are large disparities in exposure to the effects of climate change and inequities in access to resources and capacity for responding to those effects.[97]

The limited reach of broadband internet access in the state is testament to this challenge.[98] As of 2023, 46% of Alaska communities remain unserved according to the National Telecommunications and Information Administration's minimum broadband standards.[99] An additional 3% are considered "underserved," lacking internet that meets the new baseline for functional service. Many fewer communities have access to affordable internet, with some paying as much as $500 per month with usage caps. Lack of broadband and cell reception diminishes access to healthcare (via telemedicine), educational opportunities, emergency response capability, and resilience to shocks from environmental hazards and extreme weather events,[100] which are expected to increase with climate change.

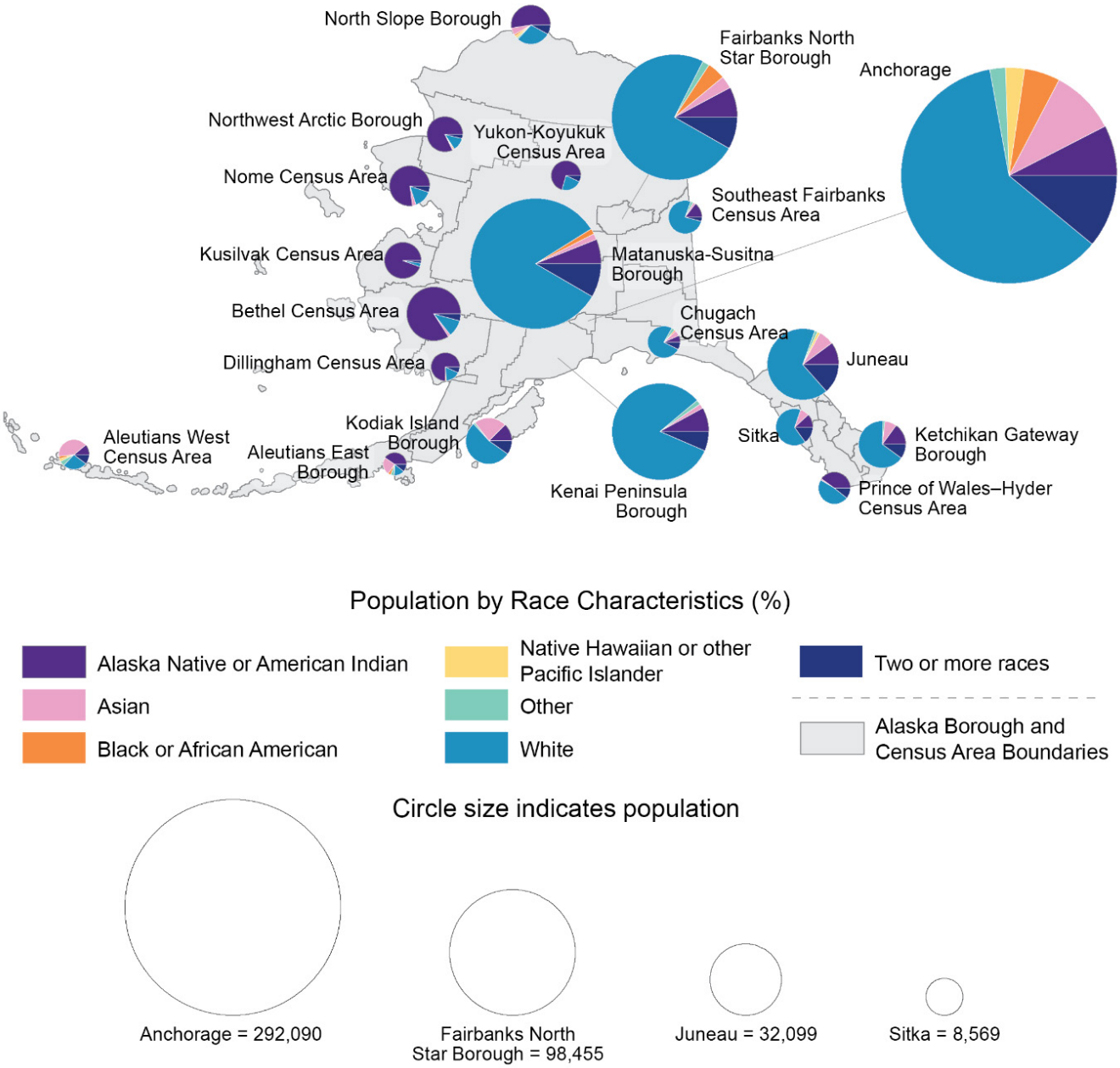
As another example, the frequency of wildfire seasons in which more than 1 million acres are burned is increasing throughout much of western and Interior Alaska (KM 7.1; Focus on Western Wildfires). In addition to health concerns (KMs 14.2, 29.1), smoke can limit visibility and interfere with air travel. This disproportionately affects rural areas accessible only by plane, leaving Alaska Native Elders, other older adults, and those with existing respiratory ailments without a means to escape environmental stressors.[34]

Both urban and rural communities face significant infrastructure and access challenges related to permafrost thaw and erosion (KM 29.4). Rural communities facing relocation are among the hardest hit, as are low-income populations in urban areas. In the Fairbanks North Star Borough (FNSB), a comparison shows that the average value of residential land[101] with shallow permafrost soil[102] is about 40% the average value of residential land borough-wide. Low-income populations in FNSB disproportionately reside in homes on or near permafrost-affected soils and are thus disproportionately impacted by damage resulting from permafrost thaw.

Alaska's population is gradually becoming more diverse (Figure 29.5). The percentage of White residents dropped 2% from 2010 to 2020.[103] The Alaska Native population increased nearly 10%, and the Black population increased 2%, but the largest growth was among residents with Asian heritage, whose population increased 32%. Much of the non-White population growth occurred in urban areas where, as in other parts of the United States, BIPOC (Black, Indigenous, and People of Color) populations historically were subject to discrimination and exclusionary housing practices. Such discrimination continues to shape the character of Alaska's urban neighborhoods today.[104] More research could illuminate the disproportionate impacts of climate change experienced by BIPOC communities in urban Alaska, which, if consistent with national

trends, are expected to be substantial. Increased knowledge of the current and historic inequities in relation to climate change and other environmental factors would help inform adaptation and mitigation measures that protect and uplift vulnerable populations.

Racial and Geographic Distribution of Alaska's Population



The racial makeup and population density of Alaska's communities vary greatly by region, creating the potential for varied exposures and disparate impacts across subpopulations

Figure 29.5. The total Alaska population estimate in 2021 was 734,323.[105] Urban areas account for the majority of Alaska's population. Racial and ethnic characteristics throughout the state vary greatly by region, as do the impacts of climate change. Alaska's urban areas are particularly diverse, and given a legacy of historic discrimination, there is still much to learn about the unique ways racial and ethnic subpopulations are impacted by climate change in Alaska and how these vary around the state. Circle sizes are proportional to population for each region. Figure credit: Northern Social-Environmental Research, Ocean Conservancy, and University of Alaska Fairbanks.

Food security is a major priority for the state of Alaska (Box 11.2).[106] Food prices may be more than twice as high in rural versus urban communities, with considerably less variety.[107] Alaska Supplemental Nutrition Assistance Program (SNAP) recipients receive the third-highest benefit per person in the United States, behind only Hawai'i and Guam. The number of households receiving SNAP benefits in Alaska increased 8% between 2019 and 2020.[108] The vast majority of food Alaskans purchase is grown elsewhere, arriving via long supply chains (Focus on Supply Chains). COVID-19 highlighted the fragility of the state's food supply and serves as an analog for the potential impacts of climate-related environmental shocks. During the pandemic, backlogged ports and restrictions on overland trucking through Canada made food and other essentials difficult to obtain. Remote regions of Alaska were among the hardest hit by supply chain disruptions after a primary air carrier in rural Alaska declared bankruptcy in April 2020 (Focus on COVID-19 and Climate Change). This left many rural off-road-system communities without a commercial airline to deliver mail and freight, including medications and food supplies.

Given the high cost of food and the vulnerability of rural transportation networks, subsistence activities (including hunting, fishing, and sharing) are critical in rural Alaska. This is especially true for Alaska Native communities, as well as for many non-Native and urban residents. About 45.4 million pounds of wild food were harvested in Alaska statewide in 2017, with an estimated replacement value of $262–$523 million (in 2022 dollars),[109] not counting their cultural and spiritual value. Yet the success of subsistence harvests is influenced by numerous external and climate-driven factors. These include shifting distribution, abundance, and migratory patterns of fish, birds, and mammals that affect availability to hunters and fishers; rising fuel costs that increase the cost of hunting, fishing, and gathering activities; and changing weather, flooding, and dangerous ice that increase risks to those engaged in these practices (KMs 8.1, 29.3).[87,109]

Climate change will have some positive impacts on Alaska food security, particularly in the agricultural sector. A longer growing season, increased number of growing degree days, and increased yields are expected to enhance the share of locally grown foods consumed by Alaskans.[110,111,112] On the other hand, pests, flooding, and ground collapse resulting from permafrost thaw will pose challenges.

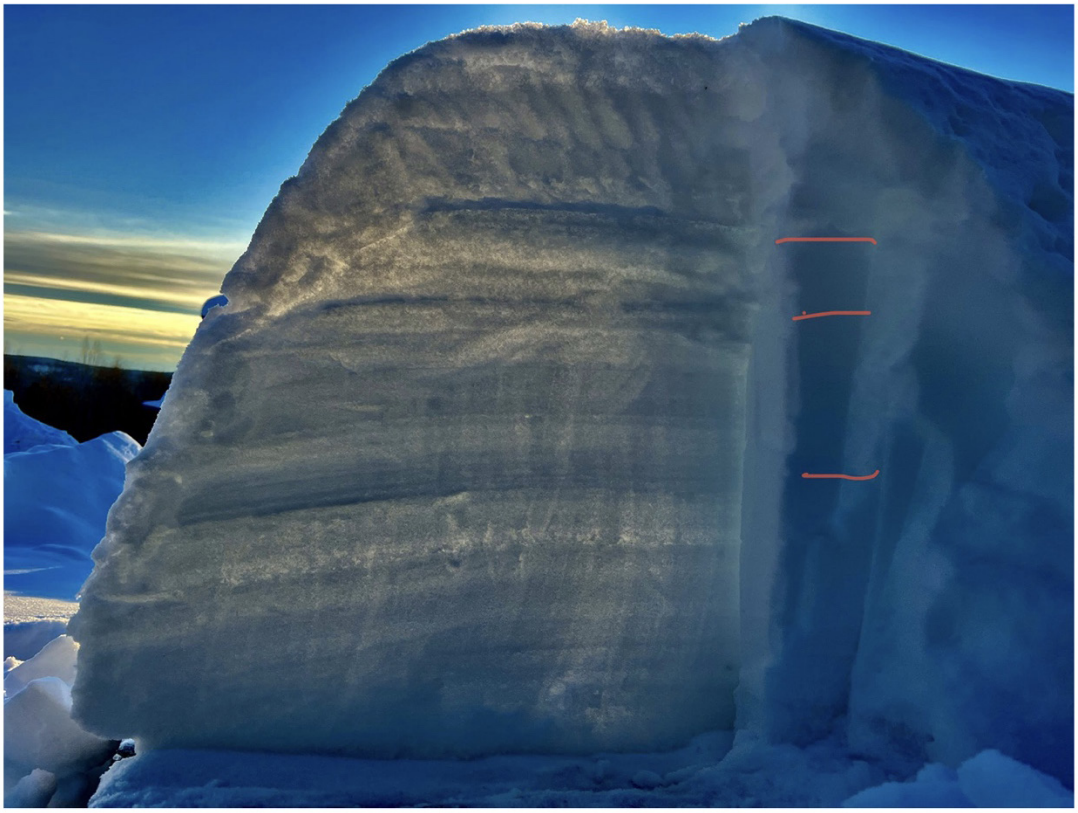
Box 29.2. "We Had to Dig In and Out of Our House"

Snow and cold are expected in Fairbanks and Interior Alaska in winter. Rain is not. More than an inch of rain fell on top of feet of snow during the 2021 holidays. The resulting ice made roads impassable, caused power outages, delayed emergency services, damaged homes, and was linked to at least one highway fatality months later as roads remained dangerously icy into spring.[113,114] State and federal disaster declarations were issued as well.[115,116] More extreme weather events are expected in a warming Alaska.

Fairbanks resident and tax preparer Marjorie Casort recalls, "I shoveled my driveway seven times in five days. In April we are still feeling the effects, with an inch of ice stubbornly clinging to roads. Many of my elderly clients are housebound, unable to even cross the road to check their mailbox because of the dangerous ice conditions".[117]

Social relationships are an essential component of resilience. Denali resident Erica Watson explained, "I trust my friends and neighbors to know what they need to do to stay warm, to check in on each other, to care for each other's homes the way we would our own."[118]

Cross-Section of Snowpack After the December 2021 Storm



A rain-on-snow event in December 2021 blocked roads and caused other damages.

Figure 29.6. Shown here is a 20-inch-high cross-section of the snowpack near Fairbanks, Alaska, taken on January 23, 2022. Red lines indicate ice layers from rain-on-snow events. The ice persisted through the winter, impeding travel for humans and moose. Photo credit: ©Bill Witte.

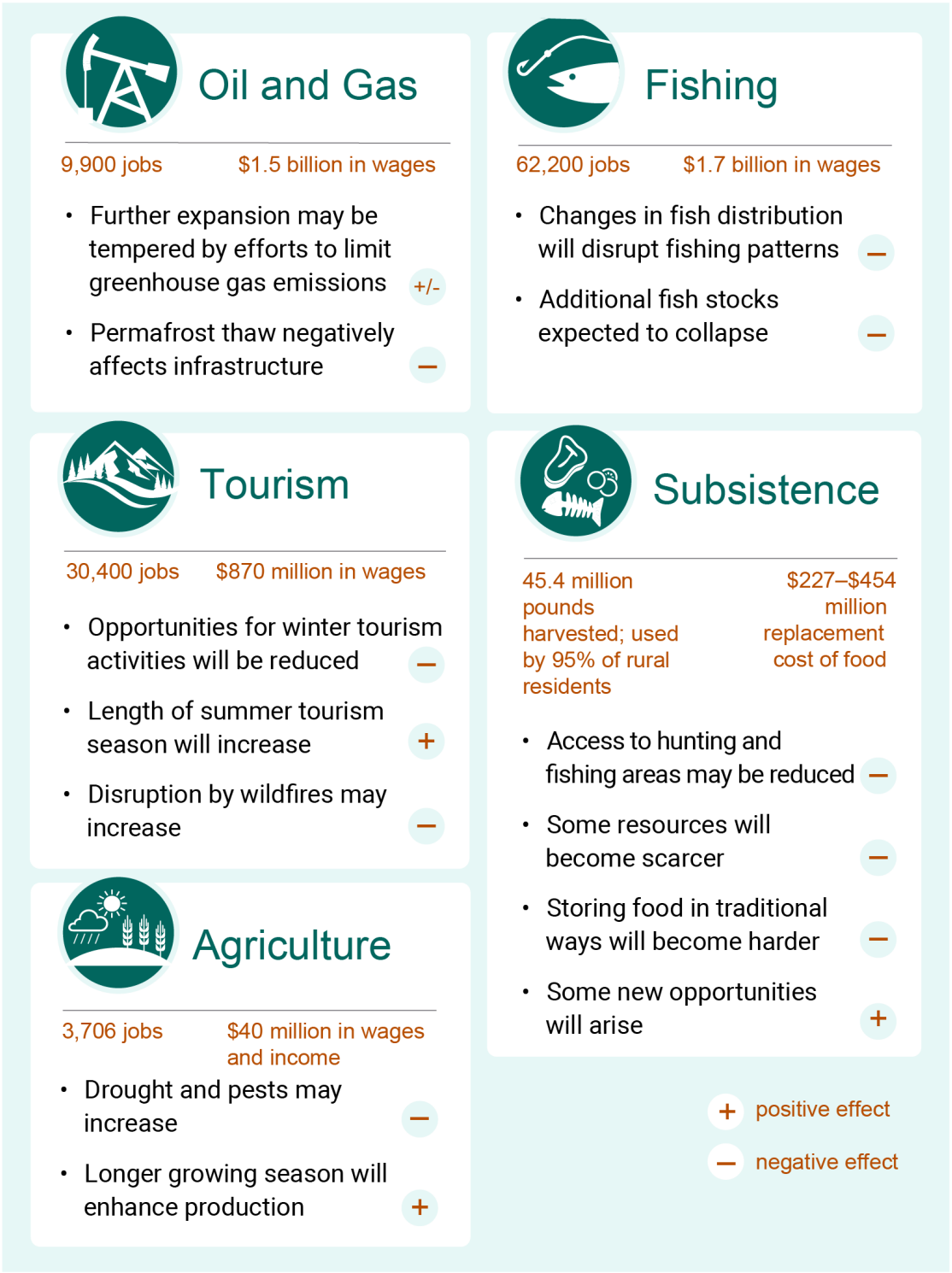
Key Message 29.3

Our Livelihoods Are Vulnerable Without Diversification

Livelihoods, especially those dependent on natural resources, are at risk around Alaska. While advancing climate change has contributed to the collapse of major fisheries and is undermining many existing jobs and ways of life (*high confidence*), it may also create some opportunities related to adaptation and response (*medium confidence*). Economic diversification, especially expansion of value-added industries, can help increase overall livelihood options (*medium confidence*).

Many jobs in Alaska are affected directly or indirectly by climate change—through alterations in abundance and distribution of fish species, through changes in access to lands and waters dominated by permafrost and ice, and through the cascading effects of a changing economy (Figure 29.7). Sustaining healthy livelihoods and ways of life in Alaska involves more than wages and salaries. Traditional cultural practices outside the cash economy include the harvest and sharing of fish, wildlife, and berries. Climate-driven changes to lands and waters, along with societal trends such as greater adoption of mainstream food practices, can reduce opportunities for subsistence harvests and thus affect cultural, nutritional, and spiritual well-being, especially for Alaska Native communities (KM 16.1).

Climate-Sensitive Employment in Alaska



Climate change is expected to have wide-ranging effects on key economic sectors in Alaska.

Figure 29.7. The figure shows examples of key sectors of Alaska's economy that are expected to be affected in various ways by climate change. Many, but not all, of the changes are negative. Data sources: Oil and Gas;[96,119] Agriculture;[120] Tourism;[121] Fishing;[122] Subsistence.[87,109] Figure credit: Northern Social-Environmental Research, University of Alaska Fairbanks, and Ocean Conservancy.

Climate impacts have severe socioeconomic consequences for Indigenous Peoples, small rural communities, and industries throughout Alaska.[123,124,125,126] For example, the Yukon River king salmon subsistence fishery has been closed river-wide since 2020, with no expected opening date in the foreseeable future. This is the first occurrence of a year-round Yukon River subsistence king salmon closure. King salmon contribute 64% of all protein to rural Yukon River communities. A multiyear closure of the subsistence king salmon fishery due to climate change (Box 29.5) and the overharvesting of ocean king salmon via bycatch is disastrous to Indigenous Peoples' physical, mental, cultural, and spiritual well-being.

Alaska's commercial fisheries have also been impacted. Alaska's seafood industry generates $6.1 billion (in 2022 dollars) in economic outputs,[122] accounting for 60% of the volume and 31% of the value of the US fishery catch.[127] A number of fisheries have been closed or dramatically reduced due to fewer fish (KM 10.2).[128,129,130,131] In January 2022, the US Department of Commerce declared several fishery disasters because of the extreme economic impact of their decline.[132] Climate change has had a large role in these fishery disasters.[133]

Climate change has negatively impacted the condition, growth, survival, reproduction, population biomass, and harvest of marine fishes,[134,135,136] salmon,[29,126,137,138,139,140] and crab.[131,141] In addition, groundfish and crab distributions have shifted northward or offshore,[142,143] following colder water, and the timing of groundfish spawning[144] and salmon spawning migration[145] has been altered (KM 8.1). Salmon are in double jeopardy because climate affects both their freshwater and marine habitats (Box 29.5). Changes in spawn timing will require changes in survey timing and stock assessments.[146,147] Changes in fish and crab distribution will require adjusting survey locations and area-based management measures.[148,149] Fishers will need to adjust the timing of harvest or switch to other harvest targets.[150] Local economies can be resilient through income diversification such as participating in several different fisheries.[151] Proactive adaptive management can help in the face of rapid climate change. One recent example is the management of Prince William Sound pink salmon during the extreme 2019 drought. After detecting high mortality early in the fishing season, managers limited harvest at critical times so that fish could successfully migrate and spawn.[23]

Warmer temperatures and changes in precipitation patterns also affect the distribution of and access to terrestrial and marine mammals (KM 8.3).[152,153] Increasingly volatile storms and changing ice and water levels are of immediate concern because they threaten the availability of wild foods, as well as safe access to these subsistence resources by boat, snowmobile, or all-terrain vehicle.[153,154] Shorter durations of suitable conditions for spring marine mammal subsistence hunting in the Arctic due to loss of sea ice will require adaptation of traditional hunting practices.[155] On land, more frequent rain-on-snow events can increase stress and mortality for wildlife,[156] reducing availability. Migratory patterns for caribou and other species are also changing,[157] again affecting access for hunters.

Berries are of high nutritional and cultural importance to Indigenous and rural communities.[158] A recent survey indicated that, statewide, berry harvests have become less reliable due to declining abundance or increased variability.[159] Changes in precipitation and temperature are expected to continue to affect berry production,[160] and they may also impact pollinators.[159]

The intersecting demands of the climate crisis and the high cost of living in Alaska have forced Alaskans to creatively address interrelated challenges related to energy and heat, crisis response, and food equity and access (KM 19.3). Union electricians and laborers, private contractors and installers, and utility inspectors are training a growing workforce in clean energy industries.[161,162] Farmers and artisans are providing local goods, training aspiring agriculturalists, and creating new employment opportunities in mariculture.[163,164] In Fairbanks, community members are working with local healthcare providers to create crisis response teams and centers that focus on harm reduction and community care, needs made greater by climate change.[165]

Box 29.3. What It Means to Lose Salmon

Prior to the recent period of unusually warm water temperatures in the Gulf of Alaska, the Chignik fishery typically supported returns of more than one million sockeye worth nearly $10.2 million (in 2022 dollars) a year to the fishermen. In 2021, in part due to the effects of ocean warming, returns were so poor that some residents chose not to subsistence fish out of fear of harming the fragile run.[166] Resident George Anderson explained how that felt: "We had something that we took for granted—that the fish were just always going to be there for smoking, salting, freezer, whatever. And to have that not be there for you is just something we were never prepared for."[166]

Some nonprofit and industry organizations have tried to help by donating fish. But for the predominantly Alutiiq community, subsistence is not just about food, it is also a connection to place and family.

"It's our lifeblood. Chignik's going to go away if we can't get this run back up to where it used to be," said Al Anderson, another Chignik fisherman.[166]

Unloading Salmon Sent to Chignik in Response to the Fishery Disaster

Donations of salmon provided much-needed food to Chignik and other small communities.

Figure 29.8. Boxes of salmon are unloaded from a small plane in response to the fishery disaster in Chignik, Alaska, July 11, 2022. Photo credit: ©Miranda Lind.

Key Message 29.4

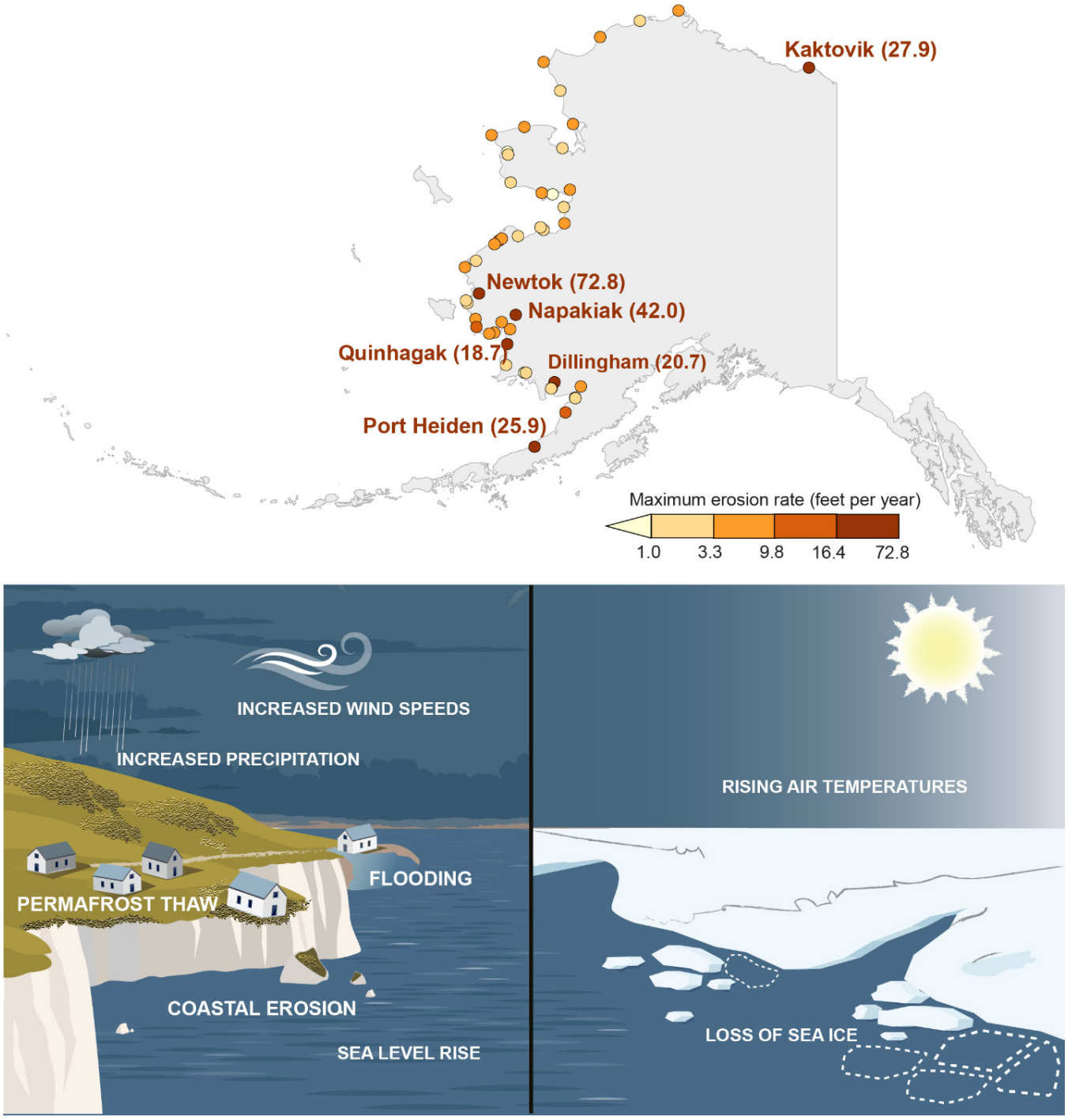
Our Built Environment Will Become More Costly

Much of Alaska's infrastructure was built for a stable climate, and changes in permafrost, ocean conditions, sea ice, air temperature, and precipitation patterns place that infrastructure at risk (*high confidence*). Further warming is expected to lead to greater needs and costs for maintenance or replacement of buildings, roads, airports, and other facilities (*high confidence*). Planning for further change and greater attention to climate trends and changes in extremes can help improve infrastructure resilience around Alaska (*high confidence*).

Power, water, and transportation infrastructure in Alaska varies from large-scale and modern in urban areas to small-scale and even rudimentary in some villages. Air transport depends on suitable weather for flying and adequate runways in the destination community. Transport by water, delivering fuel and other heavy goods to many communities, requires rivers or coastal waters deep enough for barges and adequate offloading sites or facilities. Most communities lack backup systems for water, sewer, and electricity, leaving them vulnerable to disruption. Emergency housing may be limited to the school gymnasium as the largest indoor space in the community. Many Alaskans, especially in rural areas, also depend on remote camps for hunting and fishing to produce food. These camps are vulnerable to climate-driven damage and disruption.

Buildings and other infrastructure throughout Alaska are at risk from flooding, erosion, and permafrost degradation (Table 13.1; Figure 29.9).[167,168,169,170] More than half of Alaska's communities are at the highest threatened level according to the most recent statewide report.[171] For example, on Alaska's northern and western coastlines, communities face between 1 and 72.8 feet of erosion per year (KM 9.2).[172,173] Recent progress has been made to understand local flood and erosion vulnerability for Alaska communities by determining erosion rates [173] and historical flood heights (Figure 29.15); however, these reports are not available for all communities. Given that 80% of Alaska is underlain by permafrost (Figure 8.5),[174,175] regional infrastructure damages are projected to be high.[176] Modeling erosion's dependence on permafrost integrity and persistence has been an emphasis of recent research.[177] However, the widespread lack of permafrost presence assessments, and the degree to which local erosion depends on permafrost responses, is a key source of uncertainty in forecasts for specific Alaska communities.[178] Extensive coastal and riverbank erosion has also exposed old gravesites in western Alaska,[179,180] and permafrost is integral for cold storage in many Alaska Native communities and camps.

Coastal Erosion Rates and Processes in Alaska



Coastal erosion is a major threat around Alaska.

Figure 29.9. The figure shows rates of coastal erosion in selected communities (**top**) and coastal erosion processes in Alaska (**bottom**). Data are unavailable for many parts of Alaska's extensive coastline, but erosion risk is high in much of the state (Figure 29.14). Coastal erosion processes are affected by many aspects of climate change (bottom), exacerbating the problem. (top) Adapted with permission from Overbeck et al. 2020;[173] (bottom) adapted with permission from the University of Alaska Fairbanks, Alaska Arctic Observatory and Knowledge Hub.

Alaska Native communities face an estimated $4.8 billion (in 2022 dollars) in costs to infrastructure from environmental threats over the next 50 years.[181] These costs may be significantly underestimated due to limitations in current model-based approaches[182], as well as to the omission of dispersed but culturally vital infrastructure such as fish camps. Various assessments have been completed to try to determine the cost of environmental changes to communities.[178,181] The costs of responding to climate change are unevenly distributed, with rural areas facing greater costs and few benefits, in contrast to urban areas that will realize some benefits such as reduced heating expenses and where the costs of infrastructure maintenance will be spread over a much larger population base (KMs 11.3, 12.2).[97]

Communities dealing with flooding, erosion, and permafrost degradation are responding immediately as well as planning long-term adaptations, which generally include a combination of protection of infrastructure in place, raising buildings out of the floodplain or moving them out of vulnerable areas, and entire community relocation (which has been the case for Newtok moving to the new site of Metarvik) (KM 9.3; Figure 9.5).[183] As mentioned earlier, however, relocation options may be limited by the availability of land that is culturally, economically, politically, and environmentally suitable. An additional complication is that no single agency has financial responsibility for the costs of relocation.[52]

Box 29.4. The Cost of Thawing Ground for Alaska Industries

The oil development and production industry on Alaska's North Slope also faces challenges from thawing permafrost. Intensive efforts are now required to keep the ground cold and solid to support roads, pipelines, and buildings (KM 5.3),[184,185] and these are short-term solutions. Thawing permafrost will drive up the costs of North Slope operations.[184] Similar problems are expected with infrastructure elsewhere in the state, potentially reducing the viability of some industries.

Thawing ground can damage infrastructure, affecting many economic sectors around Alaska. In 2021, a landslide from a thawing rock glacier in Denali National Park cut off a section of the 92-mile road that takes visitors deep into the park (Figure 29.2).[186,187] The rate of ground slumping and damage to the road had accelerated by summer 2022.[188] A bridge over the damaged section of the road is estimated by the National Park Service to cost $102 million (in 2022 dollars). Other sections of the road are also at risk. Access to the park, which generates some $680 million (in 2022 dollars) in tourist spending each year, will be hampered at least through the 2024 season.

Pretty Rocks Landslide, Denali Park Road

Thawing permafrost limited access to Denali National Park.

Figure 29.10. A slump in the Denali Park Road at the Pretty Rocks location was caused by movement of the rock glacier beneath the road, September 16, 2021. Photo credit: NPS.

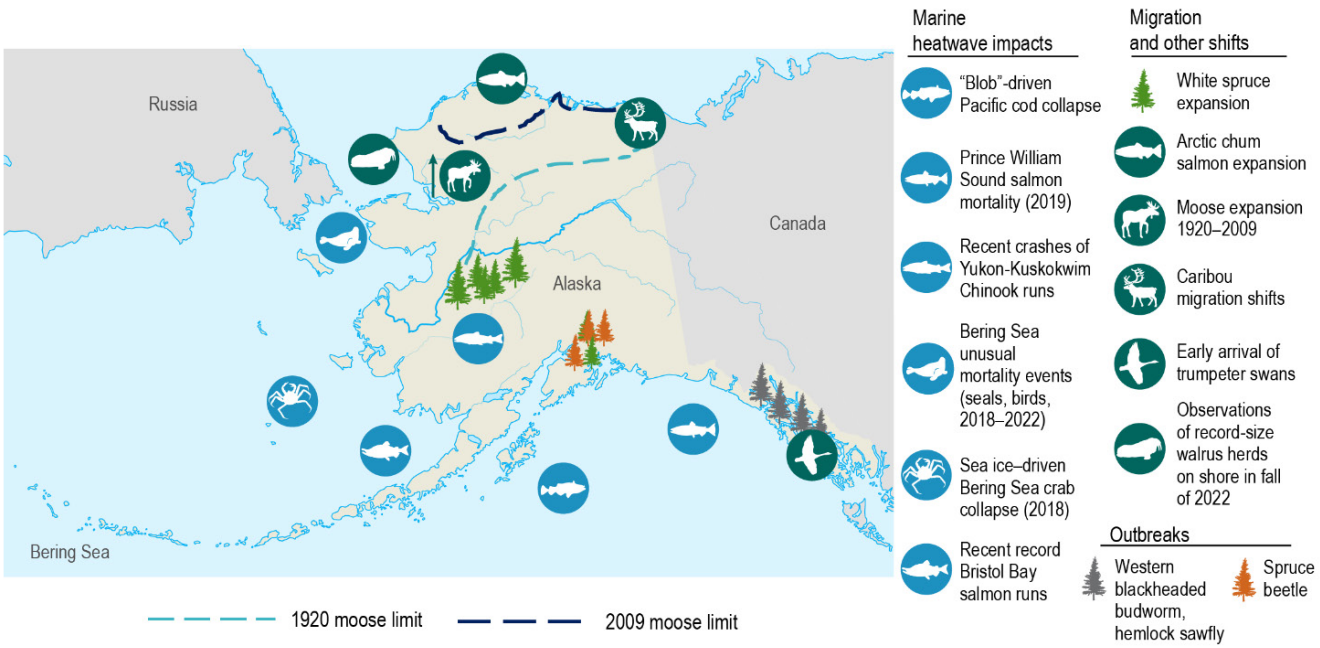
Key Message 29.5

Our Natural Environment Is Transforming Rapidly

Alaska's ecosystems are changing rapidly due to climate change (*high confidence*). Many of the ecosystem goods and services that Alaskans rely on are expected to be diminished by further change (*medium confidence*). Careful management of Alaska's natural resources to avoid additional stresses on fish, wildlife, and habitats can help avoid compounding effects on our ecosystems (*medium confidence*).

Alaska enjoys large, unfragmented marine and terrestrial ecosystems. This abundance makes possible hunting and fishing for subsistence use, cultural well-being, recreation, and commercial activities. At the same time, there are conflicts over land use and the allocation of hunting and fishing opportunities due to different land management regimes or distribution of harvest opportunities, with competing claims from traditional, commercial, and recreational constituencies.[189] Climate change is expected to exacerbate existing challenges by shifting the distribution and abundance of fish and wildlife and by increasing disturbance to lands and waters (Figure 29.11; KMs 8.1, 8.2). Climate-conscious management efforts can help individuals and communities adjust but cannot by themselves address the underlying changes that will continue to occur.

Major Recent Ecological Changes



Climate change has caused or contributed to extensive ecological effects throughout Alaska in recent years.

Figure 29.11. Warming ocean waters, extreme heat events, and other changes, including the events shown in Figure 29.1, are affecting ecosystems across Alaska. Some species' ranges are expanding, including chum salmon in Arctic rivers,[190] moose[191], and beaver[192] in the Arctic (not shown), and white spruce in western Alaska (KM 8.2).[193] Migration timings or patterns are changing, for example trumpeter swans in Southeast Alaska[194] and caribou in the eastern Arctic. Marine heatwaves and reduced sea ice cover are affecting seabird, fish, and seal populations: the North Pacific "Blob" (Figure 29.1) contributed to Pacific cod collapse, the 2019 Southcentral heatwave affected Prince William Sound king salmon survival,[139] and low sea ice caused or contributed to the collapse of crab fisheries and unusual mortality events for seabirds and ice seals in the Bering Sea region (2018–2022) (KM 10.2; Figure 10.1). In 2022, Pacific walrus hauled out in record numbers in the Bering Strait area,[195] suggesting that the minimum population estimate may be higher than previously thought, even if the range may be shrinking. Insect distributions and outbreaks have also changed.[196,197] In Southeast Alaska, outbreaks of western blackheaded budworm and hemlock sawfly have damaged forests in the wake of the 2017–2019 drought.[198] The 2019 heatwave in Southcentral Alaska contributed to spruce beetle expansion in that region and extreme fire activity on the Kenai peninsula (KM 7.1; Box 7.1). Salmon runs responded variably: Yukon–Kuskokwim River king salmon runs have been decimated,[139] while Bristol Bay has had record sockeye salmon returns. Figure credit: USGS, NOAA Fisheries, and Ocean Conservancy.

Climate change has negatively impacted nearly all aspects of the life history of commercial groundfish, salmon, and crab (KMs 10.2, 29.3). Arctic seabirds and marine mammals have also experienced reproductive failure, unprecedented mortality, and changes in migratory behavior. Extreme ocean warming and record low sea ice in the Chukchi Sea are affecting the entire food web[199,200,201] and possibly transforming the ecosystem.[143,202] For example, the lowest abundance of marine zooplankton in a decade was observed in recent warm years (2017 and 2019), combined with a decline in large, fatty Arctic species of zooplankton and an increase in smaller, less calorie-dense sub-Arctic species.[203,204] In turn, fish such as Arctic cod and saffron cod, which feed on zooplankton, were not as robust.[205] Subsequently, seabirds and marine mammals preying on these less nutritious fish experienced increasingly frequent reproductive failures and mortality. Emaciated seabird carcasses were found on beaches during extreme mortality events in the Bering and Chukchi Seas,[201] and the body condition of ice seals has declined.[206] In addition, the ranges of ice-dependent species such as polar bears[207] and walrus[208] are shrinking.

Ocean acidification is harmful to some Arctic phytoplankton and zooplankton.[209,210] Laboratory studies have shown that the early life stages of commercial fishes such as northern rock sole,[211,212] walleye pollock, Pacific cod,[213,214,215] and salmon[140,216] are sensitive to more acidic waters and to resulting food web changes.[135,211] Laboratory experiments suggest that Alaska commercial crab species are also highly vulnerable.[141,217,218,219,220,221] Although no studies of the impacts of ocean acidification on crabs in Alaska have been conducted, a study of Dungeness crab off California showed that shell dissolution was observed in areas of high acidification, reducing growth.[210] Finally, seals, walrus, and marine birds may be affected by the vulnerability of their prey.[222]

Climate changes and extreme events are also contributing to terrestrial changes, affecting species distributions, habitats, resource availability, and human access (KMs 2.2, 29.4; Focus on Compound Events). Moose and beaver are colonizing previously inhospitable Arctic areas,[191,192] in part due to temperature-driven increases in shrubs, and there is evidence salmon are colonizing streams where they were previously rare or absent,[190] presumably due to warmer waters. Ongoing warming is also associated with rapid changes in vegetation. Alaska residents are also noting unusual plants.[223] Decreases in berry production have been noted by communities in Alaska, related to multiple climatic drivers (e.g., Herman-Mercer et al. 2020[160]). Exceptionally high midsummer tundra productivity ("greening") has been observed on the North Slope of Alaska, but lower productivity ("browning") has continued in Southwest Alaska due to drying.[224] In 2019, the rapid expansion of a spruce beetle outbreak in the Susitna Valley (ongoing since 2016) caused extensive spruce mortality over 1.6 million acres (Box 7.1),[198] due in part to warmer temperatures increasing beetle development rates. In Southeast Alaska, hemlock sawfly outbreaks caused defoliation and mortality on more than 500,000 acres of forest, and a developing western blackheaded budworm outbreak is affecting Sitka spruce.[198] Both are plausibly[225] related to the unprecedented 2017–2019 drought in the region.

Landscape changes due to fires, permafrost, and their effects on other processes are climatically driven and increasing. Projected fire-driven transitions from conifer- to deciduous-dominated boreal forest[226] appear to be manifesting at regional scales. Wildfires in 2019 (Southcentral Alaska)[39] and 2022 (Southwest Alaska)[227] burned large areas in places where fire was rare or with atypical severity, as has been seen in other parts of the western US (Focus on Western Wildfires).[40] Overwintering fires, or "zombie" fires, which occur when uncharacteristically severe burning in hot, dry summers results in burning the following fire season, may also be increasing in the Arctic[228] and Alaska.[40] Permafrost thaw, including thermokarst (ground slumps or cave-ins)[229,230] and lake drainage,[231,232,233,234] is accelerating due to warming (e.g., Douglas et al. 2021[49]), particularly with recent wildfires[235,236] and uncharacteristically warm precipitation events.[237] These changes are projected to affect Arctic ecosystems and hydrology in important ways.[238] Across central and northern Alaska, changes in disturbance, vegetation productivity, and permafrost will affect the region's role in the global carbon cycle.[239,240] Current evidence suggests that carbon emissions from thawing permafrost[241] will exceed the carbon captured by increased vegetation productivity.

Box 29.5. A New Era for Pacific Salmon Research in Alaska

When aquatic ecologist Vanessa von Biela's career started in 2007, it was still a "warmer is better" era for Alaska's salmon in their cooler northern range extent. Over the last decade, however, she has been among a group of scientists and local people who have found that salmon are reaching climate-driven tipping points. Stressful conditions for salmon include warm years with poor marine feeding,[21,242] heat stress or drought during freshwater spawning migrations,[23,139] and heavy fall rains during egg incubation.[243] Stressors are minimized in oceans and deep lakes where mixing maintains cooler waters, high nutrients, and productive feeding, as well as in places where glaciers and groundwater keep lakes and rivers cold.[29,244] Positive changes include new salmon habitat with retreat of glaciers and sea ice,[143,245] although Arctic winters still limit major northward shifts.[246] Salmon may be able to tolerate and adapt to stressful habitats, or they could move to find a better habitat patch. These options have important implications for people who depend on salmon. Investment in research by Vanessa, her colleagues, and local residents concerning new and emerging stressors can help inform climate-responsive management strategies that aim to improve outcomes for people.

Chinook Salmon Research

Research on the effects of heat on salmon can help scientists understand the effects of continued warming.

Figure 29.12. Shown here is a chinook (king) salmon caught for non-lethal research on heat stress in a fish wheel on the Yukon River, July 2017. Photo credit: Shannon Waters-Dynes, USGS.

Key Message 29.6

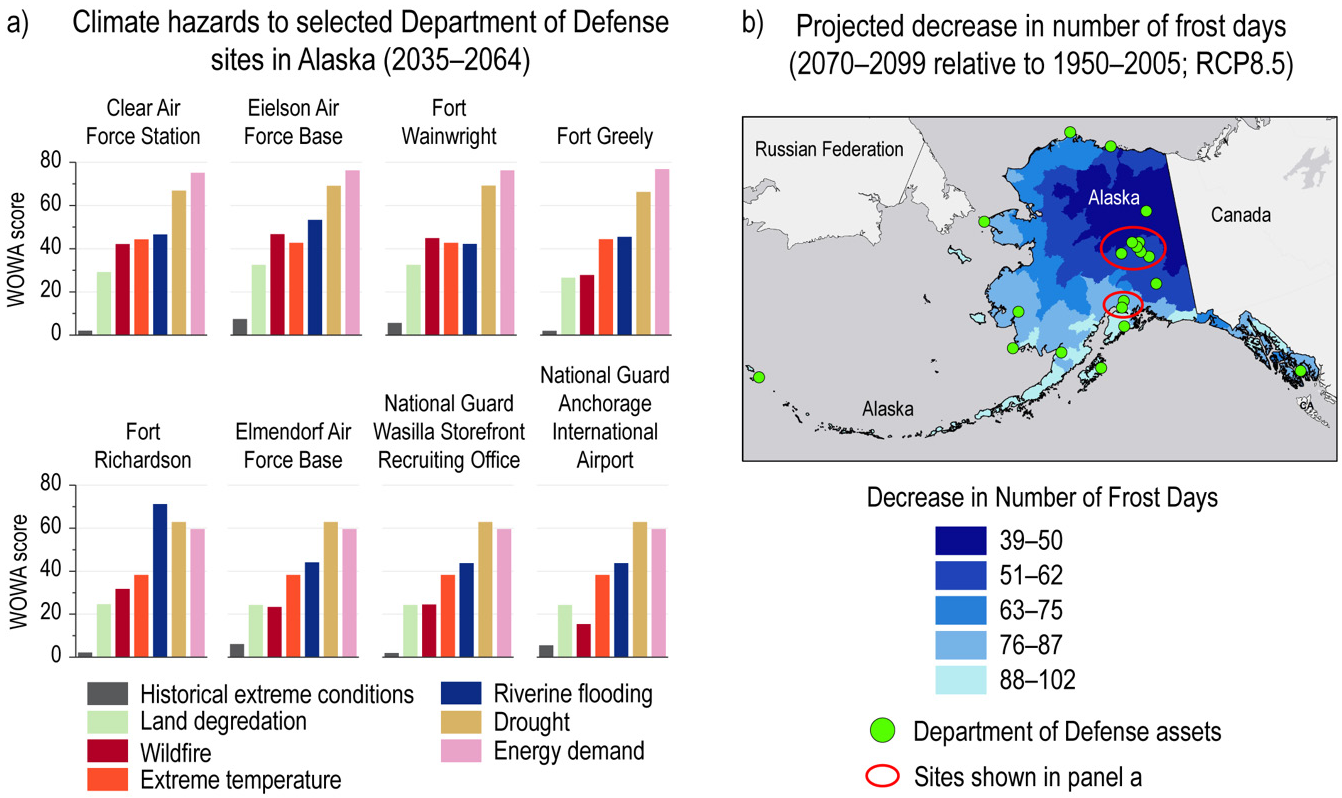
Our Security Faces Greater Threats

Rapid climate-driven change in Alaska undermines many of the assumptions of predictability on which community, state, and national security are based (*high confidence*). Further change, especially in the marine environment with loss of sea ice, will create new vulnerabilities and requirements for security from multiple perspectives and at multiple scales (*high confidence*). Greater capacity for identifying and responding to threats has the potential to help reduce security risks in the Alaska region (*medium confidence*).

Security entails a sense of well-being and safety that is protected from or resilient to disruption. It is a combination of many interests and perspectives and reflects values such as a nation's sovereignty and integrity (KM 17.1) or a community's reliance on livelihoods and food sources that enable its people to thrive (KM 29.3; Box 11.1). Different interests are prioritized at the national/homeland, state, and community levels. Security actors at the national, state, and community level may face increasing demands for security services while also confronting the additional costs of climate change on physical infrastructure and operations, creating a double burden and making decisions even more challenging.

The Department of Defense (DoD) and Department of Homeland Security are impacted by climate change.[247] For example, coastal erosion, degrading permafrost, wildfire, and other climate effects will continue to impact DoD installations in Alaska (Figure 29.13).[248,249] At the state level, increasing wildfire risk and climate impacts to infrastructure increase management costs to the state.[176] Coastal erosion and thawing permafrost are affecting many coastal villages, reducing community security (KMs 9.2, 16.1, 21.3, 22.1, 29.4). Beyond Alaska, national policy responses to climate change, such as reducing dependence on fossil fuels, may impact energy sources, prices, and industry in Alaska, with potential effects on employment, household budgets, and environment.

Climate Change Risks to Military Installations



Climate change poses risks to military assets in Alaska.

Figure 29.13. (**a**) The bar charts display climate risk for selected Department of Defense (DoD) sites in Alaska, based on the higher emission scenario for 2035–2064 data from the DoD Climate Assessment Tool. The y-axis is the weighted order–weighted average (WOWA) score of each site's exposure to aggregated climate hazards. For the Interior and Southcentral Alaska sites, drought and energy demand are the top climate hazards. At Fort Richardson, there is notably higher exposure to the riverine flooding climate hazard. In general, the scores are lower for the Southcentral region, indicating lower exposure to climate hazards. (**b**) Selected DoD sites in Alaska and projected reduction in frost days, illustrating the scale of the risk statewide (frost days are defined here as days with a minimum temperature at or below 32°F). The average annual number of frost days over the modeled baseline (1950–2005) ranges from 140–180 days in the Aleutian Islands to 260–290 days in the Brooks Range. In a higher greenhouse gas emissions scenario (RCP8.5), this will be reduced by about 20% in the Brooks Range and by over half in the Aleutians in 2070–2099. This will result in a longer ice-free season on the coast, leaving coastal communities vulnerable to storm surge more of the year. Portions of this figure include intellectual property of Esri and its licensors and are used under license. Copyright © 2020 Esri and its licensors. All rights reserved. Figure credit: USACE and DoD.

At the national level, DoD installations face a range of climate-associated hazards. For example, wildfire is a constant concern for military installations. Climate-driven drought, wind, and fire can affect operations, training, assets, and wildfire-suppression activities for DoD installations in a variety of ways.[248] The Alaska Fire Service and the US Army have recently been partnering to conduct springtime prescribed burns on military training lands in Alaska to reduce fire danger around military training targets.[250]

Climate impacts also generate national security concerns by altering maritime traffic in Alaska. Reductions in sea ice in Alaska waters enable more maritime activity. Changing and difficult-to-predict ice conditions, however, may require search-and-rescue activities that affect US Coast Guard presence and missions, as well as DoD civil support and military missions. Increasing maritime traffic in the Arctic[251] intersects with

the broader geopolitical context of competition with the People's Republic of China (PRC) and tension with Russia. The Russian government has been building (and rebuilding) military capability and capacity across its northern border, including sites near Alaska such as Wrangel Island.[252] The PRC has expressed interest in Arctic governance, resources, shipping lanes, and climate science.[253] In Alaska, recent concerns include PRC and Russian naval operations in the US exclusive economic zone; illegal, unreported, and unregulated fishing especially in the Bering Sea; and marine debris.[254]

Rising concern about climate change and increased geopolitical competition in the Arctic are reflected in recent Arctic-specific military strategy documents (e.g., DHS 2019;[255] DOD 2019;[248] USAF 2020[256]). In Alaska, the DoD is developing new capabilities and capacities in response to these changes. For example, as of spring 2022, Eielson Air Force Base has 54 F-35 aircraft, the largest concentration of the most technologically advanced airpower in the world.[257]

The state of Alaska faces direct and indirect climate change impacts to security with regard to crime, economic impacts (KMs 19.1, 19.3, 29.3), environmental impacts (KM 29.5), and state capacity to respond to such security challenges. Climate change is also increasing costs for the state, from firefighting to infrastructure maintenance (KM 29.4), with potential adverse ramifications for the state's ability to balance its budget and meet the needs of its citizens.[170]

At the community level, concerns center on food and environmental security (KM 29.2), as well as the safety of small boat operators and hunters navigating increasingly unpredictable and crowded marine and riverine environments (KM 15.1).[87] Changing sea and river ice conditions are increasing the physical risks for hunters and travelers. Climate change may also drive intensification of human offshore activities, such as increased commercial shipping, that generate additional risks such as accidents or spills.[258] Cultural practices are vital to well-being and security throughout Alaska (Box 29.3) but are often overlooked or minimized in fisheries management and in research on climate change and ecosystems.[75]

Box 29.6. Tribal Perspectives on "Security"

For Tribes in Alaska, climate change is yet another reason to exercise leadership and sovereignty on their own behalf (KM 16.3). In Bristol Bay, for example, the Native Village of Port Heiden has created Meshik Farm to improve food security and would like to build a fish processing facility too. Says Jaclyn Christensen, Brownfield Coordinator for the Tribe, "I worry about my husband making long trips in dangerous waters when he's fishing, and we need an economic base for the community."[259]

The Knik Tribe in Southcentral Alaska is deeply involved in land management. As Theo Garcia, the Tribe's Environment and Natural Resources Director, explains, "We grow potatoes to provide food, we are cultivating native plants to support streambank restoration, and we are exploring ways to use waste heat to grow cheaper fodder for livestock."[260]

As conditions continue to change, being able to adjust is essential to security, through Tribes' own efforts and in partnership with others.

Canned Red Salmon in Port Heiden

Salmon is vital for food security in much of Alaska.

Figure 29.14. A locally processed jar of red salmon sits in the sunshine in Port Heiden, Alaska, July 28, 2022. Photo credit: ©Jaclyn Christensen.

Key Message 29.7

Our Just and Prosperous Future Starts with Adaptation

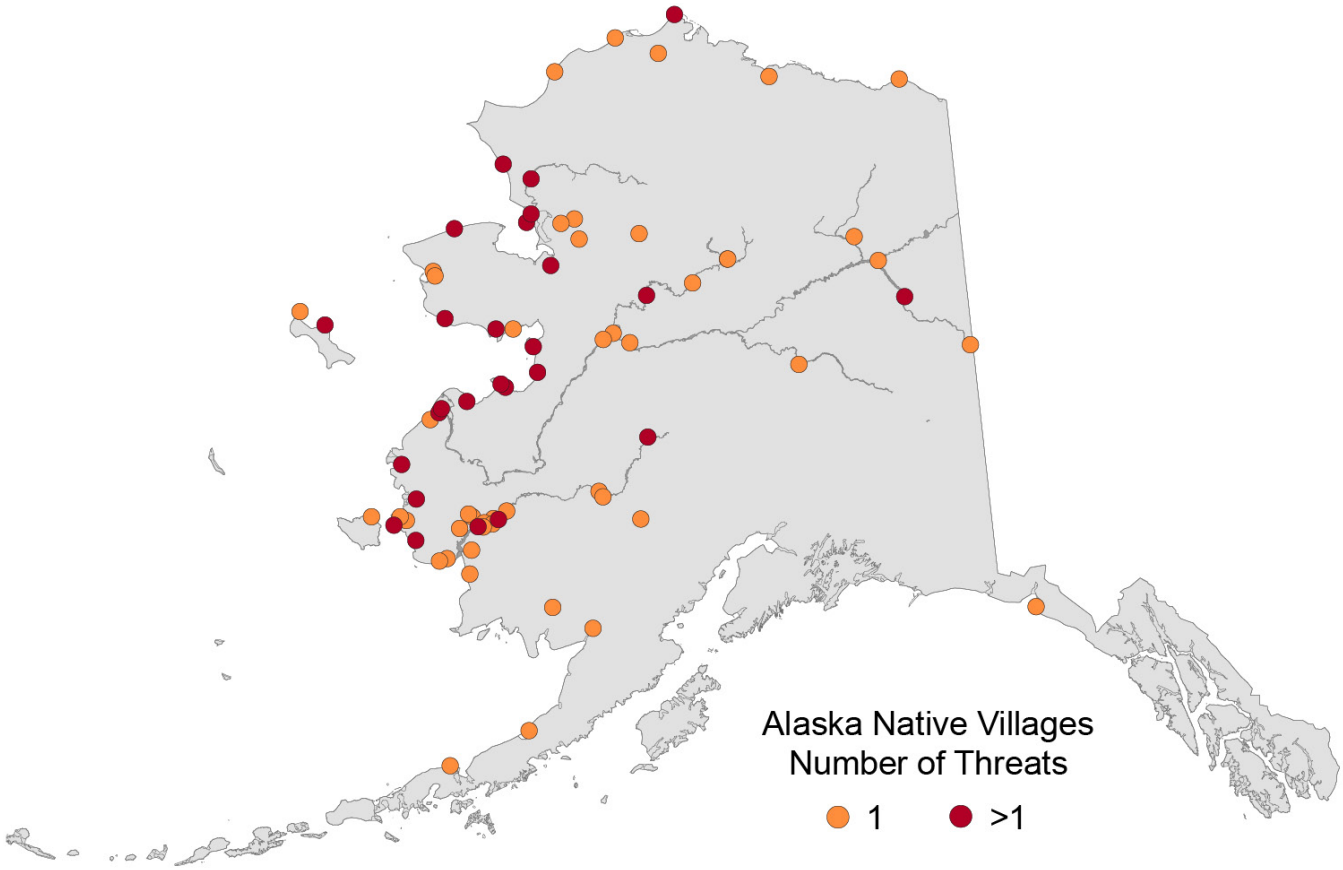
Local and regional efforts are underway around Alaska to prepare for and adapt to a changing climate (*high confidence*). The breadth of adaptation needed around the state will require substantial investment of financial resources and close coordination among agencies, including Tribal governments (*high confidence*). The effectiveness of adaptation planning and activities can be strengthened by addressing intersecting non-climate stressors, prioritizing the needs of the communities and populations experiencing the greatest impacts, building local capacity, and connecting adaptation efforts to economic and workforce development (*medium confidence*).

In recent years, Alaska has emerged as a leader of climate adaptation initiatives in the Arctic,[261] many of which have been implemented by regional entities and municipal, community, and Tribal governments.[262,263] Together, these efforts address climate change and intersecting societal challenges in ways that begin to lay a foundation for a just and prosperous Alaska. A wide variety of adaptation efforts has been undertaken statewide, from trainings and workshops to the implementation of hazard mitigation and climate action plans.[262,263,264] Despite widespread impacts (Figure 29.15), support for climate adaptation varies among communities,[263,265,266] and adaptation has not been a consistent priority for the state government (KM 31.1).[263,267,268] For many Alaskans, the ability to adapt to current and projected climate impacts is shaped by social and political factors such as food and water security, economic opportunity, and the capacity of governance systems (KM 31.4).[45,269,270,271]

Many of Alaska's Tribes have completed or are currently engaged in efforts that increase their ability to adapt to a changing climate (KM 16.3). These include applying for federal funding for climate resilience,[272] conducting risk assessments,[273] collaborating with researchers to bridge Western climate science and Indigenous Knowledge,[274] and developing and implementing community- and regional-level adaptation plans.[76,275,276] These activities are bolstered by the accumulated knowledge that has enabled Indigenous Peoples of Alaska and the Arctic to innovate and adapt to their changing environment for millennia.[270,277,278] The traditional values and practices of Alaska Native cultures focus on well-being, cultural continuity, and a holistic, integrated worldview (Figure 16.3).[75,270,279] They are often tied to components of adaptive capacity, such as environmental stewardship, communal pooling of subsistence resources, and mobility.[280,281,282,283,284] It is important to emphasize, however, that Alaska Native Peoples' ability to adapt does not mitigate the impacts of unprecedented environmental hazards or reduce the need to address the causes of climate change.

To achieve widely needed climate adaptation, communities must navigate a complex system of siloed federal agencies (Figure 29.16).[285,286,287] Overlapping local, borough, state, and federal jurisdictions can create confusing or conflicting policy directives and impede local adaptation efforts (KM 31.4).[277,288] Complex governance and resource management systems, many of which are imposed on Tribes through colonization, create challenges to adaptation efforts, which are most effective if they are timely, equitable, and community led. Also, the high adaptive capacity and self-reliance of Indigenous Peoples continues to be eroded by the ongoing impacts of colonization, including barriers to social networks and the transfer of Indigenous Knowledge.[277,279,289,290] Tribes are sovereign nations that require government-to-government consultation. Communities with strong collaboration among governing entities, including through coproduction of knowledge (research based on equitable and respectful partnerships), may be better able to respond to the adverse impacts of climate change through partnership and flexible management of natural resources.[279,281,285] Targeted coordination among and between federal, state, and Tribal entities would help build resilience to environmental threats.[286]

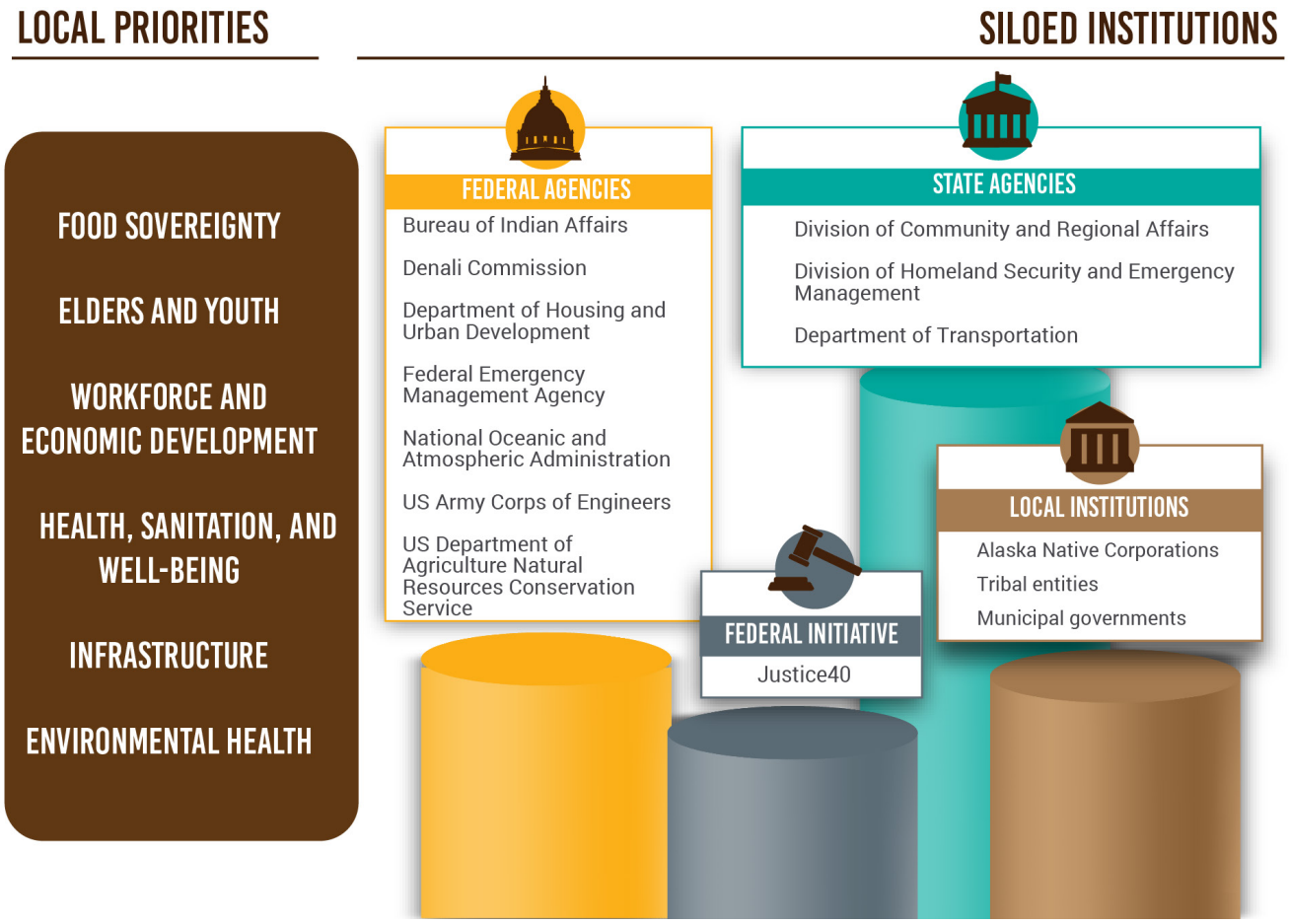
Climate Threats Across Alaska



Statewide assessments show extensive climate-related threats throughout Alaska.

Figure 29.15. The map shows threats to Alaska Native villages from permafrost thaw, flooding, and erosion. Many communities face multiple threats, compounding the challenges they face. Adapted from GAO 2022.[286]

Navigating Diverse Institutions to Meet Local and Regional Priorities



Adaptation is a complex process, requiring expertise and engagement with multiple entities.

Figure 29.16. Climate adaptation typically requires a wide range of expertise as well as engagement of those who are affected together with other entities, including but not limited to those listed in this figure.[286] Alaska Native corporations were created by the Alaska Native Claims Settlement Act of 1971.[291] Local priorities are holistic, involving integrated environmental and social issues. However, institutions on multiple levels are often siloed with specific priorities, which can lead to duplication of efforts and hamper local efforts. Figure credit: University of Alaska Fairbanks and Ocean Conservancy.

Although there are various sources of state and federal funding and technical assistance available to support municipal and Tribal climate adaptation in Alaska, the effectiveness of such efforts is hindered by institutional barriers and limited capacity across various levels of government (KMs 31.4, 31.6).[261,292] In both rural and non-rural communities, some residents have reported that climate adaptation has been impeded by a lack of local leadership or political will.[265,266,293] Many communities and organizations have stepped up to lead mitigation efforts and address the inequities compounded by climate change in the absence of consistent municipal and state action. At least four municipalities (Anchorage, Homer, Sitka, and Juneau) have adopted climate action plans,[264] with Fairbanks also currently at work on theirs. Seven Tribal governments from the Nome Eskimo Community to the Central Council of T'lingit and Haida have adopted climate action or adaptation plans.[264]

Community renewable energy initiatives like Thermalize Juneau and the Solarize initiatives in Anchorage, Fairbanks, Kenai, Mat-Su, and Palmer help residential and commercial property owners install solar capacity.[294,295,296] Local utilities such as Golden Valley Electric Association, Alaska Energy Light and Power,

and Chugach Electric Association have worked on several renewable energy projects.[297,298,299] Juneau Electric Vehicle Association specifically has worked to electrify public and personal transport in the region.[300] Many communities around the state are building local community-supported agriculture markets, shared gardens, and supply boxes to supplement neighborhoods farther away from urban grocery stores.[301] Tribal governments in Interior and Southwest Alaska delivered salmon to residents impacted by the Yukon–Kuskokwim salmon crash.[302]

Climate change can lead to divergent goals. While there are potential economic opportunities of a warming Arctic, such as increased marine traffic, growth in tourism, and resource extraction, considerations of relevant climate-related risks are not consistently incorporated into regulatory and planning processes.[266,269] For example, across coastal Alaska, communities are increasingly reliant on hard structures, such as seawalls and shoreline reinforcement. These structural adaptations can provide a sense of security, but they lack the flexibility, long-term sustainability, and cost effectiveness of regulatory and ecosystem-based approaches.[303]

Climate impacts are being experienced within the larger context of social, political, and economic change in the Arctic (KM 20.2).[281] Non-climate stressors such as food insecurity (KMs 29.1, 29.3, 29.5), limited employment (KM 29.3), substandard housing (KM 29.1), aging infrastructure (KM 29.4), limited access to healthcare (KM 29.1), the high cost of living in remote areas (KM 29.2), and limited search-and-rescue capability (KM 29.6) can affect a community's capacity and ability to pursue climate adaptation.[269,304,305] By identifying and addressing the intersections of climate risk and social and economic vulnerability, decision-makers can develop and implement adaptation initiatives that are scalable, innovative, and/or transformational.[266]

The need to center adaptation actions around and support Indigenous and local values, knowledge, and priorities has been widely identified as a critical component of community-based adaptation (KM 16.2).[45,269,270,285,289,306,307,308] In addition to integrating multiple knowledge systems and building workforce development and Tribal capacity for climate resilience,[309] climate adaptation efforts can be strengthened by fostering partnerships among diverse groups and supporting community-based leadership and monitoring.[45,267,285] This need is recognized in White House guidance to federal agencies.[310]

Education for many audiences has long been an essential component of adaptation in Alaska. Numerous educational efforts in Alaska are bringing climate change information and understanding to K–12 students, undergraduate and graduate students, educators, and community members. The Global Learning and Observations to Benefit the Environment (GLOBE) program has engaged more than 1,400 rural and urban Alaska teachers and over 20,000 students in climate change learning and citizen science in a culturally sustaining way since 1996.[311,312,313] Scientists have used Alaska students' GLOBE data.[314,315] The Arctic and Earth STEM Integrating GLOBE and NASA project braids Indigenous and Western science to engage formal and informal educators, community members, and youth in projects relevant to their communities[316], in partnership with the Association of Interior Native Educators. Other community/citizen science projects related to climate change focus on Alaska berries, freshwater ice, snow depth, and coastal community observations and knowledge.[317] Climate education efforts for adults include an online course exploring climate change in Arctic environments, community training in the Alaska Tribal Resilience Learning Network through the Alaska Climate Adaptation Science Center, and peer-to-peer learning and knowledge exchange in the community-led relocation, managed retreat, and protect-in-place coordinator cohort. The Scenarios Network for Alaska and Arctic Planning provides downscaled climate data, while the Alaska Center for Climate Assessment and Policy provides climate and weather webinars, graphics, and tools. New initiatives are also being developed.[318]

Box 29.7. Tribal Adaptation to Climate Change

Threats to traditional foods are existential concerns for Tribal communities:

> *We're at a tipping point that people need to learn how to spell food sovereignty. — Dune Lankard, Eyak Athabascan, Copper River Delta (interview with Willow Hetrick, December 16, 2020).*[319]

Food sovereignty includes the ability of communities to determine the quantity and quality of food that they consume by controlling how their food is produced and distributed. To meet this need, Chugach Regional Resources Commission (CRRC) and one of its divisions, the Alutiiq Pride Marine Institute (APMI), incorporate Indigenous Knowledge, Tribal perspectives, and Western scientific methods. To address health concerns, the harmful algal bloom program analyzes weekly water samples and warns Tribal governments of any health concerns. To bolster regionally important food sources, they place young clams on beaches with dwindling clam populations and are extending that effort to bidarkis (the local name for black leather chitons, *Katharina tunicata*). To help reduce the effects of carbon dioxide emissions, CRRC and APMI are developing kelp farming as a mitigator of ocean acidification effects, a carbon sink, and a potential source of income. These efforts show what can be accomplished with dedication and collaboration.

Harvesting Kelp in Prince William Sound

Kelp farming is an adaptation action that can reduce the impacts of ocean acidification, take up carbon dioxide, and provide income.

Figure 29.17. Kelp is being harvested on a boat in Prince William Sound, Alaska, May 15, 2022. Photo credit: ©Emily Mailman.

Traceable Accounts

Process Description

The author team reviewed the Alaska chapters in previous National Climate Assessments (NCAs) and considered the guidance from NCA leadership to make NCA5 "people-centered." The team recognized three broad topics: rapid biophysical change, compounding societal effects, and adaptation efforts. From these, the team developed seven areas for Key Messages and identified a number of themes to emphasize throughout the chapter, tying together the material in each Key Message. The team then reviewed the available information (as detailed below for each Key Message) to write the chapter. Where necessary, the team has cited reports and other non-peer-reviewed sources for specific information that is not available elsewhere. The author team agreed that the sources were credible and appropriate for the purposes for which they were cited. The team has not included likelihood statements (*very likely*, *unlikely*, etc.) because there was not a quantitative basis for doing so (Guide to the Report).

Key Messages from previous NCAs, and the overall guidance from NCA leadership, helped identify major areas where expertise would be needed. Diversity of age, race, gender, discipline, and perspective were also considered in selecting the author team, along with the ability to think broadly about connections among aspects of climate change. The chapter lead author, federal coordinating lead author, and agency chapter lead authors compiled a list of candidates and asked other organizations to suggest names so as to broaden the search. Once several persons were recruited as chapter authors, they too were asked about gaps in the team's collective expertise, and additional needs were identified along with candidates to address those needs.

The author team met twice monthly to discuss the chapter contents and the writing process. Through these meetings, the team achieved consensus on the approach to take and then on the contents as the team wrote and revised. The team held an online public engagement workshop on January 12, 2022, with approximately 175 persons registered and a maximum of about 90 participants at any given time. The workshop had a wide range of participants, including Indigenous community leaders, academic researchers, government agency personnel, individuals in the private sector, and members of the public. The team also conducted other outreach meetings and workshops to reach specific audiences, such as through the Alaska Forum on the Environment and the Interagency Arctic Research Policy Committee.

Key Message 29.1

Our Health and Healthcare Are at Risk

Description of Evidence Base

A great deal of research has been done on health status, access to healthcare, and other aspects of health in Alaska (e.g., Hennessey et al. 2008;[67] Thomas et al. 2015;[60] Eichelberger 2010;[59] Hahn et al. 2021[82]). The context in which climate change affects health is thus generally well established (KM 15.1).[61] Attention to mental health and community health has been growing in recent years, providing an increasingly firm foundation for this Key Message (KM 15.1).[74,75,76] Research specifically on the implications of climate change for health and mental health has been more limited in Alaska. The findings of that research are generally consistent.

Major Uncertainties and Research Gaps

Much of the literature about climate change and health in Alaska has focused on what is to be expected as the climate continues to warm. Evidence of the actual health effects that are occurring at present is less robust, although what does exist is consistent across studies. There is also a lack of studies documenting

health effects, especially mental and community health effects specifically tied to factors related to climate change, and determining effective public health responses. More work can be done to document Indigenous Knowledge with regard to health and mental health in Alaska.

Description of Confidence and Likelihood

Health disparities in Alaska are all too well documented (e.g., Cochran et al. 2013;[55] Thomas et al. 2015;[60] Eichelberger 2010;[59] Sohns et al. 2021[56]). Further challenges to health and to access to healthcare will compound those disparities. This can be said with *high confidence*. There is some evidence for the expected effects of climate-driven hazards and emerging diseases (e.g., Witmer et al. 2022;[84] Hahn et al. 2020,[83] Yoder 2018;[57] Huntington et al. 2021[87]), and the state's experience with COVID-19 has amply illustrated what a new disease can do (e.g., Wong et al. 2022;[64] Eichelberger et al. 2021[62]). The course of climate change in regard to health, however, has many uncertainties, and thus the team has *medium confidence* in the second statement in the Key Message. Similarly, improved health surveillance and healthcare access can be expected to contribute to resilience statewide, but further experience and evidence are needed to show that this is the case. Thus, the team has *medium confidence* in the final statement of the Key Message.

Key Message 29.2

Our Communities Are Navigating Compounding Stressors

Description of Evidence Base

Considerable work has been done to document many aspects of Alaska's communities, including social, economic, cultural, physical, and other research.[96,97,107,108,109] Some work has been done, especially in Alaska Native communities, to document observations of and effects from climate change. The findings are in broad agreement that much is changing rapidly, with far-reaching effects on communities. The details vary from place to place and study to study. There is little disagreement in the literature base. Far less work is available about other segments of the population in Alaska, making it difficult to determine whether there are racial and ethnic disparities in climate change exposure and effects among groups other than Alaska Natives.

Major Uncertainties and Research Gaps

Little is known about the effectiveness of responses and adaptations to climate change among Alaska Native communities. For other demographic groups, and for Alaska Natives in urban environments, more research would be required overall to better assess how climate change is affecting and is expected to affect these communities. More work can be done to document Indigenous Knowledge with regard to community well-being in Alaska.

Description of Confidence and Likelihood

The detailed demographic and other evidence that is available concerning community well-being in Alaska is consistent and has been documented repeatedly in the scientific literature and in reports by Tribal and federal agencies, giving the team *high confidence* in the statements in the Key Message. Risks to infrastructure are well known and not in dispute. The benefits of adaptation are addressed in greater detail in Key Message 29.7 and have been established repeatedly around the state.

Key Message 29.3

Our Livelihoods Are Vulnerable Without Diversification

Description of Evidence Base

The state and federal governments regularly collect relevant economic data, providing a firm foundation for understanding Alaska's livelihoods and employment.[96,120,121,122,123] Similarly, much work has been done to document subsistence harvests, providing reliable and consistent figures for production and participation in this vital sector of the economy of rural Alaska. The effects of climate change have been considered for many economic sectors, although to differing degrees. Not surprisingly, those sectors such as fishing that are perceived as being at highest risk from climate change have received the most attention. The findings to date are broadly consistent, allowing for differences in climate change exposure across different sectors.

Major Uncertainties and Research Gaps

Much of the work to date has focused on sectors perceived as vulnerable to climate change, including fishing and subsistence. Less has been done to examine areas of potential new opportunity (e.g., in agriculture), and more research could improve understanding of the effectiveness of various responses and adaptations to changing climate.

There is uncertainty about the economic consequences of climate-driven declines in commercial and subsistence harvest because the impacts of climate change can be moderated by economic dynamics and alternative harvest opportunities.[125,126,143]

A major uncertainty regarding climate impacts on groundfish, salmon, and crab is the unknown influences of interacting processes and parameters, such as competition, predation, density dependence, food web structure, habitat availability, and harvest.[18,131,142,144] Thus, future research on the impacts of climate on groundfish, salmon, and crab should be interdisciplinary.

Another major topic that could benefit from future research is the mechanisms linking climate drivers to biological effects on salmon, groundfish, and crab.[134,137,320] Elucidation of the details of these mechanisms could help improve predictions of ecosystem change in the context of future climate change. In addition, spatial variation in ecosystem response to climate change lends uncertainty to predicting local impacts.[21,23]

More work can be done to document Indigenous Knowledge with regard to livelihoods and the factors that affect them in Alaska.

Description of Confidence and Likelihood

Documentation of risks posed by climate change to resource-dependent livelihoods is extensive and consistent in the scientific literature and in government reports, giving the author team *high confidence* in the first statement of the Key Message. Looking to the future involves greater uncertainty, and thus the team has *medium confidence* in the second statement of the Key Message. The third statement is supported by the available literature, but there is not a great deal of it, giving the team *medium confidence*.

Key Message 29.4

Our Built Environment Will Become More Costly

Description of Evidence Base

Many major assessments have been done concerning Alaska's built environment, including economic studies of the costs associated with climate change and the risks from coastal and riverbank erosion around the state.[170,171,173,174,181] The findings are consistent that costs will be high and that many communities face high risks. The timing of erosion and other damage is less certain, as is the effectiveness of various measures to slow or stop climate-driven effects.

Major Uncertainties and Research Gaps

More work could improve understanding of the effectiveness of various responses to climate-driven damage to infrastructure. How response capacity can be created or provided, especially to remote communities, is an open question. The fact that models probably underestimate the actual costs and damages suggests another area for further work. These gaps contribute to uncertainty in estimates of the costs associated with infrastructure degradation, destruction, and collapse. More work can be done to document Indigenous Knowledge with regard to the built environment in Alaska. In addition to research gaps, knowledge fragmentation is a major hindrance to effective action. Reducing this fragmentation would require a greater effort to bring together scientists, community members and knowledge holders, and private businesses, especially engineering consulting firms that are already implementing practical solutions.

Description of Confidence and Likelihood

There is little question about the damage being done to Alaska's infrastructure due to climate change and little doubt that more damage will occur. Thus, based on well-documented experiences around the state (e.g., some of the major university and government reports cited in the Key Message text, which are consistent with one another), the author team has *high confidence* in the first two statements of the Key Message concerning what effects climate change is having on infrastructure and the further effects that are expected. The third sentence, about planning and adaptation, is of *high confidence* due to the evidence that planning can work. The team notes here that the question remains as to what is required to implement designs and ideas for protecting infrastructure to withstand the effects of climate change.

Key Message 29.5

Our Natural Environment Is Transforming Rapidly

Description of Evidence Base

Changes in Alaska's marine, terrestrial and freshwater ecosystems, including effects of climate on species ranges, species viability, community structure, ecosystem structure and function, and landscapes and riverscapes are extensively documented in the scientific literature.[1,39,143,192,198]

The strong climatic controls implicated in many, though not all, of these changes may negatively affect the abundance and/or quality of ecosystem goods and services, such as ice transportation or many ocean and anadromous fisheries, but projections of these impacts are easier for some goods and services than others. Confidence is higher for those impacts that are directly mediated by physical drivers (e.g., temperature effects on sea ice[45] or snowpack[46]) than those with complex drivers (multiple climate drivers and ecological interactions, such as berry production.[160]

The fact that some of the stressors are non-climatic and can respond to management choices or strategies indicates the possibility of avoiding some potential impacts through management. The literature on alternative strategies is limited; this is where synthetic and logical arguments can be made on the scientific information describing impacts and plausible future. But it is yet uncertain which management choices would be potentially effective, how they would be implemented, and whether they would be sufficient to decrease impacts.

Major Uncertainties and Research Gaps

As with many impacts of climatic change, attribution of the fraction of the response due directly to climatic change is challenging. Much of the work is correlative rather than deterministic, and in Alaska, the datasets that exist for attribution work are severely limited compared to places in the contiguous United States (CONUS) because of the scarcity of long-term observational datasets that can be used for training downscaling methods. Thus, datasets downscaled from CMIP6 models were not available for Alaska when they were available for CONUS. Downscaling methodology that would accelerate attribution research is also limited. However, even perfect historical and future climatologies would not eliminate uncertainty—useful attribution and projections depend on strong impacts modeling and appropriate bridging to resource management, and understanding impacts on goods and services is not the same as direct modeling of species, community, landscape, and ocean impacts. A major research gap is adequate long-term physical and biological monitoring data needed to support and improve model forecasts. More work can be done to document Indigenous Knowledge with regard to the natural environment in Alaska, keeping in mind important questions of who is doing the documentation, how, and for what purpose. The considerations have implications for climate justice and Indigenous rights. Additionally, there is a need to better coordinate and improve accessibility of existing data to help identify data needs as well as make more effective use of what is already known.

Description of Confidence and Likelihood

A great deal of scientific research, as reported widely in the scholarly literature, has examined ecological change in detail around Alaska. The confidence in ecological change is *high* and not *very high* because other non-climatic factors (such as development and other changes in land use) also contribute to ecosystem change and/or documentation of climate-driven change has yet to emerge for some observed changes.

Confidence concerning ecosystem goods and services is *medium* because 1) although impacts modeling for many species and processes indicates this is probably true, impacts modeling for goods and services is limited compared to direct physical and ecological impacts; and 2) uncertainty in both climate futures and ecosystem responses is large enough that specific predictions are elusive. Although the reasoning is sound, there is a limited body of peer-reviewed published evidence.

Confidence in the ability of careful management to help address climate concerns in the context of other needs and aims is *medium* because there is limited peer-reviewed literature documenting that climate-relevant management practices would be adopted. However, examples exist.

Key Message 29.6

Our Security Faces Greater Threats

Description of Evidence Base

Some research and planning have been done by the branches of the armed services to assess the hazards from climate change in Alaska.[248] Additionally, some work has been done to assess hazards to civilian forms of security, including food security.[75,87,251,254] The literature is consistent in identifying multiple hazards and high uncertainties, which exacerbate risks to security by impeding the ability to plan effectively and efficiently.

Major Uncertainties and Research Gaps

Obvious risks such as coastal erosion and damage from thawing permafrost are well documented. Some other risks, such as the potential for wildfires and associated smoke to disrupt airborne operations, have been recognized. The assessment of many other risks, however, remains speculative and would benefit from further study. Of note here is the unknown degree to which climate change will alter, rather than merely have a modest influence on, geopolitical concerns and national security threats. More work can be done to document Indigenous Knowledge with regard to the various aspects of security in Alaska.

Description of Confidence and Likelihood

Due to the extent and nature of climate change, as documented in numerous academic and government studies, there is *high confidence* that a changing climate has the potential to alter Alaska's security at scales from local to national. Likewise, there is little question—and thus *high confidence*—that further change will continue to create this hazard. Exactly how the appraised risks will turn into actual effects is less certain in the available literature, giving *medium confidence* in the ability to develop and put in place effective response strategies.

Key Message 29.7

Our Just and Prosperous Future Starts with Adaptation

Description of Evidence Base

Peer-reviewed academic research that analyzes or documents climate adaptation successes and challenges is less prevalent than other sources such as online portals, gray and white literature, published adaptation plans, and other reliable sources of information. However, the body of literature is growing, and all of these sources are relatively consistent in their content. Several non-climate stressors have been identified in peer-reviewed literature as factors that can affect a population's ability to adapt to climate change.[270,304,305,321] Building local capacity and connecting adaptation efforts to economic and workforce development are emerging topics that have less evidence base in existing publications,[322,323] but the authors felt it was important to include these issues based on observations and lived experience.

Major Uncertainties and Research Gaps

As noted above, existing research gaps related to climate adaptation and planning exist in the academic literature; however, there are several areas of agreement among white and gray literature and lived experience, as documented in other credible sources. Research focusing on community values, priorities, and needs, including workforce development, is just emerging. Very little research has been done evaluating the implementation of adaptation efforts, especially through Indigenous evaluation methodol-

ogies.[324] More work can be done to document Indigenous Knowledge with regard to resilience and climate response in Alaska. Additional work can also be done to learn from what is and is not working in ongoing adaptation activities.

Description of Confidence and Likelihood

There is strong evidence from many reports and studies (see citations in the Key Message text), and thus *high confidence*, that local and regional adaptation efforts are underway and that more have been funded. The new influx of federal funding opportunities is expected to provide much-needed support, building on previous investments in rural Alaska, which together give *high confidence* that the demand for investment is substantial. As of this writing, little work has been done, however, to establish locally acceptable metrics and evaluation plans to assess the actual impact of funding influx. Given that research focusing on community values, priorities and needs, including workforce development, is just emerging, the final sentence of the Key Message has been assigned *medium confidence*.

References

1. Ballinger, T.J., U.S. Bhatt, P.A. Bieniek, B. Brettschneider, R.T. Lader, J.S. Littell, R.L. Thoman, C.F. Waigl, J.E. Walsh, and M.A. Webster, 2023: Alaska terrestrial and marine climate trends, 1957–2021. *Journal of Climate*, **36**, 4375–4391. https://doi.org/10.1175/jcli-d-22-0434.1

2. Markon, C., S. Gray, M. Berman, L. Eerkes-Medrano, T. Hennessy, H. Huntington, J. Littell, M. McCammon, R. Thoman, and S. Trainor, 2018: Ch. 26. Alaska. In: *Impacts, Risks, and Adaptation in the United States: Fourth National Climate Assessment, Volume II*. Reidmiller, D.R., C.W. Avery, D. Easterling, K. Kunkel, K.L.M. Lewis, T.K. Maycock, and B.C. Stewart, Eds. U.S. Global Change Research Program, Washington, DC, USA, 1185–1241. https://doi.org/10.7930/nca4.2018.ch26

3. Stabeno, P.J. and S.W. Bell, 2019: Extreme conditions in the Bering Sea (2017–2018): Record-breaking low sea-ice extent. *Geophysical Research Letters*, **46** (15), 8952–8959. https://doi.org/10.1029/2019gl083816

4. Anderson, D.M., E. Fensin, C.J. Gobler, A.E. Hoeglund, K.A. Hubbard, D.M. Kulis, J.H. Landsberg, K.A. Lefebvre, P. Provoost, M.L. Richlen, J.L. Smith, A.R. Solow, and V.L. Trainer, 2021: Marine harmful algal blooms (HABs) in the United States: History, current status and future trends. *Harmful Algae*, **102**, 101975. https://doi.org/10.1016/j.hal.2021.101975

5. Bond, N.A., M.F. Cronin, H. Freeland, and N. Mantua, 2015: Causes and impacts of the 2014 warm anomaly in the NE Pacific. *Geophysical Research Letters*, **42** (9), 3414–3420. https://doi.org/10.1002/2015gl063306

6. Qi, D., L. Chen, B. Chen, Z. Gao, W. Zhong, Richard A. Feely, Leif G. Anderson, H. Sun, J. Chen, M. Chen, L. Zhan, Y. Zhang, and W.-J. Cai, 2017: Increase in acidifying water in the western Arctic Ocean. *Nature Climate Change*, **7** (3), 195–199. https://doi.org/10.1038/nclimate3228

7. Bathke, D.J., H.R. Prendeville, A. Jacobs, R. Heim, R. Thoman, and B. Fuchs, 2019: Defining drought in a temperate rainforest. *Bulletin of the American Meteorological Society*, **100** (12), 2665–2668. https://doi.org/10.1175/bams-d-19-0223.1

8. NWS, n.d.: Historic Drought in a Rainforest: Southeast Alaska (2017–2019). National Oceanic and Atmospheric Administration, National Weather Service, Juneau, AK. https://noaa.maps.arcgis.com/apps/MapJournal/index.html?appid=8ce2db39efde4e589ec66692be45f90a

9. Yates, S., 2020: Extreme Rain Brings Flurry of Landslides. LEO Network. https://www.leonetwork.org/en/posts/show/09e0b101-1489-44e1-8fea-221308a9661a

10. Glomsrod, S., T. Wei, R. Macdonald, L. Lindholt, S. Goldsmith, and T. Matthiasson, 2021: Ch. 4. Arctic economies within the Arctic nations. In: *The Economy of the North–ECONOR 2020*. Glomsrød, S., G. Duhaime, and I. Aslaksen, Eds. Arctic Council Secretariat, Tromso, Norway, 51–100. http://hdl.handle.net/11374/2611

11. Danielson, S.L., O. Ahkinga, C. Ashjian, E. Basyuk, L.W. Cooper, L. Eisner, E. Farley, K.B. Iken, J.M. Grebmeier, L. Juranek, G. Khen, S.R. Jayne, T. Kikuchi, C. Ladd, K. Lu, R.M. McCabe, G.W.K. Moore, S. Nishino, F. Ozenna, R.S. Pickart, I. Polyakov, P.J. Stabeno, R. Thoman, W.J. Williams, K. Wood, and T.J. Weingartner, 2020: Manifestation and consequences of warming and altered heat fluxes over the Bering and Chukchi Sea continental shelves. *Deep Sea Research Part II: Topical Studies in Oceanography*, **177**, 104781. https://doi.org/10.1016/j.dsr2.2020.104781

12. Walsh, J.E., R.L. Thoman, U.S. Bhatt, P.A. Bieniek, B. Brettschneider, M. Brubaker, S. Danielson, R. Lader, F. Fetterer, K. Holderied, K. Iken, A. Mahoney, M. McCammon, and J. Partain, 2018: The high latitude marine heat wave of 2016 and its impacts on Alaska. *Bulletin of the American Meteorological Society*, **99** (1), S39–S43. https://doi.org/10.1175/bams-d-17-0105.1

13. Pilcher, D.J., D.M. Naiman, J.N. Cross, A.J. Hermann, S.A. Siedlecki, G.A. Gibson, and J.T. Mathis, 2019: Modeled effect of coastal biogeochemical processes, climate variability, and ocean acidification on aragonite saturation state in the Bering Sea. *Frontiers in Marine Science*, **5**, 508. https://doi.org/10.3389/fmars.2018.00508

14. Carvalho, K.S., T.E. Smith, and S. Wang, 2021: Bering Sea marine heatwaves: Patterns, trends and connections with the Arctic. *Journal of Hydrology*, **600**, 126462. https://doi.org/10.1016/j.jhydrol.2021.126462

15. Cheung, W.W.L., T.L. Frölicher, V.W.Y. Lam, M.A. Oyinlola, G. Reygondeau, U. Rashid Sumaila, T.C. Tai, L.C.L. Teh, and C.C.C. Wabnitz, 2021: Marine high temperature extremes amplify the impacts of climate change on fish and fisheries. *Science Advances*, **7** (40), 1–16. https://doi.org/10.1126/sciadv.abh0895

16. Bachand, C.L. and J.E. Walsh, 2022: Extreme precipitation events in Alaska: Historical trends and projected changes. *Atmosphere*, **13** (3), 388. https://doi.org/10.3390/atmos13030388

17. Lader, R., U.S. Bhatt, J.E. Walsh, and P.A. Bieniek, 2022: Projections of hydroclimatic extremes in southeast Alaska under the RCP8.5 scenario. *Earth Interactions*, **26** (1), 180–194. https://doi.org/10.1175/ei-d-21-0023.1

18. Hunt Jr., G.L., E.M. Yasumiishi, L.B. Eisner, P.J. Stabeno, and M.B. Decker, 2020: Climate warming and the loss of sea ice: The impact of sea-ice variability on the southeastern Bering Sea pelagic ecosystem. *ICES Journal of Marine Science*, **79** (3), 937–953. https://doi.org/10.1093/icesjms/fsaa206

19. SeaBank, 2020: SeaBank Annual Report 2020. Alaska Sustainable Fisheries Trust, Sitka, AK, 129 pp. https://thealaskatrust.org/about-seabank

20. Siddon, E., 2021: Ecosystem Status Report 2021: Eastern Bering Sea, Stock Assessment and Fishery Evaluation Report. North Pacific Fishery Management Council, Anchorage, AK, 249 pp. https://apps-afsc.fisheries.noaa.gov/refm/docs/2021/ebsecosys.pdf

21. Suryan, R.M., M.L. Arimitsu, H.A. Coletti, R.R. Hopcroft, M.R. Lindeberg, S.J. Barbeaux, S.D. Batten, W.J. Burt, M.A. Bishop, J.L. Bodkin, R. Brenner, R.W. Campbell, D.A. Cushing, S.L. Danielson, M.W. Dorn, B. Drummond, D. Esler, T. Gelatt, D.H. Hanselman, S.A. Hatch, S. Haught, K. Holderied, K. Iken, D.B. Irons, A.B. Kettle, D.G. Kimmel, B. Konar, K.J. Kuletz, B.J. Laurel, J.M. Maniscalco, C. Matkin, C.A.E. McKinstry, D.H. Monson, J.R. Moran, D. Olsen, W.A. Palsson, W.S. Pegau, J.F. Piatt, L.A. Rogers, N.A. Rojek, A. Schaefer, I.B. Spies, J.M. Straley, S.L. Strom, K.L. Sweeney, M. Szymkowiak, B.P. Weitzman, E.M. Yasumiishi, and S.G. Zador, 2021: Ecosystem response persists after a prolonged marine heatwave. *Scientific Reports*, **11** (1), 6235. https://doi.org/10.1038/s41598-021-83818-5

22. ACRC, 2020: 2019 Alaska Climate Review. Alaska Climate Research Center, 27 pp. https://akclimate.org/annual_report/2019-annual-report/

23. von Biela, V.R., C.J. Sergeant, M.P. Carey, Z. Liller, C. Russell, S. Quinn-Davidson, P.S. Rand, P.A.H. Westley, and C.E. Zimmerman, 2022: Premature mortality observations among Alaska's Pacific salmon during record heat and drought in 2019. *Fisheries*, **47** (4), 157–168. https://doi.org/10.1002/fsh.10705

24. AMAP, 2018: *AMAP Assessment 2018: Arctic Ocean Acidification*. Arctic Monitoring and Assessment Programme, Tromsø, Norway, 187 pp. https://www.amap.no/documents/doc/amap-assessment-2018-arctic-ocean-acidification/1659

25. Cheng, W., A.J. Hermann, A.B. Hollowed, K.K. Holsman, K.A. Kearney, D.J. Pilcher, C.A. Stock, and K.Y. Aydin, 2021: Eastern Bering Sea shelf environmental and lower trophic level responses to climate forcing: Results of dynamical downscaling from CMIP6. *Deep Sea Research Part II: Topical Studies in Oceanography*, **193**, 104975. https://doi.org/10.1016/j.dsr2.2021.104975

26. Frölicher, T.L., E.M. Fischer, and N. Gruber, 2018: Marine heatwaves under global warming. *Nature*, **560** (7718), 360–364. https://doi.org/10.1038/s41586-018-0383-9

27. Hermann, A.J., K. Kearney, W. Cheng, D. Pilcher, K. Aydin, K.K. Holsman, and A.B. Hollowed, 2021: Coupled modes of projected regional change in the Bering Sea from a dynamically downscaling model under CMIP6 forcing. *Deep Sea Research Part II: Topical Studies in Oceanography*, **194**, 104974. https://doi.org/10.1016/j.dsr2.2021.104974

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

29. Shaftel, R., S. Mauger, J. Falke, D. Rinella, J. Davis, and L. Jones, 2020: Thermal diversity of salmon streams in the Matanuska-Susitna Basin, Alaska. *Journal of the American Water Resources Association*, **56** (4), 630–646. https://doi.org/10.1111/1752-1688.12839

30. O'Neel, S., C. McNeil, L.C. Sass, C. Florentine, E.H. Baker, E. Peitzsch, D. McGrath, A.G. Fountain, and D. Fagre, 2019: Reanalysis of the US Geological Survey benchmark glaciers: Long-term insight into climate forcing of glacier mass balance. *Journal of Glaciology*, **65** (253), 850–866. https://doi.org/10.1017/jog.2019.66

31. Wolken, G.J., B. Wouters, M. Sharp, L.M. Andreassen, D. Burgess, J. Kohler, and B. Luks, 2020: NOAA Arctic Report Card 2020: Glaciers and Ice Caps Outside Greenland. National Oceanic and Atmospheric Administration, Office of Oceanic and Atmospheric Research, 8 pp. https://doi.org/10.25923/nwqq-8736

32. Romanovsky, V.E., S.L. Smith, K. Isaksen, K.E. Nyland, A.L. Kholodov, N.I. Shiklomanov, D.A. Streletskiy, L.M. Farquharson, D.S. Drozdov, G.V. Malkova, and H.H. Christiansen, 2020: [The Arctic] terrestrial permafrost [in "State of the Climate in 2019"]. *Bulletin of the American Meteorological Society*, **101** (8), S265–S271. https://doi.org/10.1175/bams-d-20-0086.1

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

34. Grabinski, Z. and H.R. McFarland, 2020: Alaska's Changing Wildfire Environment [Outreach Booklet]. University of Alaska Fairbanks, International Arctic Research Center, Alaska Fire Science Consortium. https://www.frames.gov/afsc/acwe

35. Redilla, K., S. Pearl, P. Bieniek, and J. Walsh, 2019: Wind climatology for Alaska: Historical and future. *Atmospheric and Climate Sciences*, **9**, 683–702. https://doi.org/10.4236/acs.2019.94042

36. Hartmann, B. and G. Wendler, 2005: The significance of the 1976 Pacific climate shift in the climatology of Alaska. *Journal of Climate*, **18** (22), 4824–4839. https://doi.org/10.1175/jcli3532.1

37. Walsh, J.E. and B. Brettschneider, 2019: Attribution of recent warming in Alaska. *Polar Science*, **21**, 101–109. https://doi.org/10.1016/j.polar.2018.09.002

38. Dobricic, S., S. Russo, L. Pozzoli, J. Wilson, and E. Vignati, 2020: Increasing occurrence of heat waves in the terrestrial Arctic. *Environmental Research Letters*, **15** (2), 024022. https://doi.org/10.1088/1748-9326/ab6398

39. Bhatt, U.S., R.T. Lader, J.E. Walsh, P.A. Bieniek, R. Thoman, M. Berman, C. Borries-Strigle, K. Bulock, J. Chriest, M. Hahn, A.S. Hendricks, R. Jandt, J. Little, D. McEvoy, C. Moore, T.S. Rupp, J. Schmidt, E. Stevens, H. Strader, C. Waigl, J. White, A. York, and R. Ziel, 2021: Emerging anthropogenic influences on the Southcentral Alaska temperature and precipitation extremes and related fires in 2019. *Land*, **10** (1), 82. https://doi.org/10.3390/land10010082

40. Jandt, R. and A. York, 2021: Wildfire is transforming Alaska and amplifying climate change. *Scientific American*, **325** (4), 42–49. https://www.scientificamerican.com/article/wildfire-is-transforming-alaska-and-amplifying-climate-change/

41. Gutiérrez, J.M., R.G. Jones, G.T. Narisma, L.M. Alves, M. Amjad, I.V. Gorodetskaya, M. Grose, N.A.B. Klutse, S. Krakovska, J. Li, D. Martínez-Castro, L.O. Mearns, S.H. Mernild, T. Ngo-Duc, B. van den Hurk, and J.-H. Yoon, 2021: Atlas. In: *Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*. Masson-Delmotte, V., P. Zhai, A. Pirani, S.L. Connors, C. Péan, S. Berger, N. Caud, Y. Chen, L. Goldfarb, M.I. Gomis, M. Huang, K. Leitzell, E. Lonnoy, J.B.R. Matthews, T.K. Maycock, T. Waterfield, O. Yelekçi, R. Yu, and B. Zhou, Eds. Cambridge University Press, Cambridge, UK and New York, NY, USA, 1927–2058. https://doi.org/10.1017/9781009157896.021

42. Iturbide, M., J. Fernández, J.M. Gutiérrez, J. Bedia, E. Cimadevilla, J. Díez-Sierra, R. Manzanas, A. Casanueva, J. Baño-Medina, J. Milovac, S. Herrera, A.S. Cofiño, D. San Martín, M. García-Díez, M. Hauser, D. Huard, and Ö. Yelekci. 2021: Repository Supporting the Implementation of Fair Principles in the IPCC WG1 Atlas. Zenodo. https://doi.org/10.5281/zenodo.3691645

43. Parding, K.M., A. Dobler, C.F. McSweeney, O.A. Landgren, R. Benestad, H.B. Erlandsen, A. Mezghani, H. Gregow, O. Räty, E. Viktor, J. El Zohbi, O.B. Christensen, and H. Loukos, 2020: GCMeval—An interactive tool for evaluation and selection of climate model ensembles. *Climate Services*, **18**, 100167. https://doi.org/10.1016/j.cliser.2020.100167

44. Bieniek, P.A., J.E. Walsh, R.L. Thoman, and U.S. Bhatt, 2014: Using climate divisions to analyze variations and trends in Alaska temperature and precipitation. *Journal of Climate*, **27** (8), 2800–2818. https://doi.org/10.1175/jcli-d-13-00342.1

45. Meredith, M., M. Sommerkorn, S. Cassotta, C. Derksen, A. Ekaykin, A. Hollowed, G. Kofinas, A. Mackintosh, J. Melbourne-Thomas, M.M.C. Muelbert, H. Ottersen, H. Pritchard, and E.A.G. Schuur, 2022: Ch. 3. Polar Regions. In: *IPCC Special Report on the Ocean and Cryosphere in a Changing Climate*. Pörtner, H.O., D.C. Roberts, V. Masson-Delmotte, P. Zhai, M. Tignor, E. Poloczanska, K. Mintenbeck, A. Alegría, M. Nicolai, A. Okem, J. Petzold, B. Rama, and N.M. Weyer, Eds. Cambridge University Press, Cambridge, UK and New York, NY, USA, 203–320. https://doi.org/10.1017/9781009157964.005

46. Littell, J.S., S.A. McAfee, and G.D. Hayward, 2018: Alaska snowpack response to climate change: Statewide snowfall equivalent and snowpack water scenarios. *Water*, **10** (5), 668. https://doi.org/10.3390/w10050668

47. Mudryk, L., M. Santolaria-Otín, G. Krinner, M. Ménégoz, C. Derksen, C. Brutel-Vuilmet, M. Brady, and R. Essery, 2020: Historical Northern Hemisphere snow cover trends and projected changes in the CMIP6 multi-model ensemble. *Cryosphere*, **14** (7), 2495–2514. https://doi.org/10.5194/tc-14-2495-2020

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

49. Douglas, T.A., C.A. Hiemstra, J.E. Anderson, R.A. Barbato, K.L. Bjella, E.J. Deeb, A.B. Gelvin, P.E. Nelsen, S.D. Newman, S.P. Saari, and A.M. Wagner, 2021: Recent degradation of interior Alaska permafrost mapped with ground surveys, geophysics, deep drilling, and repeat airborne lidar. *Cryosphere*, **15** (8), 3555–3575. https://doi.org/10.5194/tc-15-3555-2021

50. Osterkamp, T.E., M.T. Jorgenson, E.A.G. Schuur, Y.L. Shur, M.Z. Kanevskiy, J.G. Vogel, and V.E. Tumskoy, 2009: Physical and ecological changes associated with warming permafrost and thermokarst in interior Alaska. *Permafrost and Periglacial Processes*, **20** (3), 235–256. https://doi.org/10.1002/ppp.656

51. Farquharson, L.M., V.E. Romanovsky, A. Kholodov, and D. Nicolsky, 2022: Sub-aerial talik formation observed across the discontinuous permafrost zone of Alaska. *Nature Geoscience*, **15** (6), 475–481. https://doi.org/10.1038/s41561-022-00952-z

52. Marino, E., 2015: *Fierce Climate, Sacred Ground: An Ethnography of Climate Change in Shishmaref, Alaska*. University of Alaska Press, Fairbanks, AK, 122 pp. https://upcolorado.com/university-of-alaska-press/item/5674-fierce-climate-sacred-ground

53. KTOO, 2018: Major earthquake damages buildings and roads in Anchorage. *KTOO Public Media*, November 30, 2018. https://www.ktoo.org/2018/11/30/6-7-magnitude-earthquake-rocks-buildings-in-anchorage/

54. Balbus, J., A. Crimmins, J.L. Gamble, D.R. Easterling, K.E. Kunkel, S. Saha, and M.C. Sarofim, 2016: Ch. 1. Introduction: Climate change and human health. In: *The Impacts of Climate Change on Human Health in the United States: A Scientific Assessment*. U.S. Global Change Research Program, Washington, DC, 25–42. https://doi.org/10.7930/j0vx0dfw

55. Cochran, P., O.H. Huntington, C. Pungowiyi, S. Tom, F.S. Chapin, III, H.P. Huntington, N.G. Maynard, and S.F. Trainor, 2013: Indigenous frameworks for observing and responding to climate change in Alaska. *Climatic Change*, **120** (3), 557–567. https://doi.org/10.1007/s10584-013-0735-2

56. Sohns, A., J.D. Ford, J. Adamowski, and B.E. Robinson, 2021: Participatory modeling of water vulnerability in remote Alaskan households using causal loop diagrams. *Environmental Management*, **67** (1), 26–42. https://doi.org/10.1007/s00267-020-01387-1

57. Yoder, S., 2018: Assessment of the potential health impacts of climate change in Alaska. *State of Alaska Epidemiology Bulletin*, **20** (1). https://arctichealth.org/en/permalink/ahliterature287905

58. Driscoll, D.L., E. Mitchell, R. Barker, J.M. Johnston, and S. Renes, 2016: Assessing the health effects of climate change in Alaska with community-based surveillance. *Climatic Change*, **137** (3), 455–466. https://doi.org/10.1007/s10584-016-1687-0

59. Eichelberger, L.P., 2010: Living in utility scarcity: Energy and water insecurity in northwest Alaska. *American Journal of Public Health*, **100** (6), 1010–1018. https://doi.org/10.2105/ajph.2009.160846

60. Thomas, T.K., T. Ritter, D. Bruden, M. Bruce, K. Byrd, R. Goldberger, J. Dobson, K. Hickel, J. Smith, and T. Hennessy, 2015: Impact of providing in-home water service on the rates of infectious diseases: Results from four communities in Western Alaska. *Journal of Water and Health*, **14** (1), 132–141. https://doi.org/10.2166/wh.2015.110

61. OCCHE, 2022: Climate Change and Health Equity. U.S. Department of Health and Human Services, Office of Climate Change and Health Equity. https://www.hhs.gov/climate-change-health-equity-environmental-justice/climate-change-health-equity/index.html

62. Eichelberger, L., S. Dev, T. Howe, D.L. Barnes, E. Bortz, B.R. Briggs, P. Cochran, A.D. Dotson, D.M. Drown, M.B. Hahn, K. Mattos, and S. Aggarwal, 2021: Implications of inadequate water and sanitation infrastructure for community spread of COVID-19 in remote Alaskan communities. *Science of The Total Environment*, **776**, 145842. https://doi.org/10.1016/j.scitotenv.2021.145842

63. Rodriguez-Lonebear, D., N.E. Barceló, R. Akee, and S.R. Carroll, 2020: American Indian reservations and COVID-19: Correlates of early infection rates in the pandemic. *Journal of Public Health Management and Practice*, **26** (4), 371–377. https://doi.org/10.1097/phh.0000000000001206

64. Wong, M.S., D.M. Upchurch, W.N. Steers, T.P. Haderlein, A.T. Yuan, and D.L. Washington, 2022: The role of community-level factors on disparities in COVID-19 infection among American Indian/Alaska Native veterans. *Journal of Racial and Ethnic Health Disparities*, **9** (5), 1861–1872. https://doi.org/10.1007/s40615-021-01123-3

65. ADEC, 2013: Alaska Water and Sewer Challenge. Alaska Department of Environmental Conservation. http://watersewerchallenge.alaska.gov/

66. ANTHC, 2019: Portable Alternative Sanitation System Connects In-Home Sanitation Systems Where It Was Impossible Before. Alaska Native Tribal Health Consortium. https://www.anthc.org/news/portable-alternative-sanitation-system-connects-in-home-sanitation-systems-where-it-was-impossible-before/

67. Hennessy, T.W., T. Ritter, R.C. Holman, D.L. Bruden, K.L. Yorita, L. Bulkow, J.E. Cheek, R.J. Singleton, and J. Smith, 2008: The relationship between in-home water service and the risk of respiratory tract, skin, and gastrointestinal tract infections among rural Alaska natives. *American Journal of Public Health*, **98** (11), 2072–2078. https://doi.org/10.2105/ajph.2007.115618

68. Hicks, K.L., S.K. Robler, A. Platt, S.N. Morton, J.R. Egger, and S.D. Emmett, 2023: Environmental factors for hearing loss and middle ear disease in Alaska Native children and adolescents: A cross-sectional analysis from a cluster randomized trial. *Ear and Hearing*, **44** (1), 2–9. https://doi.org/10.1097/aud.0000000000001265

69. Mosites, E., B. Lefferts, S. Seeman, G. January, J. Dobson, D. Fuente, M. Bruce, T. Thomas, and T. Hennessy, 2020: Community water service and incidence of respiratory, skin, and gastrointestinal infections in rural Alaska, 2013–2015. *International Journal of Hygiene and Environmental Health*, **225**, 113475. https://doi.org/10.1016/j.ijheh.2020.113475

70. Brock, R.L., M.W. O'Hara, K.J. Hart, J.E. McCabe-Beane, J.A. Williamson, A. Brunet, D.P. Laplante, C. Yu, and S. King, 2015: Peritraumatic distress mediates the effect of severity of disaster exposure on perinatal depression: The Iowa flood study. *Journal of Traumatic Stress*, **28** (6), 515–522. https://doi.org/10.1002/jts.22056

71. Mallett, L.H. and R.A. Etzel, 2018: Flooding: What is the impact on pregnancy and child health? *Disasters*, **42** (3), 432–458. https://doi.org/10.1111/disa.12256

72. Thoman, R., 2022: Typhoon Merbok, fueled by unusually warm Pacific Ocean, pounded Alaska's vulnerable coastal communities at a critical time. *The Conversation*. https://theconversation.com/typhoon-merbok-fueled-by-unusually-warm-pacific-ocean-pounded-alaskas-vulnerable-coastal-communities-at-a-critical-time-190898

73. Cunsolo, A. and N.R. Ellis, 2018: Ecological grief as a mental health response to climate change-related loss. *Nature Climate Change*, **8** (4), 275–281. https://doi.org/10.1038/s41558-018-0092-2

74. Cianconi, P., S. Betrò, and L. Janiri, 2020: The impact of climate change on mental health: A systematic descriptive review. *Frontiers in Psychiatry*, **11**, 74. https://doi.org/10.3389/fpsyt.2020.00074

75. Donkersloot, R., J.C. Black, C. Carothers, D. Ringer, W. Justin, P.M. Clay, M.R. Poe, E.R. Gavenus, W. Voinot-Baron, C. Stevens, M. Williams, J. Raymond-Yakoubian, F. Christiansen, S.J. Breslow, S.J. Langdon, J.M. Coleman, and S.J. Clark, 2020: Assessing the sustainability and equity of Alaska salmon fisheries through a well-being framework. *Ecology and Society*, **25** (2). https://doi.org/10.5751/es-11549-250218

76. Oscarville Traditional Village, 2019: Pektayiinata = We Are Resilient: Oscarville Tribal Climate Adaptation Plan. U.S. Department of Interior, Bureau of Indian Affairs, Tribal Resilience Program, Oscarville, AK. https://www.nna-co.org/index.php/resource/oscarville-tribal-climate-adaptation-plan

77. Dannenberg, A.L., H. Frumkin, J.J. Hess, and K.L. Ebi, 2019: Managed retreat as a strategy for climate change adaptation in small communities: Public health implications. *Climatic Change*, **153** (1), 1–14. https://doi.org/10.1007/s10584-019-02382-0

78. Knodel, M., 2014: Conceptualizing climate justice in Kivalina. *Seattle University Law Review*, **37** (4). https://digitalcommons.law.seattleu.edu/sulr/vol37/iss4/4

79. Trombley, J., S. Chalupka, and L. Anderko, 2017: Climate change and mental health. *AJN The American Journal of Nursing*, **117** (4), 44–52. https://doi.org/10.1097/01.naj.0000515232.51795.fa

80. Allen, J., L. Wexler, and S. Rasmus, 2022: Protective factors as a unifying framework for strength-based intervention and culturally responsive American Indian and Alaska Native suicide prevention. *Prevention Science*, **23** (1), 59–72. https://doi.org/10.1007/s11121-021-01265-0

81. Cunsolo Willox, A., E. Stephenson, J. Allen, F. Bourque, A. Drossos, S. Elgarøy, M.J. Kral, I. Mauro, J. Moses, T. Pearce, J.P. MacDonald, and L. Wexler, 2015: Examining relationships between climate change and mental health in the circumpolar North. *Regional Environmental Change*, **15** (1), 169–182. https://doi.org/10.1007/s10113-014-0630-z

82. Hahn, M.B., G. Kuiper, K. O'Dell, E.V. Fischer, and S. Magzamen, 2021: Wildfire smoke is associated with an increased risk of cardiorespiratory emergency department visits in Alaska. *GeoHealth*, **5** (5), e2020GH000349. https://doi.org/10.1029/2020gh000349

83. Hahn, M.B., G. Disler, L.A. Durden, S. Coburn, F. Witmer, W. George, K. Beckmen, and R. Gerlach, 2020: Establishing a baseline for tick surveillance in Alaska: Tick collection records from 1909–2019. *Ticks and Tick-borne Diseases*, **11** (5), 101495. https://doi.org/10.1016/j.ttbdis.2020.101495

84. Witmer, F.D.W., T.W. Nawrocki, and M. Hahn, 2022: Modeling geographic uncertainty in current and future habitat for potential populations of *Ixodes pacificus* (Acari: Ixodidae) in Alaska. *Journal of Medical Entomology*, **59** (3), 976–986. https://doi.org/10.1093/jme/tjac001

85. Beckmen, K., 2021: Rabies outbreak in western Alaska sparks team response. *Alaska Fish and Wildlife News*, June 2021. https://www.adfg.alaska.gov/index.cfm?adfg=wildlifenews.view_article&articles_id=993

86. Kim, B.I., J.D. Blanton, A. Gilbert, L. Castrodale, K. Hueffer, D. Slate, and C.E. Rupprecht, 2014: A conceptual model for the impact of climate change on fox rabies in Alaska, 1980–2010. *Zoonoses and Public Health*, **61** (1), 72–80. https://doi.org/10.1111/zph.12044

87. Huntington, H.P., J. Raymond-Yakoubian, G. Noongwook, N. Naylor, C. Harris, Q. Harcharek, and B. Adams, 2021: "We never get stuck:" A collaborative analysis of change and coastal community subsistence practices in the Northern Bering and Chukchi Seas, Alaska. *Arctic*, **74** (2), 113–126. https://doi.org/10.14430/arctic72446

88. Christie, K.S., T.E. Hollmen, H.P. Huntington, and J.R. Lovvorn, 2018: Structured decision analysis informed by traditional ecological knowledge as a tool to strengthen subsistence systems in a changing Arctic. *Ecology and Society*, **23** (4), 42. https://doi.org/10.5751/es-10596-230442

89. Hendrix, A.M., K.A. Lefebvre, L. Quakenbush, A. Bryan, R. Stimmelmayr, G. Sheffield, G. Wisswaesser, M.L. Willis, E.K. Bowers, P. Kendrick, E. Frame, T. Burbacher, and D.J. Marcinek, 2021: Ice seals as sentinels for algal toxin presence in the Pacific Arctic and subarctic marine ecosystems. *Marine Mammal Science*, **37** (4), 1292–1308. https://doi.org/10.1111/mms.12822

90. Lefebvre, K.A., L. Quakenbush, E. Frame, K. Burek, G. Sheffield, R. Stimmelmayr, A. Bryan, P. Kendrick, H. Ziel, T. Goldstein, J.A. Snyder, T. Gelatt, F. Gulland, B. Dickerson, and V. Gill, 2016: Prevalence of algal toxins in Alaskan marine mammals foraging in a changing arctic and subarctic environment. *Harmful Algae*, **55**, 13–24. https://doi.org/10.1016/j.hal.2016.01.007

91. Van Hemert, C., J.D. Robert, M.S. Matthew, K. Robert, S. Gay, M.D. Lauren, J.K. Kathy, K. Susan, S.L. Julia, D.R. Hardison, R.W. Litaker, J. Timothy, K.B. Hillary, and K.P. Julia, 2021: Investigation of algal toxins in a multispecies seabird die-off in the Bering and Chukchi seas. *Journal of Wildlife Diseases*, **57** (2), 399–407. https://doi.org/10.7589/jwd-d-20-00057

92. Van Hemert, C., S.K. Schoen, R.W. Litaker, M.M. Smith, M.L. Arimitsu, J.F. Piatt, W.C. Holland, D. Ransom Hardison, and J.M. Pearce, 2020: Algal toxins in Alaskan seabirds: Evaluating the role of saxitoxin and domoic acid in a large-scale die-off of common murres. *Harmful Algae*, **92**, 101730. https://doi.org/10.1016/j.hal.2019.101730

93. Johnson-Agbakwu, C.E., N.S. Ali, C.M. Oxford, S. Wingo, E. Manin, and D.V. Coonrod, 2022: Racism, COVID-19, and health inequity in the USA: A call to action. *Journal of Racial and Ethnic Health Disparities*, **9** (1), 52–58. https://doi.org/10.1007/s40615-020-00928-y

94. van Dorn, A., R.E. Cooney, and M.L. Sabin, 2020: COVID-19 exacerbating inequalities in the US. *The Lancet*, **395** (10232), 1243–1244. https://doi.org/10.1016/s0140-6736(20)30893-x

95. Cana Uluaq Itchuaqiyaq (Author), May 13, 2022: Email communication with Gladys I'yiiqpak Pungowiyi (Iñupiaq), Kotzebue, Alaska.

96. ADLWD, 2020: Alaska Population Overview: 2019 Estimates. Alaska Department of Labor and Workforce Development, Research and Analysis Section. https://live.laborstats.alaska.gov/pop/estimates/pub/19popover.pdf

97. Berman, M. and J.I. Schmidt, 2019: Economic effects of climate change in Alaska. *Weather, Climate, and Society*, **11** (2), 245–258. https://doi.org/10.1175/wcas-d-18-0056.1

98. NTIA, 2020: Indicators of Broadband Need Map. U.S. Department of Commerce, National Telecommunications and Information Administration. https://broadbandusa.ntia.doc.gov/resources/data-and-mapping

99. Tracie Curry (Author), March 10, 2023: Telephone and email communication with Thomas Lochner, director of the Alaska broadband office, Alaska Department of Commerce, Community, and Economic Development.

100. Hudson, H.E., V. Hanna, A. Hill, K. Parker, S. Sharp, K. Spiers, and K. Wark, 2021: Toward Universal Broadband in Rural Alaska: Final Report. State of Alaska, Governor's Task Force on Broadband. https://indd.adobe.com/view/42ddcfe3-5ea9-4bcb-bd09-a71bcb63869a

101. FNSB, 2021: Geographic Information Services (GIS). Fairbanks North Star Borough. https://fnsb.gov/433/geographic-information-services-gis

102. NRCS, 2019: Web Soil Survey. U.S. Department of Agriculture, Natural Resources Conservation Service. https://websoilsurvey.nrcs.usda.gov/app/

103. U.S. Census Bureau, 2021: American Community Survey (ACS). U.S. Department of Commerce, U.S. Census Bureau. https://www.census.gov/programs-surveys/acs

104. Hartman, I.C., 2020: *Black History in the Last Frontier*. Johnson, K., Ed. National Park Service. https://www.nps.gov/articles/upload/black-history-in-the-last-frontier_reader_compressed.pdf

105. ADLWD, 2021: 2021 Population Estimates by Borough, Census Area, and Economic Region. Alaska Department of Labor and Workforce Development, Juneau, AK. https://live.laborstats.alaska.gov/pop/index.cfm

106. State of Alaska, 2022: Administrative Order No. 331: Alaska Food Security and Independence Task Force. State of Alaska, Office of the Governor. https://gov.alaska.gov/admin-orders/administrative-order-no-331/

107. Fried, N., 2019: The Cost of Living: 2018 and Early 2019. State of Alaska, Department of Labor and Workforce Development. https://live.laborstats.alaska.gov/trends-articles/2019/07/the-cost-of-living-in-alaska

108. SNAP, 2022: State Activity Report: Fiscal Year 2020. Food and Nutrition Service, Supplemental Nutrition Assistance Program. https://www.fns.usda.gov/pd/snap-state-activity-reports

109. Fall, J.A., 2018: Subsistence in Alaska: A Year 2017 Update. Alaska Department of Fish and Game, Division of Subsistence, Anchorage, AK, 4 pp. http://www.adfg.alaska.gov/static/home/subsistence/pdfs/subsistence_update_2017.pdf

110. Cheng, M., M. Zhang, R.M. Van Veldhuizen, and C.W. Knight, 2021: Growing season and phenological stages of small grain crops in response to climate change in Alaska. *American Journal of Climate Change*, **10** (4), 490–511. https://doi.org/10.4236/ajcc.2021.104025

111. Fresco, N., A. Bennett, P. Bieniek, and C. Rosner, 2021: Climate change, farming, and gardening in Alaska: Cultivating opportunities. *Sustainability*, **13** (22), 12713. https://doi.org/10.3390/su132212713

112. Lader, R., J.E. Walsh, U.S. Bhatt, and P.A. Bieniek, 2018: Agro-climate projections for a warming Alaska. *Earth Interactions*, **22** (18), 1–24. https://doi.org/10.1175/ei-d-17-0036.1

113. Clifford, L., 2022: North Pole man killed in head-on collision on the Richardson Highway. *Fairbanks Daily News-Miner*, March 2, 2022. https://www.newsminer.com/news/alaska_news/north-pole-man-killed-in-head-on-collision-on-the-richardson-highway/article_f25008e0-9a9b-11ec-bfef-6f7855147b3b.html

114. Williams, T., 2021: Interior Alaska storm wreaks havoc as highways temporarily close and thousands remain without power. *Anchorage Daily News*, December 27, 2021. https://www.adn.com/alaska-news/weather/2021/12/27/interior-alaska-storm-wreaks-havoc-as-highways-temporarily-close-and-thousands-remain-without-power/

115. Kitchenman, A., 2022: Gov. Dunleavy issues disaster declaration for Interior Alaska and Mat-Su storms. *KTOO Public Media*, January 3, 2022. https://www.ktoo.org/2022/01/03/dunleavy-disaster-declaration-alaska-storms/

116. The White House, 2022: President Joseph R. Biden, Jr. Approves Alaska Disaster Declaration. The White House. https://www.whitehouse.gov/briefing-room/statements-releases/2022/03/24/president-joseph-r-biden-jr-approves-alaska-disaster-declaration-4/

117. Alyssa Quintyne (Author), May 4, 2022: Email communication with Marjorie Casort, Fairbanks, Alaska.

118. Watson, E., 2022: I hope people talk about this storm for a long time. *Anchorage Daily News*, January 4, 2022. https://www.adn.com/opinions/2022/01/04/i-hope-people-talk-about-this-storm-for-a-long-time/

119. AMAP, 2021: Arctic Climate Change Update 2021: Key Trends and Impacts. Arctic Monitoring and Assessment Programme, Tromsø, Norway. https://www.amap.no/documents/download/6759/inline

120. NASS, 2019: Census of Agriculture: 2017 State and Area Profiles—Alaska. U.S. Department of Agriculture, National Agricultural Statistics Service. https://www.nass.usda.gov/publications/agcensus/2017/online_resources/county_profiles/alaska/index.php

121. McDowell Group, 2018: Economic Impact of Alaska's Visitor Industry 2017. State of Alaska, Department of Commerce, Community, and Economic Development. https://www.mcdowellgroup.net/wp-content/uploads/2018/11/visitor-impacts-2016-17-report.pdf

122. McKinley Research Group, 2022: The Economic Value of Alaska's Seafood Industry. The Alaska Seafood Marketing Institute. https://www.alaskaseafood.org/wp-content/uploads/MRG_ASMI-Economic-Impacts-Report_final.pdf

123. Barbeaux, S.J., K. Holsman, and S. Zador, 2020: Marine heatwave stress test of ecosystem-based fisheries management in the Gulf of Alaska Pacific cod fishery. *Frontiers in Marine Science*, **7**, 703. https://doi.org/10.3389/fmars.2020.00703

124. Conrad, S. and D. Gray, 2018: Overview of the 2017 Southeast Alaska and Yakutat Commercial, Personal Use, and Subsistence Salmon Fisheries. Fishery Management Report No. 18-01. Alaska Department of Fish and Game, Division of Sport Fish, Research and Technical Services, Anchorage, AK. https://www.adfg.alaska.gov/fedaidpdfs/fmr18-01.pdf

125. Garber-Yonts, B. and J. Lee, 2020: Stock Assessment and Fishery Evaluation Report for the King and Tanner Crab Fisheries of the Gulf of Alaska and Bering Sea/Aleutian Islands Area: Economic Status of the BSAI King and Tanner Crab Fisheries off Alaska, 2019. National Oceanic and Atmospheric Administration, National Marine Fisheries Service, Seattle, WA. https://repository.library.noaa.gov/view/noaa/23002

126. Oke, K.B., C.J. Cunningham, P.A.H. Westley, M.L. Baskett, S.M. Carlson, J. Clark, A.P. Hendry, V.A. Karatayev, N.W. Kendall, J. Kibele, H.K. Kindsvater, K.M. Kobayashi, B. Lewis, S. Munch, J.D. Reynolds, G.K. Vick, and E.P. Palkovacs, 2020: Recent declines in salmon body size impact ecosystems and fisheries. *Nature Communications*, **11** (1), 1–13. https://doi.org/10.1038/s41467-020-17726-z

127. NMFS, 2022: Fisheries of the United States, 2020. NOAA Current Fishery Statistics No. 2020. National Oceanic and Atmospheric Administration, National Marine Fisheries Service. https://www.fisheries.noaa.gov/resource/document/fisheries-united-states-2020

128. Alaska Department of Fish and Game, 2021: 2021 Upper Cook Inlet Commercial Salmon Fishery Season Summary. Alaska Department of Fish and Game, Division of Commercial Fisheries, 15 pp. https://www.adfg.alaska.gov/static/applications/dcfnewsrelease/1346668657.pdf

129. Barbeaux, S., K. Aydin, B. Fissel, K. Holsman, W. Palsson, K. Shotwell, Q. Yang, and S. Zador, 2017: Assessment of the Pacific cod stock in the Gulf of Alaska. In: *NPFMC Gulf of Alaska SAFE*. North Pacific Fishery Management Council, 183–326. https://repository.library.noaa.gov/view/noaa/17515

130. Dorn, M., K. Aydin, B. Fissel, W. Palsson, K. Spalinger, S. Stienessen, K. Williams, and S. Zador, 2018: Ch. 1. Assessment of the walleye pollock stock in the Gulf of Alaska. In: *NPFMC Gulf of Alaska SAFE*. North Pacific Fishery Management Council, 130. https://apps-afsc.fisheries.noaa.gov/refm/docs/2018/goa/goapollock.pdf

131. Szuwalski, C., W. Cheng, R. Foy, A.J. Hermann, A. Hollowed, K. Holsman, J. Lee, W. Stockhausen, and J. Zheng, 2021: Climate change and the future productivity and distribution of crab in the Bering Sea. *ICES Journal of Marine Science*, **78** (2), 502–515. https://doi.org/10.1093/icesjms/fsaa140

132. MacArthur, A.R., 2022: Federal disasters declared for 14 Alaska fisheries. *Alaska Public Media*, January 25, 2022. https://alaskapublic.org/2022/01/25/federal-disasters-declared-for-kuskokwim-and-yukon-salmon-fisheries/

133. NCEI, 2022: Climate at a Glance: Global Mapping. National Oceanic and Atmospheric Administration, National Environmental Satellite, Data, and Information Service, National Centers for Environmental Information. https://www.ncei.noaa.gov/access/monitoring/climate-at-a-glance/global

134. Hunt, G.L., L. Eisner, and N.M. Call, 2021: How will diminishing sea ice impact commercial fishing in the Bering Sea? *Arctic, Antarctic, and Alpine Research*, **53** (1), 269–270. https://doi.org/10.1080/15230430.2021.1974668

135. Hurst, T.P., L.A. Copeman, S.A. Haines, S.D. Meredith, K. Daniels, and K.M. Hubbard, 2019: Elevated CO_2 alters behavior, growth, and lipid composition of Pacific cod larvae. *Marine Environmental Research*, **145**, 52–65. https://doi.org/10.1016/j.marenvres.2019.02.004

136. Rogers, L.A., M.T. Wilson, J.T. Duffy-Anderson, D.G. Kimmel, and J.F. Lamb, 2021: Pollock and "the blob": Impacts of a marine heatwave on walleye pollock early life stages. *Fisheries Oceanography*, **30** (2), 142–158. https://doi.org/10.1111/fog.12508

137. Carey, M.P., V.R. von Biela, A. Dunker, K.D. Keith, M. Schelske, C. Lean, and C.E. Zimmerman, 2021: Egg retention of high-latitude sockeye salmon (*Oncorhynchus nerka*) in the Pilgrim River, Alaska, during the Pacific marine heatwave of 2014–2016. *Polar Biology*, **44** (8), 1643–1654. https://doi.org/10.1007/s00300-021-02902-8

138. Shanley, C.S., S. Pyare, M.I. Goldstein, P.B. Alaback, D.M. Albert, C.M. Beier, T.J. Brinkman, R.T. Edwards, E. Hood, A. MacKinnon, M.V. McPhee, T.M. Patterson, L.H. Suring, D.A. Tallmon, and M.S. Wipfli, 2015: Climate change implications in the northern coastal temperate rainforest of North America. *Climatic Change*, **130** (2), 155–170. https://doi.org/10.1007/s10584-015-1355-9

139. von Biela, V.R., L. Bowen, S.D. McCormick, M.P. Carey, D.S. Donnelly, S. Waters, A.M. Regish, S.M. Laske, R.J. Brown, S. Larson, S. Zuray, and C.E. Zimmerman, 2020: Evidence of prevalent heat stress in Yukon River Chinook salmon. *Canadian Journal of Fisheries and Aquatic Sciences*, **77** (12), 1878–1892. https://doi.org/10.1139/cjfas-2020-0209

140. Williams, C.R., A.H. Dittman, P. McElhany, D.S. Busch, M.T. Maher, T.K. Bammler, J.W. MacDonald, and E.P. Gallagher, 2019: Elevated CO_2 impairs olfactory-mediated neural and behavioral responses and gene expression in ocean-phase coho salmon (*Oncorhynchus kisutch*). *Global Change Biology*, **25** (3), 963–977. https://doi.org/10.1111/gcb.14532

141. Dickinson, G.H., S. Bejerano, T. Salvador, C. Makdisi, S. Patel, W.C. Long, K.M. Swiney, R.J. Foy, B.V. Steffel, K.E. Smith, and R.B. Aronson, 2021: Ocean acidification alters properties of the exoskeleton in adult Tanner crabs, *Chionoecetes bairdi*. *Journal of Experimental Biology*, **224** (3), 232819. https://doi.org/10.1242/jeb.232819

142. Alabia, I.D., J. García Molinos, S.I. Saitoh, T. Hirawake, T. Hirata, and F.J. Mueter, 2018: Distribution shifts of marine taxa in the Pacific Arctic under contemporary climate changes. *Diversity and Distributions*, **24** (11), 1583–1597. https://doi.org/10.1111/ddi.12788

143. Huntington, H.P., S.L. Danielson, F.K. Wiese, M. Baker, P. Boveng, J.J. Citta, A. De Robertis, D.M.S. Dickson, E. Farley, J.C. George, K. Iken, D.G. Kimmel, K. Kuletz, C. Ladd, R. Levine, L. Quakenbush, P. Stabeno, K.M. Stafford, D. Stockwell, and C. Wilson, 2020: Evidence suggests potential transformation of the Pacific Arctic ecosystem is underway. *Nature Climate Change*, **10** (4), 342–348. https://doi.org/10.1038/s41558-020-0695-2

144. Rogers, L.A. and A.B. Dougherty, 2019: Effects of climate and demography on reproductive phenology of a harvested marine fish population. *Global Change Biology*, **25** (2), 708–720. https://doi.org/10.1111/gcb.14483

145. Kovach, R.P., S.C. Ellison, S. Pyare, and D.A. Tallmon, 2015: Temporal patterns in adult salmon migration timing across southeast Alaska. *Global Change Biology*, **21** (5), 1821–1833. https://doi.org/10.1111/gcb.12829

146. Dorn, M.W., A.L. Deary, B.E. Fissel, D.T. Jones, M. Levine, A.L. McCarthy, W.A. Palsson, L.A. Rogers, S.K. Shotwell, K.A. Spalinger, K. Williams, and S.G. Zador, 2020: Ch. 1. Assessment of the walleye pollock stock in the Gulf of Alaska. In: *NPFMC Gulf of Alaska SAFE*. North Pacific Fishery Management Council, 135. https://apps-afsc.fisheries.noaa.gov/refm/docs/2020/goapollock.pdf

147. Nichol, D.G., S. Kotwicki, T.K. Wilderbuer, R.R. Lauth, and J.N. Ianelli, 2019: Availability of yellowfin sole *Limanda aspera* to the eastern Bering Sea trawl survey and its effect on estimates of survey biomass. *Fisheries Research*, **211**, 319–330. https://doi.org/10.1016/j.fishres.2018.11.017

148. Logerwell, E.A., M. Wang, L.L. Jörgensen, and K. Rand, 2022: Winners and losers in a warming Arctic: Potential habitat gain and loss for epibenthic invertebrates of the Chukchi and Bering Seas, 2008–2100. *Deep Sea Research Part II: Topical Studies in Oceanography*, **206**, 105210. https://doi.org/10.1016/j.dsr2.2022.105210

149. Rooper, C.N., I. Ortiz, A.J. Hermann, N. Laman, W. Cheng, K. Kearney, and K. Aydin, 2021: Predicted shifts of groundfish distribution in the eastern Bering Sea under climate change, with implications for fish populations and fisheries management. *ICES Journal of Marine Science*, **78** (1), 220–234. https://doi.org/10.1093/icesjms/fsaa215

150. Huntington, H.P., A. Begossi, S.F. Gearheard, B. Kersey, P.A. Loring, T. Mustonen, P.K. Paudel, R.A.M. Silvano, and R. Vave, 2017: How small communities respond to environmental change: Patterns from tropical to polar ecosystems. *Ecology and Society*, **22** (3), 9. https://doi.org/10.5751/es-09171-220309

151. Kasperski, S. and D.S. Holland, 2013: Income diversification and risk for fishermen. *Proceedings of the National Academy of Sciences of the United States of America*, **110** (6), 2076–2081. https://doi.org/10.1073/pnas.1212278110

152. Halofsky, J.E., J.S. Littell, D.L. Peterson, G.D. Hayward, and R. Gravenmier, 2019: Ch. 3. Managing effects of drought and other water resource challenges in Alaska and the Pacific Northwest. In: *Effects of Drought on Forests and Rangelands in the United States: Translating Science Into Management Responses*. Vose, J.M., D.L. Peterson, C.H. Luce, and T. Patel-Weynand, Eds. U.S. Department of Agriculture, Forest Service, Washington Office, Washington, DC, 41–69. https://www.fs.usda.gov/research/treesearch/59162

153. Hasbrouck, T.R., T.J. Brinkman, G. Stout, E. Trochim, and K. Kielland, 2020: Quantifying effects of environmental factors on moose harvest in Interior Alaska. *Wildlife Biology*, **2020** (2). https://doi.org/10.2981/wlb.00631

154. Green, K.M., A.H. Beaudreau, M.H. Lukin, and L.B. Crowder, 2021: Climate change stressors and social-ecological factors mediating access to subsistence resources in Arctic Alaska. *Ecology and Society*, **26** (4). https://doi.org/10.5751/es-12783-260415

155. Huntington, H.P., L.T. Quakenbush, and M. Nelson, 2017: Evaluating the effects of climate change on indigenous marine mammal hunting in northern and western Alaska using traditional knowledge. *Frontiers in Marine Science*, **4**, 319. https://doi.org/10.3389/fmars.2017.00319

156. Bieniek, P.A., U.S. Bhatt, J.E. Walsh, R. Lader, B. Griffith, J.K. Roach, and R.L. Thoman, 2018: Assessment of Alaska rain-on-snow events using dynamical downscaling. *Journal of Applied Meteorology and Climatology*, **57** (8), 1847–1863. https://doi.org/10.1175/jamc-d-17-0276.1

157. Joly, K., A. Gunn, S.D. Côté, M. Panzacchi, J. Adamczewski, M.J. Suitor, and E. Gurarie, 2021: Caribou and reindeer migrations in the changing Arctic. *Animal Migration*, **8** (1), 156–167. https://doi.org/10.1515/ami-2020-0110

158. Mulder, C.P.H., K.V. Spellman, and J. Shaw, 2021: Berries in winter: A natural history of fruit retention in four species across Alaska. *Madroño*, **68** (4), 487–510. https://doi.org/10.3120/0024-9637-68.4.487

159. Hupp, J., M. Brubaker, K. Wilkinson, and J. Williamson, 2015: How are your berries? Perspectives of Alaska's environmental managers on trends in wild berry abundance. *International Journal of Circumpolar Health*, **74** (1), 28704. https://doi.org/10.3402/ijch.v74.28704

160. Herman-Mercer, N.M., R.A. Loehman, R.C. Toohey, and C. Paniyak, 2020: Climate- and disturbance-driven changes in subsistence berries in coastal Alaska: Indigenous Knowledge to inform ecological inference. *Human Ecology*, **48** (1), 85–99. https://doi.org/10.1007/s10745-020-00138-4

161. Alaska Native Renewable Industries, 2022: Alaska Native Renewable Industries [Webpage], accessed April 3, 2023. https://anr-industries.com/

162. Goddard, E., 2023: Solar Professionals Installation Training. University of Alaska Fairbanks, Bristol Bay Campus, accessed April 3, 2023. https://uaf.edu/bbc/academics/sustainable-energy/solarprofessionalstraining.php

163. Alutiiq Pride Marine Institute, 2021: Welcome to the Alutiiq Pride Marine Institute [Website], accessed April 3, 2023. https://www.alutiiqprideak.org/

164. Calypso Farm and Ecology Center, 2022: Calypso Farm & Ecology Center [Website]. https://calypsofarm.org/

165. City of Fairbanks, 2022: Mobile Crisis Team. City of Fairbanks, Alaska. https://www.fairbanksalaska.us/crisis/page/mobile-crisis-team-call-911-access-mobile-crisis-team

166. Ross, I., 2021: As low Chignik salmon runs continue, people worry their communities will disappear. *KTOO Public Media*, September 13, 2021. https://www.ktoo.org/2021/09/13/as-low-chignik-salmon-runs-continue-people-worry-their-communities-will-disappear/

167. Fang, Z., P.T. Freeman, C.B. Field, and K.J. Mach, 2018: Reduced sea ice protection period increases storm exposure in Kivalina, Alaska. *Arctic Science*, **4** (4), 525–537. https://doi.org/10.1139/as-2017-0024

168. Gibbs, A.E., A. Ohman. Karen, and B.M. Richmond, 2015: National Assessment of Shoreline Change: A GIS Compilation of Vector Shorelines and Associated Shoreline Change Data for the North Coast of Alaska, U.S.-Canadian Border to Icy Cape. USGS Open-File Report 2015-1030. U.S. Geological Survey, Reston, VA. https://doi.org/10.3133/ofr20151030

169. Irrgang, A.M., M. Bendixen, L.M. Farquharson, A.V. Baranskaya, L.H. Erikson, A.E. Gibbs, S.A. Ogorodov, P.P. Overduin, H. Lantuit, M.N. Grigoriev, and B.M. Jones, 2022: Drivers, dynamics and impacts of changing Arctic coasts. *Nature Reviews Earth & Environment*, **3** (1), 39–54. https://doi.org/10.1038/s43017-021-00232-1

170. Melvin, A.M., P. Larsen, B. Boehlert, J.E. Neumann, P. Chinowsky, X. Espinet, J. Martinich, M.S. Baumann, L. Rennels, A. Bothner, D.J. Nicolsky, and S.S. Marchenko, 2017: Climate change damages to Alaska public infrastructure and the economics of proactive adaptation. *Proceedings of the National Academy of Sciences of the United States of America*, **114** (2), E122–E131. https://doi.org/10.1073/pnas.1611056113

171. UAFINE, 2019: Statewide Threat Assessment: Identification of Threats from Erosion, Flooding, and Thawing Permafrost in Remote Alaska Communities. Report #INE 19.03. University of Alaska Fairbanks, Institute of Northern Engineering. https://www.denali.gov/wp-content/uploads/2019/11/Statewide-Threat-Assessment-Final-Report-20-November-2019.pdf

172. Gorokhovich, Y. and A. Leiserowiz, 2012: Historical and future coastal changes in Northwest Alaska. *Journal of Coastal Research*, **28** (1A), 174–186. https://doi.org/10.2112/jcoastres-d-11-00031.1

173. Overbeck, J.R., R.M. Buzard, M.M. Turner, K.Y. Miller, and R.J. Glenn, 2020: Shoreline Change at Alaska Coastal Communities. Report of Investigation 2020-10. Alaska Division of Geological and Geophysical Surveys, 29 pp. https://doi.org/10.14509/30552

174. Jorgenson, M.T., G.V. Frost, and D. Dissing, 2018: Drivers of landscape changes in coastal ecosystems on the Yukon-Kuskokwim Delta, Alaska. *Remote Sensing*, **10** (8), 1280. https://doi.org/10.3390/rs10081280

175. Jorgenson, T., K. Yoshikawa, M. Kanevskiy, Y. Shur, V. Romanovsky, S. Marchenko, G. Grosse, J. Brown, and B. Jones, 2008: Permafrost characteristics of Alaska. In: *Proceedings of the Ninth International Conference on Permafrost*. Kane, D.L. and K.M. Hinkel, Eds. Institute of Northern Engineering, University of Alaska Fairbanks, Fairbanks, AK. https://permafrost.gi.alaska.edu/sites/default/files/AlaskaPermafrostMap_Back_Jun2008_Jorgenson_etal_2008.pdf

176. Streletskiy, D.A., S. Clemens, J.-P. Lanckman, and N.I. Shiklomanov, 2023: The costs of Arctic infrastructure damages due to permafrost degradation. *Environmental Research Letters*, **18** (1), 015006. https://doi.org/10.1088/1748-9326/acab18

177. Bull, D.L., E.M. Bristol, E. Brown, R.C. Choens, C.T. Connolly, C. Flanary, J.M. Frederick, B.M. Jones, C.A. Jones, M. Ward Jones, J.W. McClelland, A. Mota, and I.K. Tezaur, 2020: Arctic Coastal Erosion: Modeling and Experimentation. U.S. Department of Energy, Office of Scientific and Technical Information. https://doi.org/10.2172/1670531

178. Buzard, R.M., M.M. Turner, K.Y. Miller, D.C. Antrobus, and J.R. Overbeck, 2021: Erosion Exposure Assessment of Infrastructure in Alaska Coastal Communities. DGGS RI 2021-3. Alaska Division of Geological and Geophysical Surveys, 29 pp. https://doi.org/10.14509/30672

179. Chiskok, D., 2019: Erosion of Russian Era Graves. LEO Network. https://www.leonetwork.org/en/posts/show/db77d295-6d87-4741-9c93-d626c8a38108

180. Seetook, D., M. Brubaker, and M. Neale, 2019: Erosion Threatening Burial Site. LEO Network. https://www.leonetwork.org/en/posts/show/0aaffcaf-13b0-4017-80b6-7e628d7ca21e

181. BIA, 2020: The Unmet Infrastructure Needs of Tribal Communities and Alaska Native Villages in Process of Relocating to Higher Ground as a Result of Climate Change. Department of Interior, Bureau of Indian Affairs, Albuquerque, NM. https://www.bia.gov/news/unmet-infrastructure-needs-tribal-communities-and-alaska-native-villages-process-relocation

182. Schneider von Deimling, T., H. Lee, T. Ingeman-Nielsen, S. Westermann, V. Romanovsky, S. Lamoureux, D.A. Walker, S. Chadburn, E. Trochim, L. Cai, J. Nitzbon, S. Jacobi, and M. Langer, 2021: Consequences of permafrost degradation for Arctic infrastructure—Bridging the model gap between regional and engineering scales. *Cryosphere*, **15** (5), 2451–2471. https://doi.org/10.5194/tc-15-2451-2021

183. Albert, S., R. Bronen, N. Tooler, J. Leon, D. Yee, J. Ash, D. Boseto, and A. Grinham, 2018: Heading for the hills: Climate-driven community relocations in the Solomon Islands and Alaska provide insight for a 1.5 °C future. *Regional Environmental Change*, **18** (8), 2261–2272. https://doi.org/10.1007/s10113-017-1256-8

184. BLM, 2020: Appendix I.2 ConocoPhillips road optimization memorandum. In: *Willow Master Development Plan*. Bureau of Land Management, U.S. Department of the Interior, 9. https://eplanning.blm.gov/eplanning-ui/project/109410/570

185. Herz, N., 2020: Big oil's answer to melting Arctic: Cooling the ground so it can keep drilling. *The Guardian*, October 19, 2020. https://www.theguardian.com/environment/2020/oct/19/oil-alaska-arctic-global-heating-local-cooling

186. Herz, N., 2021: At Denali National Park, climate change threatens the only road in and out. *Anchorage Daily News*, October 16, 2021. https://www.adn.com/alaska-news/2021/10/16/at-denali-national-park-in-alaska-climate-change-threatens-the-only-road-in-and-out/

187. NPS, 2022: Pretty Rocks Landslide. U.S. Department of Interior, National Park Service. https://www.nps.gov/dena/learn/nature/pretty-rocks.htm

188. Krakow, M., 2022: The Denali Park Road landslide made 'shocking' progress this winter, reinforcing the need for a fix. *Anchorage Daily News*, April 20, 2022. https://www.adn.com/outdoors-adventure/2022/04/20/the-denali-park-road-landslide-made-shocking-progress-this-winter-reinforcing-the-need-for-a-fix/

189. Fullman, T.J., K. Joly, and A. Ackerman, 2017: Effects of environmental features and sport hunting on caribou migration in northwestern Alaska. *Movement Ecology*, **5** (1), 4. https://doi.org/10.1186/s40462-017-0095-z

190. Dunmall, K.M., D.G. McNicholl, C.E. Zimmerman, S.E. Gilk-Baumer, S. Burril, and V.R. von Biela, 2022: First juvenile chum salmon confirms successful reproduction for Pacific salmon in the North American Arctic. *Canadian Journal of Fisheries and Aquatic Sciences*, **79** (5), 703–707. https://doi.org/10.1139/cjfas-2022-0006

191. Tape, K.D., D.D. Gustine, R.W. Ruess, L.G. Adams, and J.A. Clark, 2016: Range expansion of Moose in Arctic Alaska linked to warming and increased shrub habitat. *PLoS ONE*, **11** (4), e0152636. https://doi.org/10.1371/journal.pone.0152636

192. Tape, K.D., B.M. Jones, C.D. Arp, I. Nitze, and G. Grosse, 2018: Tundra be dammed: Beaver colonization of the Arctic. *Global Change Biology*, **24** (10), 4478–4488. https://doi.org/10.1111/gcb.14332

193. Juday, G.P., C. Alix, and T.A. Grant, 2015: Spatial coherence and change of opposite white spruce temperature sensitivities on floodplains in Alaska confirms early-stage boreal biome shift. *Forest Ecology and Management*, **350**, 46–61. https://doi.org/10.1016/j.foreco.2015.04.016

194. Cohen, J., 2019: Trumpeter Swan (*Cygnus buccinator*) Entering Breeding Grounds Early. LEO Network. https://www.leonetwork.org/en/posts/show/eaed8cdb-8b11-4972-8ad3-6bf195ed8610

195. Fischbach, A.S. and D.C. Douglas, 2022: Pacific Walrus Coastal Haulout Occurrences Interpreted from Satellite Imagery (ver. 2.0, December 2022), Data Release. U.S. Geological Survey. https://doi.org/10.5066/p9csm0kn

196. Ahtuangaruak, R., 2019: Dragon Flies Reach the Colville Nigliq Channel. LEO Network. https://www.leonetwork.org/en/posts/show/22ea9fc9-5540-4700-9de6-98f4f7599dca

197. White, R., 2019: Burying Beetle (Genus *Nicrophorus*) in Southwest Alaska. LEO Network. https://www.leonetwork.org/en/posts/show/cf977f4d-1283-4754-b145-b214f10721b8

198. USFS, 2020: Forest Health Conditions in Alaska 2020. R10-PR-46. U.S. Department of Agriculture, Forest Service, Alaska Region, Anchorage, AK, 76 pp. https://www.fs.usda.gov/Internet/FSE_DOCUMENTS/fseprd903361.pdf

199. Citta, J.J., L.T. Quakenbush, S.R. Okkonen, M.L. Druckenmiller, W. Maslowski, J. Clement-kinney, J.C. George, H. Brower, R.J. Small, C.J. Ashjian, L.A. Harwood, and M.P. Heide-Jørgensen, 2015: Ecological characteristics of core-use areas used by Bering–Chukchi–Beaufort (BCB) bowhead whales, 2006–2012. *Progress in Oceanography*, **136**, 201–222. https://doi.org/10.1016/j.pocean.2014.08.012

200. Quakenbush, L.T. and J.J. Citta, 2019: Satellite Tracking of Bowhead Whales: Habitat Use, Passive Acoustics and Environmental Monitoring. OCS Study BOEM 2019-076. U.S. Department of the Interior, Bureau of Ocean Energy Management, Alaska Outer Continental Shelf Region, Anchorage, AK. https://espis.boem.gov/final%20reports/BOEM_2019-076.pdf

201. Romano, M.D., H.M. Renner, K.J. Kuletz, J.K. Parrish, T. Jones, H.K. Burgess, D.A. Cushing, and D. Causey, 2020: Die-offs, reproductive failure, and changing at-sea abundance of murres in the Bering and Chukchi Seas in 2018. *Deep Sea Research Part II: Topical Studies in Oceanography*, **181–182**, 104877. https://doi.org/10.1016/j.dsr2.2020.104877

202. Wiese, F.K. and R.J. Nelson, 2022: Pathways between climate, fish, fisheries, and management: A conceptual integrated ecosystem management approach. *Journal of Marine Science and Engineering*, **10** (3), 338. https://doi.org/10.3390/jmse10030338

203. Ershova, E.A., J.M. Questel, K. Kosobokova, and R.R. Hopcroft, 2017: Population structure and production of four sibling species of *Pseudocalanus* spp. in the Chukchi Sea. *Journal of Plankton Research*, **39** (1), 48–64. https://doi.org/10.1093/plankt/fbw078

204. Mordy, C.W., K. Axler, L. Copeman, A. Deary, J.T. Duffy-Anderson, L. Eisner, E. Goldstein, H. Tabisola, J.W. Krause, D. Kimmel, C. Ladd, M.W. Lomas, R.M. McCabe, J.M. Nielsen, A. Schnetzer, A. Spear, and P. Stabeno, 2022: Arctic Integrated Ecosystem Research Program Final Report for Arctic Integrated Ecosystem Survey (IES) Phase II: Oceanography and Lower Trophic Level Productivity (A92) and Microzooplankton Biomass and Grazing Rates on the Arctic Program Cruises (A70). North Pacific Research Board, Arctic Program. https://nprb-public-website.s3.us-west-2.amazonaws.com/arctic-program/A92_Arctic+IES+Oceanography+%26+Lower+Trophic+Levels.pdf

205. Copeman, L.A., C.D. Salant, M.A. Stowell, M.L. Spencer, D.G. Kimmel, A.I. Pinchuk, and B.J. Laurel, 2022: Annual and spatial variation in the condition and lipid storage of juvenile Chukchi Sea gadids during a recent period of environmental warming (2012 to 2019). *Deep Sea Research Part II: Topical Studies in Oceanography*, **205**, 105180. https://doi.org/10.1016/j.dsr2.2022.105180

206. Boveng, P.L., H.L. Ziel, B.T. McClintock, and M.F. Cameron, 2020: Body condition of phocid seals during a period of rapid environmental change in the Bering Sea and Aleutian Islands, Alaska. *Deep Sea Research Part II: Topical Studies in Oceanography*, **181-182**, 104904–104904. https://doi.org/10.1016/j.dsr2.2020.104904

207. Pagano, A.M., G.M. Durner, T.C. Atwood, and D.C. Douglas, 2021: Effects of sea ice decline and summer land use on polar bear home range size in the Beaufort Sea. *Ecosphere*, **12** (10), 03768. https://doi.org/10.1002/ecs2.3768

208. Taylor, P.C., W. Maslowski, J. Perlwitz, and D.J. Wuebbles, 2017: Ch. 11. Arctic changes and their effects on Alaska and the rest of the United States. In: *Climate Science Special Report: Fourth National Climate Assessment, Volume I*. Wuebbles, D.J., D.W. Fahey, K.A. Hibbard, D.J. Dokken, B.C. Stewart, and T.K. Maycock, Eds. U.S. Global Change Research Program, Washington, DC, USA, 303-332. https://doi.org/10.7930/j00863gk

209. Ardyna, M. and K.R. Arrigo, 2020: Phytoplankton dynamics in a changing Arctic Ocean. *Nature Climate Change*, **10** (10), 892–903. https://doi.org/10.1038/s41558-020-0905-y

210. Bednaršek, N., K.A. Naish, R.A. Feely, C. Hauri, K. Kimoto, A.J. Hermann, C. Michel, A. Niemi, and D. Pilcher, 2021: Integrated assessment of ocean acidification risks to pteropods in the northern high latitudes: Regional comparison of exposure, sensitivity and adaptive capacity. *Frontiers in Marine Science*, **8**, 671497. https://doi.org/10.3389/fmars.2021.671497

211. Hurst, T.P., B.J. Laurel, E. Hanneman, S.A. Haines, and M.L. Ottmar, 2017: Elevated CO_2 does not exacerbate nutritional stress in larvae of a Pacific flatfish. *Fisheries Oceanography*, **26** (3), 336–349. https://doi.org/10.1111/fog.12195

212. Hurst, T.P., B.J. Laurel, J.T. Mathis, and L.R. Tobosa, 2016: Effects of elevated CO_2 levels on eggs and larvae of a North Pacific flatfish. *ICES Journal of Marine Science*, **73** (3), 981–990. https://doi.org/10.1093/icesjms/fsv050

213. Hurst, T.P., L.A. Copeman, J.F. Andrade, M.A. Stowell, C.E. Al-Samarrie, J.L. Sanders, and M.L. Kent, 2021: Expanding evaluation of ocean acidification responses in a marine gadid: Elevated CO_2 impacts development, but not size of larval walleye pollock. *Marine Biology*, **168** (8), 119. https://doi.org/10.1007/s00227-021-03924-w

214. Hurst, T.P., E.R. Fernandez, and J.T. Mathis, 2013: Effects of ocean acidification on hatch size and larval growth of walleye pollock (*Theragra chalcogramma*). *ICES Journal of Marine Science*, **70** (4), 812–822. https://doi.org/10.1093/icesjms/fst053

215. Hurst, T.P., E.R. Fernandez, J.T. Mathis, J.A. Miller, C.M. Stinson, and E.F. Ahgeak, 2012: Resiliency of juvenile walleye pollock to projected levels of ocean acidification. *Aquatic Biology*, **17** (3), 247–259. https://doi.org/10.3354/ab00483

216. Ou, M., T.J. Hamilton, J. Eom, E.M. Lyall, J. Gallup, A. Jiang, J. Lee, D.A. Close, S.-S. Yun, and C.J. Brauner, 2015: Responses of pink salmon to CO_2-induced aquatic acidification. *Nature Climate Change*, **5** (10), 950–955. https://doi.org/10.1038/nclimate2694

217. Long, W.C., S.B. Van Sant, K.M. Swiney, R.J. Foy, W.C. Long, V. Sant, S.B. Swiney, and K.M. Foy, 2017: Survival, growth, and morphology of blue king crabs: Effect of ocean acidification decreases with exposure time. *ICES Journal of Marine Science*, **74** (4), 1033–1041. https://doi.org/10.1093/icesjms/fsw197

218. Long, W.C., K.M. Swiney, and R.J. Foy, 2013: Effects of ocean acidification on the embryos and larvae of red king crab, *Paralithodes camtschaticus*. *Marine Pollution Bulletin*, **69** (1-2), 38–47. https://doi.org/10.1016/j.marpolbul.2013.01.011

219. Long, W.C., K.M. Swiney, C. Harris, H.N. Page, and R.J. Foy, 2013: Effects of ocean acidification on juvenile red king crab (*Paralithodes camtschaticus*) and Tanner crab (*Chionoecetes bairdi*) growth, condition, calcification, and survival. *PLoS ONE*, **8** (4), e60959. https://doi.org/10.1371/journal.pone.0060959

220. Meseck, S.L., J.H. Alix, K.M. Swiney, W.C. Long, G.H. Wikfors, and R.J. Foy, 2016: Ocean acidification affects hemocyte physiology in the tanner crab (*Chionoecetes bairdi*). *PLoS ONE*, **11** (2), 0148477. https://doi.org/10.1371/journal.pone.0148477

221. Swiney, K.M., W.C. Long, and R.J. Foy, 2016: Effects of high pCO_2 on Tanner crab reproduction and early life history—Part I: Long-term exposure reduces hatching success and female calcification, and alters embryonic development. *ICES Journal of Marine Science*, **73** (3), 825–835. https://doi.org/10.1093/icesjms/fsv201

222. Tai, T.C., U.R. Sumaila, and W.W.L. Cheung, 2021: Ocean acidification amplifies multi-stressor impacts on global marine invertebrate fisheries. *Frontiers in Marine Science*, **8**, 596644. https://doi.org/10.3389/fmars.2021.596644

223. Hoffman II, H., 2021: Strange Plant Found Below Oskawalik on the Kuskokwim River. LEO Network. https://www.leonetwork.org/en/posts/show/d54b385c-ae44-45a7-82a4-550ced699500

224. Frost, G.V., M.J. Macander, U.S. Bhatt, L.T. Berner, J.W. Bjerke, H.E. Epstein, B.C. Forbes, S.J. Goetz, M.J. Lara, T. Park, G.K. Phoenix, S.P. Serbin, H. Tømmervik, D.A. Walker, and D. Yang, 2021: Arctic Report Card 2021: Tundra Greenness. NOAA Technical Report OAR ARC; 21-08. National Oceanic and Atmospheric Administration, Office of Oceanic and Atmospheric Research, 8 pp. https://doi.org/10.25923/8n78-wp73

225. Hard, J.S., 1976: Natural control of hemlock sawfly, *Neodiprion tsugae* (Hymenoptera: Diprionidae), populations in Southeast Alaska. *The Canadian Entomologist*, **108** (5), 485–498. https://doi.org/10.4039/ent108485-5

226. Mann, D.H., T.S. Rupp, M.A. Olson, and P.A. Duffy, 2012: Is Alaska's boreal forest now crossing a major ecological threshold? *Arctic, Antarctic, and Alpine Research*, **44** (3), 319–331. https://doi.org/10.1657/1938-4246-44.3.319

227. Thoman, R., 2022: Alaska on fire: Thousands of lightning strikes and a warming climate put Alaska on pace for another historic fire season. *The Conversation*, July 6, 2022. https://theconversation.com/alaska-on-fire-thousands-of-lightning-strikes-and-a-warming-climate-put-alaska-on-pace-for-another-historic-fire-season-186453

228. Scholten, R.C., R. Jandt, E.A. Miller, B.M. Rogers, and S. Veraverbeke, 2021: Overwintering fires in boreal forests. *Nature*, **593** (7859), 399–404. https://doi.org/10.1038/s41586-021-03437-y

229. Chen, Y., M.J. Lara, B.M. Jones, G.V. Frost, and F.S. Hu, 2021: Thermokarst acceleration in Arctic tundra driven by climate change and fire disturbance. *One Earth*, **4** (12), 1718–1729. https://doi.org/10.1016/j.oneear.2021.11.011

230. Lara, M.J., H. Genet, A.D. McGuire, E.S. Euskirchen, Y. Zhang, D.R.N. Brown, M.T. Jorgenson, V. Romanovsky, A. Breen, and W.R. Bolton, 2016: Thermokarst rates intensify due to climate change and forest fragmentation in an Alaskan boreal forest lowland. *Global Change Biology*, **22** (2), 816–829. https://doi.org/10.1111/gcb.13124

231. Lara, M.J., Y. Chen, and B.M. Jones, 2021: Recent warming reverses forty-year decline in catastrophic lake drainage and hastens gradual lake drainage across northern Alaska. *Environmental Research Letters*, **16** (12). https://doi.org/10.1088/1748-9326/ac3602

232. Lindgren, P.R., L.M. Farquharson, V.E. Romanovsky, and G. Grosse, 2021: Landsat-based lake distribution and changes in western Alaska permafrost regions between the 1970s and 2010s. *Environmental Research Letters*, **16** (2). https://doi.org/10.1088/1748-9326/abd270

233. Nitze, I., S. W. Cooley, C. R. Duguay, B. M. Jones, and G. Grosse, 2020: The catastrophic thermokarst lake drainage events of 2018 in northwestern Alaska: Fast-forward into the future. *Cryosphere*, **14** (12), 4279–4297. https://doi.org/10.5194/tc-14-4279-2020

234. Webb, E.E., A.K. Liljedahl, J.A. Cordeiro, M.M. Loranty, C. Witharana, and J.W. Lichstein, 2022: Permafrost thaw drives surface water decline across lake-rich regions of the Arctic. *Nature Climate Change*, **12** (9), 841–846. https://doi.org/10.1038/s41558-022-01455-w

235. Chipman, M.L. and F.S. Hu, 2017: Linkages among climate, fire, and Thermoerosion in Alaskan tundra over the past three millennia. *Journal of Geophysical Research: Biogeosciences*, **122** (12), 3362–3377. https://doi.org/10.1002/2017jg004027

236. Rey, D.M., M.A. Walvoord, B.J. Minsley, B.A. Ebel, C.I. Voss, and K. Singha, 2020: Wildfire-initiated talik development exceeds current thaw projections: Observations and models from Alaska's continuous permafrost zone. *Geophysical Research Letters*, **47** (15). https://doi.org/10.1029/2020gl087565

237. Mekonnen, Z.A., W.J. Riley, R.F. Grant, and V.E. Romanovsky, 2021: Changes in precipitation and air temperature contribute comparably to permafrost degradation in a warmer climate. *Environmental Research Letters*, **16** (2). https://doi.org/10.1088/1748-9326/abc444

238. Jones, B.M., G. Grosse, L.M. Farquharson, P. Roy-Léveillée, A. Veremeeva, M.Z. Kanevskiy, B.V. Gaglioti, A.L. Breen, A.D. Parsekian, M. Ulrich, and K.M. Hinkel, 2022: Lake and drained lake basin systems in lowland permafrost regions. *Nature Reviews Earth & Environment*, **3** (1), 85–98. https://doi.org/10.1038/s43017-021-00238-9

239. McGuire, A.D., H. Genet, Z. Lyu, N. Pastick, S. Stackpoole, R. Birdsey, D. D'Amore, Y. He, T.S. Rupp, R. Striegl, B.K. Wylie, X. Zhou, Q. Zhuang, and Z. Zhu, 2018: Assessing historical and projected carbon balance of Alaska: A synthesis of results and policy/management implications. *Ecological Applications*, **28** (6), 1396–1412. https://doi.org/10.1002/eap.1768

240. Miner, K.R., M.R. Turetsky, E. Malina, A. Bartsch, J. Tamminen, A.D. McGuire, A. Fix, C. Sweeney, C.D. Elder, and C.E. Miller, 2022: Permafrost carbon emissions in a changing Arctic. *Nature Reviews Earth and Environment*, **3** (1), 55–67. https://doi.org/10.1038/s43017-021-00230-3

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

242. Arimitsu, M.L., J.F. Piatt, S. Hatch, R.M. Suryan, S. Batten, M.A. Bishop, R.W. Campbell, H. Coletti, D. Cushing, K. Gorman, R.R. Hopcroft, K.J. Kuletz, C. Marsteller, C. McKinstry, D. McGowan, J. Moran, S. Pegau, A. Schaefer, S. Schoen, J. Straley, and V.R. von Biela, 2021: Heatwave-induced synchrony within forage fish portfolio disrupts energy flow to top pelagic predators. *Global Change Biology*, **27** (9), 1859–1878. https://doi.org/10.1111/gcb.15556

243. Jones, L.A., E.R. Schoen, R. Shaftel, C.J. Cunningham, S. Mauger, D.J. Rinella, and A. St. Saviour, 2020: Watershed-scale climate influences productivity of Chinook salmon populations across southcentral Alaska. *Global Change Biology*, **26** (9), 4919–4936. https://doi.org/10.1111/gcb.15155

244. Armstrong, J.B., E.J. Ward, D.E. Schindler, and P.J. Lisi, 2016: Adaptive capacity at the northern front: Sockeye salmon behaviourally thermoregulate during novel exposure to warm temperatures. *Conservation Physiology*, **4** (1). https://doi.org/10.1093/conphys/cow039

245. Pitman, K.J., J.W. Moore, M. Huss, M.R. Sloat, D.C. Whited, T.J. Beechie, R. Brenner, E.W. Hood, A.M. Milner, G.R. Pess, G.H. Reeves, and D.E. Schindler, 2021: Glacier retreat creating new Pacific salmon habitat in western North America. *Nature Communications*, **12** (1), 6816. https://doi.org/10.1038/s41467-021-26897-2

246. Carey, M.P., V.R. von Biela, R.J. Brown, and C.E. Zimmerman, 2021: Migration strategies supporting salmonids in Arctic Rivers: A case study of Arctic Cisco and Dolly Varden. *Animal Migration*, **8** (1), 132–143. https://doi.org/10.1515/ami-2020-0115

247. DOD, 2021: Department of Defense Climate Risk Analysis. Report Submitted to National Security Council. U.S. Department of Defense, Office of the Undersecretary for Policy, 18 pp. https://media.defense.gov/2021/oct/21/2002877353/-1/-1/0/dod-climate-risk-analysis-final.pdf

248. DOD, 2019: Report to Congress on Military Structure in Permafrost Areas. U.S. Department of Defense, Office of The Under Secretary of Defense. https://www.acq.osd.mil/eie/downloads/fim/2019%20report%20to%20congress%20on%20military%20structures%20in%20permafrost%20areas.pdf

249. Hjort, J., O. Karjalainen, J. Aalto, S. Westermann, V.E. Romanovsky, F.E. Nelson, B. Etzelmüller, and M. Luoto, 2018: Degrading permafrost puts Arctic infrastructure at risk by mid-century. *Nature Communications*, **9** (1), 5147. https://doi.org/10.1038/s41467-018-07557-4

250. BLM AFS, 2022: Prescribed Burn Operations Planned on Military Training Lands in the Fairbanks North Star Borough to Reduce Wildfire Threat. U.S. Department of Interior, Bureau of Land Managment, Alaska Fire Service, Fairbanks, AK. https://akfireinfo.files.wordpress.com/2022/05/afs_fwa-yta_2022newrelease.pdf

251. CMTS, 2019: A Ten-Year Projection of Maritime Activity in the U.S. Arctic Region, 2020–2030. U.S. Committee on the Marine Transportation System, Washington, DC, 118 pp. https://www.cmts.gov/assets/uploads/documents/cmts_2019_arctic_vessel_projection_report.pdf

252. Boulègue, M., 2019: *Russia's Military Posture in the Arctic*. Chatham House. https://www.chathamhouse.org/2019/06/russias-military-posture-arctic

253. Pezard, S., S.J. Flanagan, S.W. Harold, I.A. Chindea, B.J. Sacks, A. Tingstad, T. Finazzo, and S. Kim, 2022: China's Strategy and Activities in the Arctic: Implications for North American and Transatlantic Security. RAND Corporation, Santa Monica, CA. https://doi.org/10.7249/rra1282-1-v2

254. NOAA Marine Debris Program, 2021: Bering Strait Marine Debris Event Report. National Oceanic and Atmospheric Administration, National Ocean Service, Office of Response and Restoration, Marine Debris Program, Silver Spring, MD. https://marinedebris.noaa.gov/emergency-response/bering-strait-marine-debris-event-report

255. DHS, 2019: Strategic Approach for Arctic Homeland Security. U.S. Department of Homeland Security, Office of Strategy, Policy, and Plans, 25 pp. https://www.dhs.gov/sites/default/files/publications/21_0113_plcy_dhs-arctic-strategy_0.pdf

256. USAF, 2020: The Department of the Air Force Arctic Strategy. U.S. Air Force. https://www.af.mil/portals/1/documents/2020saf/july/arcticstrategy.pdf

257. Hudson, A., 2022: Eielson days away from achieving full complement of F-35s. *Air & Space Forces Magazine*. https://www.airforcemag.com/eielson-days-away-from-achieving-full-complement-of-f-35s/

258. Bennett, M.M., S.R. Stephenson, K. Yang, M.T. Bravo, and B. De Jonghe, 2020: The opening of the Transpolar Sea Route: Logistical, geopolitical, environmental, and socioeconomic impacts. *Marine Policy*, **121**, 104178. https://doi.org/10.1016/j.marpol.2020.104178

259. Henry Huntington (Chapter Lead), October 19, 2022: Email communication with Jacqueline Christensen, Native Village of Port Heiden (Alaska).

260. Henry Huntington (Chapter Lead), August 29, 2022: Email communication with Theo Garcia, Knik Tribal Council (Alaska).

261. Canosa, I.V., J.D. Ford, G. McDowell, J. Jones, and T. Pearce, 2020: Progress in climate change adaptation in the Arctic. *Environmental Research Letters*, **15** (9), 093009. https://doi.org/10.1088/1748-9326/ab9be1

262. Adapt Alaska, 2022: Adapt Alaska: Resources. University of Alaska, Fairbanks. https://adaptalaska.org/resources/

263. Hahn, M.B., C. Kemp, C. Ward-Waller, S. Donovan, J.I. Schmidt, and S. Bauer, 2020: Collaborative climate mitigation and adaptation planning with university, community, and municipal partners: A case study in Anchorage, Alaska. *Local Environment*, **25** (9), 648–665. https://doi.org/10.1080/13549839.2020.1811655

264. Steffen, A., S.A. Greenlaw, M. Biermann, and A.L. Lovecraft, 2021: Alaska's Climate Change Policy Development. University of Alaska, Center for Arctic Policy Studies, Fairbanks, AK, 59 pp. https://www.uaf.edu/caps/our-work/CAPS-alaskas-climate-policy-development-March2021-corrected.pdf

265. Birchall, J.S. and N. Bonnett, 2020: Thinning sea ice and thawing permafrost: Climate change adaptation planning in Nome, Alaska. *Environmental Hazards*, **19** (2), 152–170. https://doi.org/10.1080/17477891.2019.1637331

266. Birchall, S.J. and N. Bonnett, 2019: Local-scale climate change stressors and policy response: The case of Homer, Alaska. *Journal of Environmental Planning and Management*, **62** (13), 2238–2254. https://doi.org/10.1080/09640568.2018.1537975

267. Bronen, R., D. Pollock, J. Overbeck, D. Stevens, S. Natali, and C. Maio, 2020: Usteq: Integrating indigenous knowledge and social and physical sciences to coproduce knowledge and support community-based adaptation. *Polar Geography*, **43** (2-3), 188–205. https://doi.org/10.1080/1088937x.2019.1679271

268. DCRA, n.d.: Community Resilience and Climate Adaptation Programs. Alaska Department of Commerce, Community, and Economic Development, Division of Community and Regional Affairs. https://www.commerce.alaska.gov/web/dcra/CommunityResilienceandClimateAdaptationPrograms.aspx

269. AMAP, 2017: Adaptation Actions for a Changing Arctic: Perspectives From the Beringchukchi-Beaufort Region. Arctic Monitoring and Assessment Programme, Oslo, Norway. https://www.amap.no/documents/download/2993

270. ICC Alaska, 2020: Food Sovereignty and Self-Governance: Inuit Role in Managing Arctic Marine Resources. Inuit Circumpolar Council Alaska, Anchorage, AK. https://www.inuitcircumpolar.com/project/food-sovereignty-and-self-governance-inuit-role-in-managing-arctic-marine-resources/

271. Loring, P.A., S.C. Gerlach, and H.J. Penn, 2016: "Community work" in a climate of adaptation: Responding to change in rural Alaska. *Human Ecology*, **44** (1), 119–128. https://doi.org/10.1007/s10745-015-9800-y

272. BIA, n.d.: Tribal Climate Resilience Program Awards. Bureau of Indian Affairs. https://biamaps.doi.gov/portal/apps/webappviewer/index.html?id=19ad66da24704639b09ae64a81154eb4

273. ANTHC, 2023: Assessment Reports Archive. Alaska Native Tribal Health Consortium. https://www.anthc.org/what-we-do/community-environment-and-health/center-for-climate-and-health/climate-health-3/

274. Chase, M., K. Heeringa, J. Littell, R. Toohey, and M. Tankersley, 2020: Looking Forward, Looking Back: Building Resilience Today: Training Two Report. Aleutian Pribilof Islands Association, Fairbanks, AK, 26 pp. https://pubs.er.usgs.gov/publication/70243265

275. Beck, C.A., H.L. Stewart, and I. Dutton, 2019: Adapt Y-K Delta: Climate Adaptation Strategies for the Yukon-Kuskokwim (Y-K) Delta Region. Adapt Y-K Delta Steering Committee, Anchorage, AK. https://adaptalaska.org/wp-content/uploads/2020/01/ADAPT-YK_Strategies_FINAL_sm.pdf

276. CCTHITA, 2019: Climate Change Adaptation Plan. Central Council of the Tlingit and Haida Indian Tribes of Alaska. http://www.ccthita.org/services/community/environmental/documents/t%26hclimatechangeadaptationplan.pdf

277. Blair, B. and G.P. Kofinas, 2020: Cross-scale risk perception: Differences between tribal leaders and resource managers in Arctic Alaska. *Ecology and Society*, **25** (4). https://doi.org/10.5751/es-11776-250409

278. Ellam Yua, J. Raymond-Yakoubian, R. Aluaq Daniel, and C. Behe, 2022: A framework for co-production of knowledge in the context of Arctic research. *Ecology and Society*, **27** (1), 34. https://doi.org/10.5751/es-12960-270134

279. Carlo, N., 2020: Arctic Observing: Indigenous Peoples' History, Perspectives, and Approaches for Partnership. University of Alaska, Center for Arctic Policy Studies, Fairbanks, AK. https://www.uaf.edu/caps/our-work/Carlo_Arctic-Observing_Indigenous-Peoples-History_CAPS_5MAR2020.pdf

280. ANKN, 2006: Alaska Native Values for the Curriculum. University of Alaska Fairbanks, Alaska Native Knowledge Network. http://www.ankn.uaf.edu/ancr/values/

281. Berman, M., J. Baztan, G. Kofinas, J.P. Vanderlinden, O. Chouinard, J.M. Huctin, A. Kane, C. Mazé, I. Nikulkina, and K. Thomson, 2020: Adaptation to climate change in coastal communities: Findings from seven sites on four continents. *Climatic Change*, **159** (1), 1–16. https://doi.org/10.1007/s10584-019-02571-x

282. CCTHITA, n.d.: Southeast Traditional Tribal Values. Central Council of the Tlingit and Haida Indian Tribes of Alaska. http://www.ccthita.org/about/values/index.html

283. Curry, T., C. Meek, and M. Berman, 2021: Informal institutions and adaptation: Patterns and pathways of influence in a remote Arctic community. *Local Environment*, **26** (9), 1070–1091. https://doi.org/10.1080/13549839.2021.1962828

284. Fauchald, P., V.H. Hausner, J.I. Schmidt, and D.A. Clark, 2017: Transitions of social-ecological subsistence systems in the Arctic. *International Journal of the Commons*, **11** (1), 275–329. https://doi.org/10.18352/ijc.698/metrics/

285. Figus, E., B.K.Y. Jackson, and S.F. Trainor, 2022: The Kake Climate Partnership: Implementing a knowledge co-production framework to provide climate services in Southeast Alaska. *Frontiers in Climate*, **4**, 885494. https://doi.org/10.3389/fclim.2022.885494

286. GAO, 2022: Alaska Native Issues: Federal Agencies Could Enhance Support for Native Village Efforts to Address Environmental Threats. GAO-22-104241. U.S. Government Accountability Office. https://www.gao.gov/assets/gao-22-104241.pdf

287. Ristroph, E.B., 2022: How Alaska Native corporations can better support Alaska Native villages. *American Indian Law Journal*, **10** (1), 5. https://digitalcommons.law.seattleu.edu/ailj/vol10/iss1/5

288. Adaptation Advisory Group, 2010: Alaska's Climate Change Strategy: Addressing Impacts in Alaska. Georgetown Climate Center. https://www.adaptationclearinghouse.org/resources/alaska-s-climate-change-strategy-addressing-impacts-in-alaska.html

289. Nakashima, D.J., K. Galloway McLean, H.D. Thulstrup, A. Ramos Castillo, and J.T. Rubis, 2012: *Weathering Uncertainty: Traditional Knowledge for Climate Change Assessment and Adaptation*. UNESCO, Paris and Darwin, UNU, 120 pp. https://unesdoc.unesco.org/ark:/48223/pf0000216613

290. Naylor, A., J. Ford, T. Pearce, and J. Van Alstine, 2020: Conceptualizing climate vulnerability in complex adaptive systems. *One Earth*, **2** (5), 444–454. https://doi.org/10.1016/j.oneear.2020.04.011

291. Alaska Native Claims Settlement Act. Pub. L. No. 92–203, 85 Stat. 688, December 18, 1971. https://uscode.house.gov/view.xhtml?path=/prelim@title43/chapter33&edition=prelim

292. Ristroph, E.B., 2021: Navigating climate change adaptation assistance for communities: A case study of Newtok Village, Alaska. *Journal of Environmental Studies and Sciences*, **11** (3), 329–340. https://doi.org/10.1007/s13412-021-00711-3

293. Ristroph, E., 2019: Fulfilling climate justice and government obligations to Alaska Native villages: What is the government role? *William & Mary Environmental Law and Policy Review*, **43** (2). https://scholarship.law.wm.edu/wmelpr/vol43/iss2/4

294. The Alaska Center, 2017: Solarize Your Community [Website], accessed April 4, 2023. https://akcenter.org/climate-clean-energy/solarize/

295. Solarize the Kenai, 2021: Solarize the Kenai [Website], accessed April 4, 2023. https://www.solarizethekenai.org/

296. Alaska Heat Smart, n.d.: Thermalize Juneau [Webpage], accessed April 3, 2023. https://akheatsmart.org/programs/thermalize-juneau/

297. AEL&P, 2016: Alternative Energy. Alaska Electric Light and Power, Juneau, AK, accessed April 4, 2023. https://www.aelp.com/energy-conservation/alternative-energy

298. Chugach Electric Association, 2023: Energy Solutions: Net Metering and Buyback Generation [Webpage], accessed April 4, 2023. https://www.chugachelectric.com/energy-solutions/net-metering-and-buyback-generation

299. GVEA, 2018: GVEA's Solar Farm. Golden Valley Electric Association, accessed April 3, 2023. https://www.gvea.com/services/energy/sources-of-power/gveas-solar-farm/

300. Juneau Electric Vehicle Association, n.d.: Juneau EV [Website], accessed April 3, 2023. https://juneauev.org/

301. BuyAlaska, 2023: Community Supported Agriculture [Website], accessed April 5, 2023. https://buyalaska.com/csa/

302. Naiden, A., 2021: Donated salmon gets shipped to communities on the Yukon. *Fairbanks Daily News-Miner*, August 6, 2021. https://www.newsminer.com/news/alaska_news/donated-salmon-gets-shipped-to-communities-on-the-yukon/article_52d45244-f622-11eb-9bd2-7f6bc3fca171.html

303. Bonnett, N. and S.J. Birchall, 2020: Coastal communities in the Circumpolar North and the need for sustainable climate adaptation approaches. *Marine Policy*, **121**, 104175. https://doi.org/10.1016/j.marpol.2020.104175

304. Ford, J.D., T. Pearce, I.V. Canosa, and S. Harper, 2021: The rapidly changing Arctic and its societal implications. *Wiley Interdisciplinary Reviews: Climate Change*, **12** (6), e735–e735. https://doi.org/10.1002/wcc.735

305. Huntington, H.P., M. Carey, C. Apok, B.C. Forbes, S. Fox, L.K. Holm, A. Ivanova, J. Jaypoody, G. Noongwook, and F. Stammler, 2019: Climate change in context: Putting people first in the Arctic. *Regional Environmental Change*, **19** (4), 1217–1223. https://doi.org/10.1007/s10113-019-01478-8

306. Adger, W.N., J.M. Pulhin, J. Barnett, G.D. Dabelko, G.K. Hovelsrud, M. Levy, S. Ú. Oswald, and C.H. Vogel, 2014: Ch. 12. Human security. In: *Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part A: Global and Sectoral Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel of Climate Change*. Field, C.B., V.R. Barros, D.J. Dokken, K.J. Mach, M.D. Mastrandrea, T.E. Bilir, M. Chatterjee, K.L. Ebi, Y.O. Estrada, R.C. Genova, B. Girma, E.S. Kissel, A.N. Levy, S. MacCracken, P.R. Mastrandrea, and L.L. White, Eds. Cambridge University Press, Cambridge, UK and New York, NY, USA, 755-791. https://www.ipcc.ch/report/ar5/wg2/human-security/

307. David-Chavez, D.M. and M.C. Gavin, 2018: A global assessment of Indigenous community engagement in climate research. *Environmental Research Letters*, **13** (12), 123005. https://doi.org/10.1088/1748-9326/aaf300

308. Roy, J., P. Tschakert, H. Waisman, S. Abdul Halim, P. Antwi-Agyei, P. Dasgupta, B. Hayward, M. Kanninen, D. Liverman, C. Okereke, P.F. Pinho, K. Riahi, and A.G. Suarez Rodriguez, 2018: Ch. 5. Sustainable development, poverty eradication and reducing inequalities. In: *Global Warming of 1.5°C. an IPCC Special Report on the Impacts of Global Warming of 1.5°C Above Pre-Industrial Levels and Related Global Greenhouse Gas Emission Pathways, in the Context of Strengthening the Global Response to the Threat of Climate Change, Sustainable Development, and Efforts To Eradicate Poverty*. Masson-Delmotte, V., P. Zhai, H.-O. Pörtner, D. Roberts, J. Skea, P.R. Shukla, A. Pirani, W. Moufouma-Okia, C. Péan, R. Pidcock, S. Connors, J.B.R. Matthews, Y. Chen, X. Zhou, M.I. Gomis, E. Lonnoy, T. Maycock, M. Tignor, and T. Waterfield, Eds. Cambridge University Press, Cambridge, UK and New York, NY, USA, 445–538. https://doi.org/10.1017/9781009157940.007

309. Morales, K., C. Avery, M. Chase, K. Cozzetto, P. Ezcurra, P. Hardison, A. Herrmann, H. Mullen, and K. Whyte, 2021: Ch. 12. Emerging topics. In: *Status of Tribes and Climate Change Report*. Marks-Marino, D., Ed. Institute for Tribal Environmental Professionals, 277–295. http://nau.edu/stacc2021

310. The White House, 2022: White House Releases First-of-a-Kind Indigenous Knowledge Guidance for Federal Agencies. The White House. https://www.whitehouse.gov/ceq/news-updates/2022/12/01/white-house-releases-first-of-a-kind-indigenous-knowledge-guidance-for-federal-agencies/

311. Sparrow, E., C. Keill, C. Breest, T. Clucas, and T. Moran, 2017: Innovative experiences in STEM education. In: *INTED2017 Proceedings: 11th International Technology, Education and Development Conference*, Chova, L.G., A.L. Martínez, and I.C. Torres, Eds. Valencia, Spain, 6–8 March 2017, 7619–7628. https://doi.org/10.21125/inted.2017

312. Sparrow, E.B. and S. Yule, 2010: Seasons and biomes and the GLOBE Program: Monitoring seasons through global learning communities. In: *Polar Science and Global Climate: An International Resource for Education & Outreach*, Kaiser, B., Ed. London, UK. Pearson, 152–153. https://polareducator.org/resources/prb-2/

313. Yoshikawa, K., E. Sparrow, and J. Stanilovskaya, 2014: Engaging Alaska communities and students in cryospheric research. In: *Geoscience Research and Outreach: Schools and Public Engagement*. Tong, V.C.H., Ed. Springer, Dordrecht, Netherlands, 19–45. https://doi.org/10.1007/978-94-007-6943-4_3

314. Gazal, R., M.A. White, R. Gillies, E. Rodemaker, E. Sparrow, and L. Gordon, 2008: GLOBE students, teachers, and scientists demonstrate variable differences between urban and rural leaf phenology. *Global Change Biology*, **14** (7), 1568–1580. https://doi.org/10.1111/j.1365-2486.2008.01602.x

315. Robin, J., R. Dubayah, E. Sparrow, and E. Levine, 2008: Monitoring start of season in Alaska with GLOBE, AVHRR, and MODIS data. *Journal of Geophysical Research: Biogeosciences*, **113** (G1). https://doi.org/10.1029/2007jg000407

316. Spellman, K.V., E.B. Sparrow, M.J. Chase, A. Larson, and K. Kealy, 2018: Connected climate change learning through citizen science: An assessment of priorities and needs of formal and informal educators and community members in Alaska. *Connected Science Learning*, **1** (6). https://www.nsta.org/connected-science-learning/connected-science-learning-april-june-2018-0/connected-climate-change

317. Hauser, D.D.W., R.T. Glenn, E.D. Lindley, K.K. Pikok, K. Heeringa, J. Jones, B. Adams, J.M. Leavitt, G.N. Omnik, R. Schaeffer, C. SimsKayotuk, E.B. Sparrow, A.M. Ravelo, O. Lee, and H. Eicken, 2023: Nunaaqqit Savaqatigivlugich—Working with communities: Evolving collaborations around an Alaska Arctic observatory and knowledge hub. *Arctic Science*, **9** (3), 635–656. https://doi.org/10.1139/as-2022-0044

318. Chase, M., F. Olin IV, and H. Stewart., 2021: Adaptation Planning Pathways Coordinated Pathways. Aleutian Pribilof Islands Association and Agnew, Anchorage, AK. [Print].

319. Willow Hetrick (Technical Contributor), December 16, 2020: Oral communication with Dune Lankard (Eyak Athabascan), Copper River Delta, Alaska.

320. Fedewa, E.J., T.M. Jackson, J.I. Richar, J.L. Gardner, and M.A. Litzow, 2020: Recent shifts in northern Bering Sea snow crab (*Chionoecetes opilio*) size structure and the potential role of climate-mediated range contraction. *Deep Sea Research Part II: Topical Studies in Oceanography*, **181–182**, 104878. https://doi.org/10.1016/j.dsr2.2020.104878

321. Ford, J.D., G. McDowell, and T. Pearce, 2015: The adaptation challenge in the Arctic. *Nature Climate Change*, **5** (12), 1046–1053. https://doi.org/10.1038/nclimate2723

322. *Solving the Climate Crisis: Key Accomplishments, Additional Opportunities, and the Need for Continued Action, House Select Committee on the Climate Crisis*, 2022: 117 Congress. https://www.congress.gov/event/117th-congress/house-event/115211?s=1&r=70

323. The White House, 2021: Executive Order on Catalyzing Clean Energy Industries and Jobs Through Federal Sustainability. The White House. https://www.whitehouse.gov/briefing-room/presidential-actions/2021/12/08/executive-order-on-catalyzing-clean-energy-industries-and-jobs-through-federal-sustainability/

324. LaFrance, J. and R. Nichols, 2008: Reframing evaluation: Defining an Indigenous evaluation framework. *Canadian Journal of Program Evaluation*, **23** (2), 13–31. https://psycnet.apa.org/record/2010-10284-001

Fifth National Climate Assessment: Chapter 30

Hawai‘i and US-Affiliated Pacific Islands

Chapter 30. Hawai‘i and US-Affiliated Pacific Islands

Authors and Contributors

Federal Coordinating Lead Author

Mari-Vaughn V. Johnson, US Geological Survey, Pacific Islands Climate Adaptation Science Center

Chapter Lead Author

Abby G. Frazier, Clark University, Graduate School of Geography

Chapter Authors

Lucas Berio Fortini, US Geological Survey, Pacific Island Ecosystems Research Center

Christian P. Giardina, USDA Forest Service, Institute of Pacific Islands Forestry

Zena N. Grecni, Arizona State University, Pacific Research on Island Solutions for Adaptation (RISA)

Haunani H. Kane, Arizona State University

Victoria W. Keener, Arizona State University, Pacific Research on Island Solutions for Adaptation (RISA)

Romina King, University of Guam, Pacific Islands Climate Adaptation Science Center

Richard A. MacKenzie, USDA Forest Service, Institute of Pacific Islands Forestry

Malia Nobrega-Olivera, University of Hawai‘i at Mānoa, Hawai‘inuiākea School of Hawaiian Knowledge

Kirsten L. L Oleson, University of Hawai‘i at Mānoa, Department of Natural Resources and Environmental Management

Christopher K. Shuler, University of Hawai‘i, Water Resources Research Center

Ann K. Singeo, Ebiil Society

Curt D. Storlazzi, US Geological Survey, Pacific Coastal and Marine Science Center

Richard J. Wallsgrove, University of Hawai‘i at Mānoa, William S. Richardson School of Law

Phoebe A. Woodworth-Jefcoats, NOAA Fisheries, Pacific Islands Fisheries Science Center

Technical Contributors

Malia K. H. Akutagawa, University of Hawai‘i at Mānoa, Hawai‘inuiākea School of Hawaiian Knowledge

Rosanna A. Alegado, University of Hawai‘i at Mānoa

Kristen C. Alkins, US Geological Survey, Pacific Coastal and Marine Science Center

Marie Auyong, NOAA Office for Coastal Management

John I. Borja, University of Guam, Pacific Islands Climate Adaptation Science Center

Laura Brewington, Arizona State University

Jeff Burgett, US Fish and Wildlife Service

Janice E. Castro, NOAA Office for Coastal Management

Sandra P. Chang, University of Hawai‘i at Mānoa

Patrick L. Colin, Coral Reef Research Foundation

Catherine A. Courtney, Tetra Tech Inc.

Laxmikant Dhage, University of Hawai’i at Mānoa

Diana Felton, Hawai'i Department of Health
Patricia Fifita, Oregon State University
L. Kealoha Fox, Institute for Climate and Peace
Kathleen S. Friday, USDA Forest Service
Scott J. Glenn, Hawai'i State Energy Office
Rodney L. Itaki, Pohnpei Department of Health & Social Services
L. Alex Kahl, NOAA Fisheries, Pacific Islands Regional Office
Heather Kerkering, US Geological Survey, Pacific Islands Climate Adaptation Science Center
Elizabeth Kiefer, University of Hawai'i, John A. Burns School of Medicine
Kelli A. Kokame, University of Hawai'i at Mānoa, John A. Burns School of Medicine
Natalie Kurashima, Kamehameha Schools
Dennis A. LaPointe, US Geological Survey, Pacific Island Ecosystems Research Center
Scott Laursen, Pacific Islands Climate Adaptation Science Center
Carlotta A. Leon Guerrero, Office of the Governor of Guam
Roseo Marquez, Micronesia Conservation Trust
Stephen E. Miller, US Fish and Wildlife Service, Pacific Islands Office
Tomoaki Miura, University of Hawai'i at Mānoa
Kanoe Morishige, NOAA Papahānaumokuākea Marine National Monument
Michael Parke, NOAA Pacific Islands Fisheries Science Center
Elliott W. Parsons, University of Hawai'i at Mānoa, Sea Grant College Program
Kalani Quiocho Jr., NOAA National Ocean Service, Office of National Marine Sanctuaries
Laurie J. Raymundo, University of Guam Marine Laboratory
Nicole Read, Duke University
Bradley M. Romine, University of Hawai'i at Mānoa, Pacific Islands Climate Adaptation Science Center
Clay Trauernicht, University of Hawai'i at Mānoa, Department of Natural Resources and Environmental Management
Yinphan Tsang, University of Hawai'i at Mānoa, Department of Natural Resources and Environmental Management
Colette C.C. Wabnitz, University of British Columbia, Institute for the Oceans and Fisheries
Matthew J. Widlansky, University of Hawai'i at Mānoa, School of Ocean and Earth Science and Technology
Myeong-Ho Chris Yeo, University of Guam, Water and Environmental Research Institute

Review Editor

Carolyn V. Balk, Federal Emergency Management Agency

Cover Art

James Keul

Recommended Citation

Frazier, A.G., M.-V.V. Johnson, L. Berio Fortini, C.P. Giardina, Z.N. Grecni, H.H. Kane, V.W. Keener, R. King, R.A. MacKenzie, M. Nobrega-Olivera, K.L.L. Oleson, C.K. Shuler, A.K. Singeo, C.D. Storlazzi, R.J. Wallsgrove, and P.A. Woodworth-Jefcoats, 2023: Ch. 30. Hawai'i and US-Affiliated Pacific Islands. In: *Fifth National Climate Assessment*. Crimmins, A.R., C.W. Avery, D.R. Easterling, K.E. Kunkel, B.C. Stewart, and T.K. Maycock, Eds. U.S. Global Change Research Program, Washington, DC, USA. https://doi.org/10.7930/NCA5.2023.CH30

Table of Contents

Introduction 6

Box 30.1. Historical Under-Resourcing Results in Continuing Data Inequities for the Pacific Islands Region and US Caribbean 6

Climate Variability and Change 9

Increasingly Severe Climate Impacts Are Causing Cascading Impacts for People 12

Mitigation and Adaptation Through Indigenous Knowledge Systems, Collective Action, and Planning 16

Box 30.2. Sustainable Development Goals and Collective Action 16

Key Message 30.1

Climate Change Impairs Access to Healthy Food and Water 17

Changing Climate Threatens Freshwater Resources 17

Food Systems Disrupted 18

Box 30.3. Changing Fisheries: Local Knowledge from Palau 19

Box 30.4. Food Security and Traditional Knowledge 20

Key Message 30.2

Climate Change Undermines Human Health, but Community Strength Boosts Resilience 21

The Health Impacts of Extreme Events 21

Health-Associated Impacts from Migration 22

Mental Health Consequences and Climate Grief 23

Increase in Vector-Borne Disease 23

High Temperatures and Heat-Related Illness and Death 23

Social Adaptive Capacity and Community Resilience 24

Key Message 30.3

Rising Sea Levels Threaten Infrastructure and Local Economies and Exacerbate Existing Inequities 25

Built Environment 25

Livelihoods and Economy 27

Decarbonization, Sequestration, and Resilience 29

Key Message 30.4

Responses to Rising Threats May Help Safeguard Tropical Ecosystems and Biodiversity 30

Marine and Coastal Ecosystems 30

Box 30.5. Blue Carbon Ecosystems 31

High Island Ecosystems 32

Responding to Rising Threats 33

Key Message 30.5
Indigenous Knowledge Systems Strengthen Island Resilience 35
Reciprocal Relationships Between People and Place 35
Box 30.6. Local Cultural Resilience to Climate Change 36
Cultural and Historical Sites 36
Indigenous Knowledge Systems and Values of Ecosystem Services 37

Traceable Accounts 38
Process Description 38
Key Message 30.1 38
Key Message 30.2 40
Key Message 30.3 42
Key Message 30.4 43
Key Message 30.5 45

References 46

Introduction

Moananuiākea, Hawaiian for the Pacific Ocean, connects a diverse group of island peoples who share reciprocal and spiritual relationships with the lands, waters, natural resources, and cultures of the region. Indigenous Knowledge systems derived from thousands of years of stewardship and underlying observations have sustained Pacific Islanders, as evidenced in the cultural practices of seafaring,[1] canoe building, agroforestry (a farming system that includes trees),[2,3,4,5] harvesting fish and other marine life,[6,7,8] traditional medicine,[9] and managing water.[10]

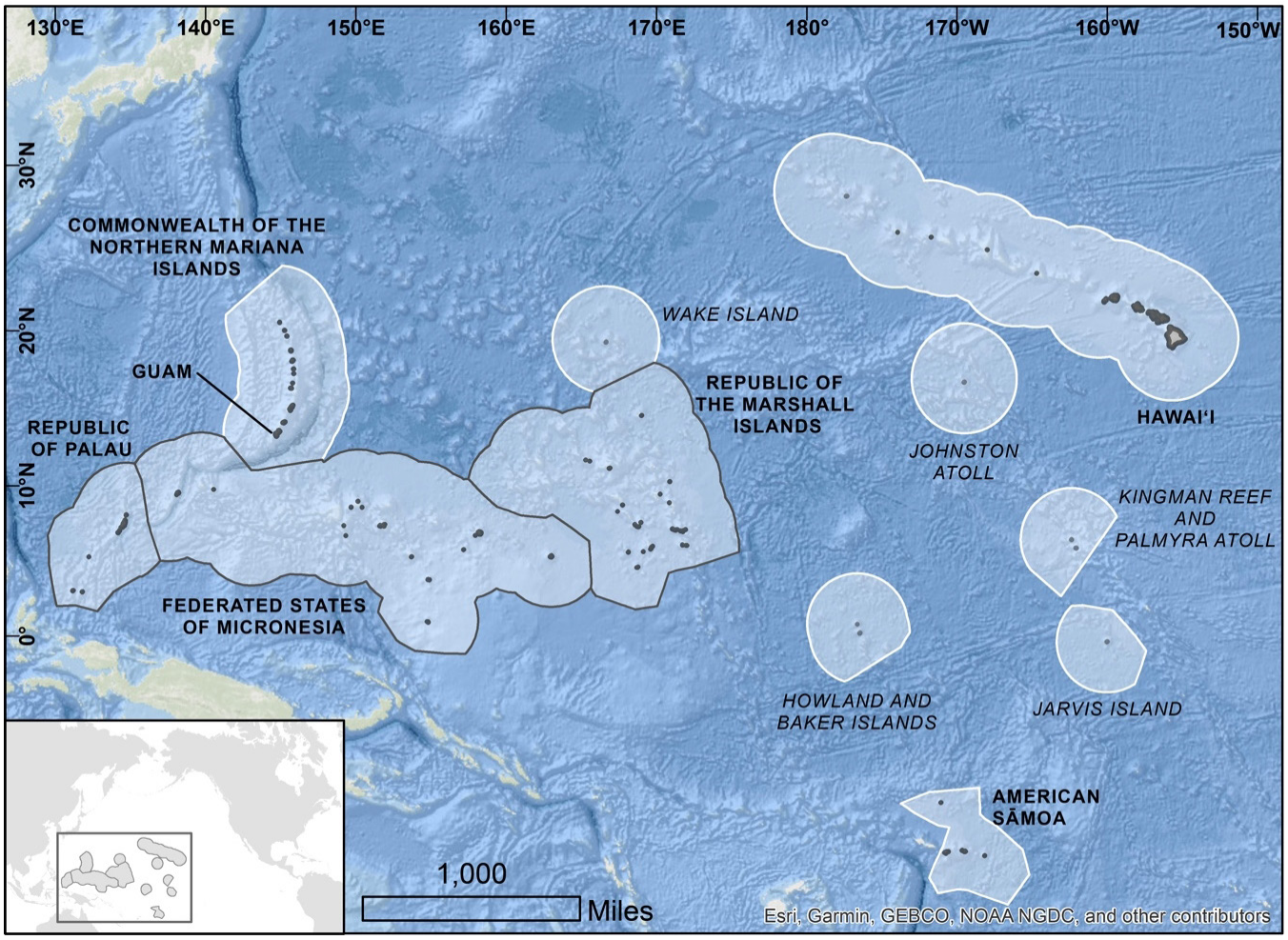
The Pacific Islands region is defined here as Hawai'i and the US-Affiliated Pacific Islands (USAPI). The USAPI comprises the Commonwealth of the Northern Mariana Islands (CNMI); the unincorporated territories of American Sāmoa, Guam, and the Pacific Remote Islands (PRI); and the Freely Associated States (FAS): the Federated States of Micronesia (FSM), the Republic of the Marshall Islands (RMI), and the Republic of Palau. The region spans a vast geography and encompasses over 2,000 islands, ranging from small low-lying atolls to large volcanic islands, with the highest peak rising to 13,803 feet (Figures 30.1, 30.2). Marine and terrestrial biodiversity and species endemism are exceptionally high. These islands (excluding FAS) total only 14,060 square miles in land area but define nearly half (47.2%) of the entire US exclusive economic zone (EEZ). The islands also support more than two dozen defense installations key to US security, including the headquarters for the US Indo-Pacific Command. As a consequence of colonization, the lands, waters, and peoples of the Pacific Islands were significantly involved in World War II,[11] resulting in widespread environmental devastation, displacement of Indigenous Peoples, and nuclear weapons testing.[12,13,14]

The 1.9 million people who call the region home are predominantly (more than 77%) Pacific Islanders, many of whom are Indigenous Peoples (CHamoru, Chuukese, Kosraean, Marshallese, Native Hawaiian, Palauan, Pohnpeian, Samoan, Yapese, and others)—who speak more than 20 Indigenous languages[15]—and members of diverse communities of Asian heritage. Population is declining on all islands (except Hawai'i) and is increasingly urban.[16,17,18,19,20,21,22] Important economic sectors include tourism, agriculture, and fishing, with government assistance, foreign direct investment, and remittances as major sources of capital. Average per capita income ranges from a high of 124% above the US average in Hawai'i to 4%–20% in the FAS.[22,23,24] Governance arrangements across the islands vary, but all share histories of colonization that contribute to structural inequities and vulnerabilities that exacerbate the social and economic impacts of climate change (Box 30.1).[14,25]

Box 30.1. Historical Under-Resourcing Results in Continuing Data Inequities for the Pacific Islands Region and US Caribbean

The Pacific Islands region and the US Caribbean continue to face similar climate change–related challenges (Ch. 23; see Keener et al. 2018[26]), including geographic isolation and reliance on imports, critical dependence on local natural resources (fresh water, fisheries), and vulnerabilities to drought, sea level rise (SLR), and natural disasters. Missing data in both regions is representative of ongoing exclusion in data collection efforts and perpetuates historical social injustices that are reinforced by colonial and postcolonial governance systems (KM 31.2). In the Pacific Islands, this has resulted in sparse and discontinuous climate data records, the absence of coastal flood hazard modeling and detailed SLR exposure mapping for most islands, a lack of downscaled future climate projections in most locations (App. 3), insufficient information about groundwater and surface water resources, and limited data on ecosystem response.[15,27,28,29,30] Similar gaps are apparent in socioeconomic and health data: for example, on migration and health outcomes, including morbidity and mortality related to extreme weather events; food supply chain vulnerabilities; and resource-dependent livelihoods.[31,32,33,34] Indigenous Knowledge systems and stewardship are foundational in responding to climate change, but generations of knowledge have been undervalued, suppressed, and ignored by Western science and were only recently recognized as valid knowledge sources at the federal level.[35,36,37] This lack of climate-relevant data is evident throughout NCA5. Filling these data gaps could better enable data-driven decision-making and improve climate services in the region.

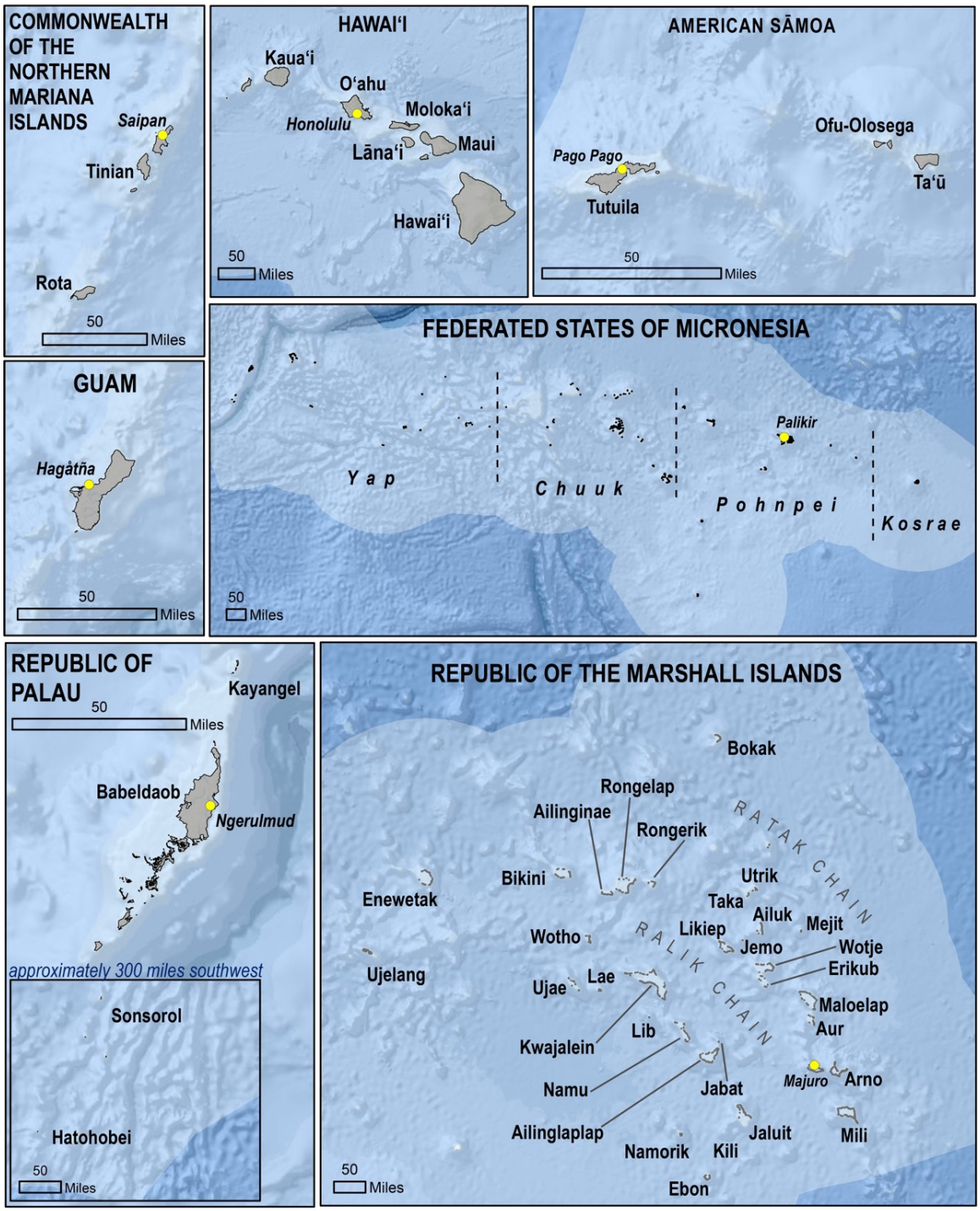
Hawai‘i and the US-Affiliated Pacific Islands



Hawai‘i and the US-Affiliated Pacific Islands span a vast geography.

Figure 30.1. The map shows the geographic breadth of the state of Hawai’i and the US-Affiliated Pacific Islands (USAPI). The USAPI comprises the US territories of American Sāmoa, Guam, and the Pacific Remote Islands (Baker Island, Howland Island, Jarvis Island, Johnston Atoll, Kingman Reef, Palmyra Atoll, and Wake Island); the Commonwealth of the Northern Mariana Islands; and the Freely Associated States: the Federated States of Micronesia, the Republic of the Marshall Islands, and the Republic of Palau. The exclusive economic zones around each jurisdiction are shown. Figure credit: University of Guam, Clark University, NOAA NCEI, and CISESS NC. Sources: Esri, Garmin, GEBCO, NOAA NGDC, and other contributors. Map image is the intellectual property of Esri and is used herein under license. Copyright © 2020 Esri and its licensors. All rights reserved.

Detailed View of Hawai‘i and the US-Affiliated Pacific Islands



Service Layer Credits: Esri, Garmin, GEBCO, NOAA NGDC, and other contributors

The Pacific Islands region contains a diversity of high and low islands.

Figure 30.2. These detailed maps show the inhabited Pacific Islands region with islands and capital cities labeled. Shown are American Sāmoa; the Commonwealth of the Northern Mariana Islands; the Federated States of Micronesia (with its four states labeled: Yap, Chuuk, Pohnpei, and Kosrae); Guam; Hawai‘i; the Republic of the Marshall Islands; and the Republic of Palau. Figure credit: Clark University, Arizona State University, University of Guam, NOAA NCEI, and CISESS NC. Sources: Esri, Garmin, GEBCO, NOAA NGDC, and other contributors. Map image is the intellectual property of Esri and is used herein under license. Copyright © 2020 Esri and its licensors. All rights reserved.

Climate Variability and Change

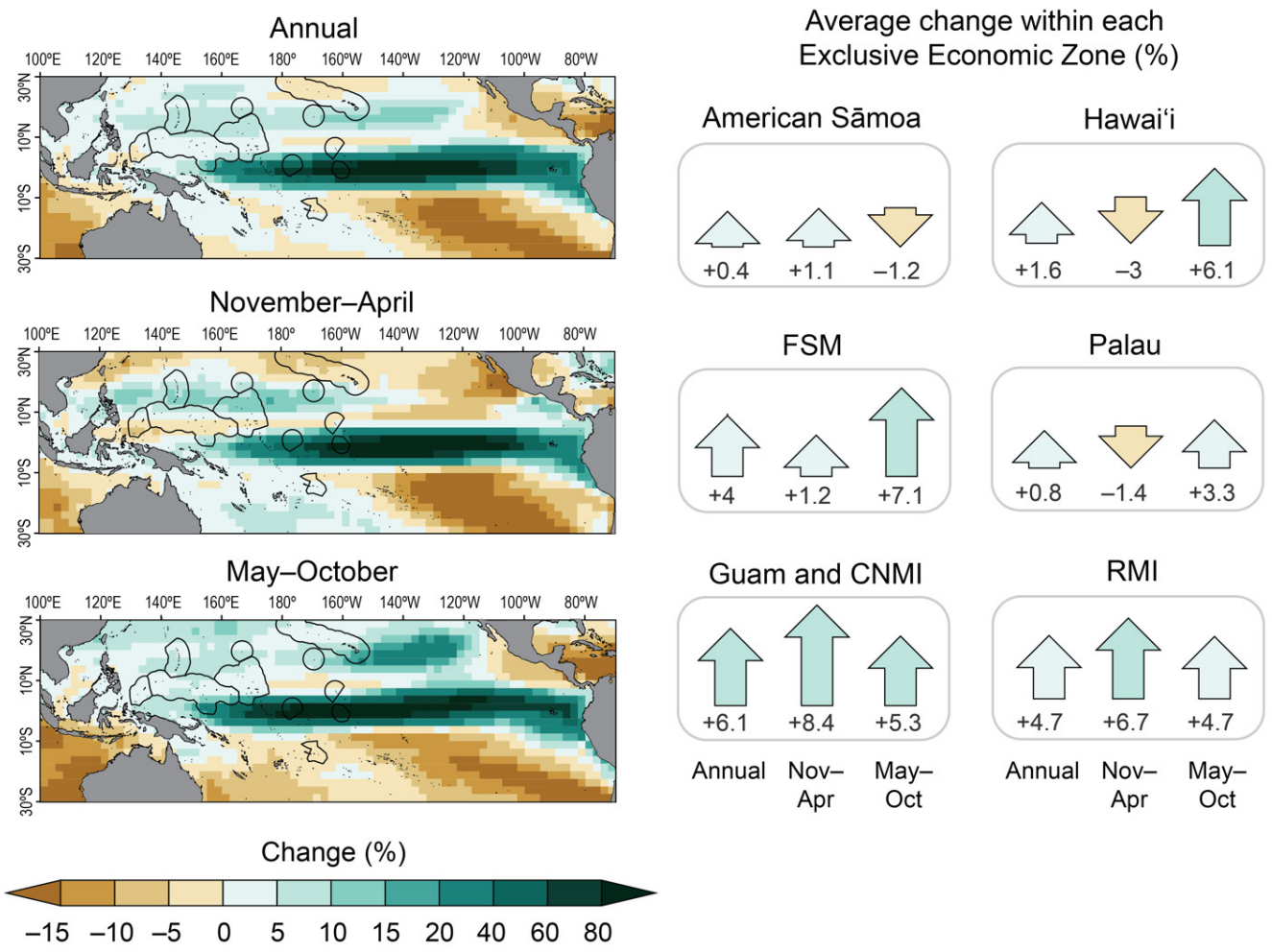
The El Niño–Southern Oscillation (ENSO) and Pacific Decadal Oscillation (KMs 2.1, 3.3) are dominant sources of climate variability in the Pacific Islands region, affecting rainfall, air and ocean temperature, sea surface height, and trade winds (Box 27.1 in Keener et al. 2018[38]).[30,39,40,41] ENSO and other sources of climate variability interact with climate change to reduce or amplify trends and their impacts on decadal and shorter timescales. Natural variability in sea level and tides, for example, affects tidal flooding experienced at various Pacific Island locations.[42,43,44]

Between 1951 and 2020, annual average air temperatures across the Pacific Islands region increased 2°F (1°C).[45,46] End-of-century projections indicate up to 4.5°F (2.5°C) higher temperatures at high elevations (above 9,800 feet) for an intermediate scenario (RCP4.5) and up to 9°F (5°C) under a very high scenario (RCP8.5).[47] Historical precipitation trends are variable across the region, with some islands seeing long-term drying and increases in drought frequency, severity, and duration (KM 4.1).[48,49,50] The magnitude and direction of projected precipitation changes are currently highly uncertain (Figure 30.3); some areas are projected to experience drying (e.g., leeward [western] areas of Hawai'i;[51] KM 2.1), while increases in precipitation are expected for others (e.g., American Sāmoa).[52]

Although the findings are uncertain and geographically diverse, current analyses indicate that the frequency of tropical cyclones is expected to decrease,[53] but associated wind speeds, rainfall rates, and storm surge heights are projected to increase across the entire region (KM 2.2).[53,54,55,56,57]

The rate of increase in regional sea surface temperatures (SSTs) has exceeded global rates, while ocean acidification (declining ocean pH)[58] in the region has reached levels not seen over the past 30 years.[59] These region-wide changes are projected to continue over the remainder of this century,[60] with dire consequences for coral reef ecosystems (KM 10.1).[61,62] Relative sea level rise (SLR) rates vary across the Pacific region,[63] with the highest SLR rates observed in the western Pacific.[64] With warming above 3.6°F (2°C), SLR projections of 3.5 to 7.5 feet by 2100 are increasingly possible (Figure 30.4; KM 9.1).[65]

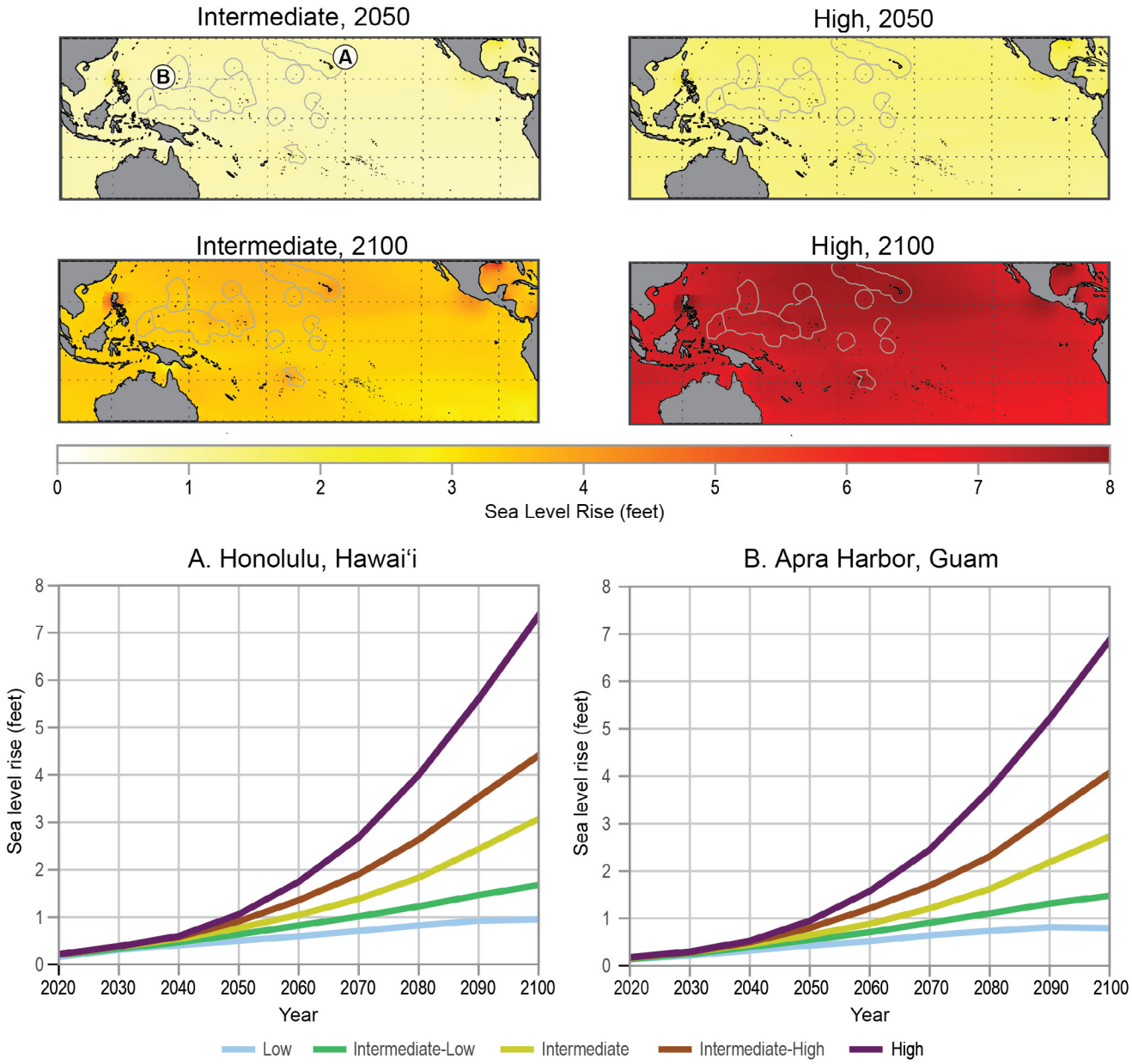
Projected Changes in Rainfall at 3°C (5.4°F) of Global Warming (Relative to 1985–2014)



Rainfall is projected to increase across most of the region with 3°C (5.4°F) of global warming.

Figure 30.3. The figure shows projected percent change in annual and seasonal rainfall by 2100 across the Pacific Islands region under a global warming level of 3°C (5.4°F) relative to 1985–2014. Large increases in future rainfall are seen for the Commonwealth of the Northern Mariana Islands (CNMI), the Federated States of Micronesia (FSM), Guam, and the Republic of the Marshall Islands (RMI), while almost no change is projected for American Sāmoa. Hawai‘i and Palau are projected to see decreases in November–April rainfall and increases in May–October rainfall. Adapted from Dhage and Widlansky 2022[66] [CC BY 4.0].

Regional Sea Level Rise Projections



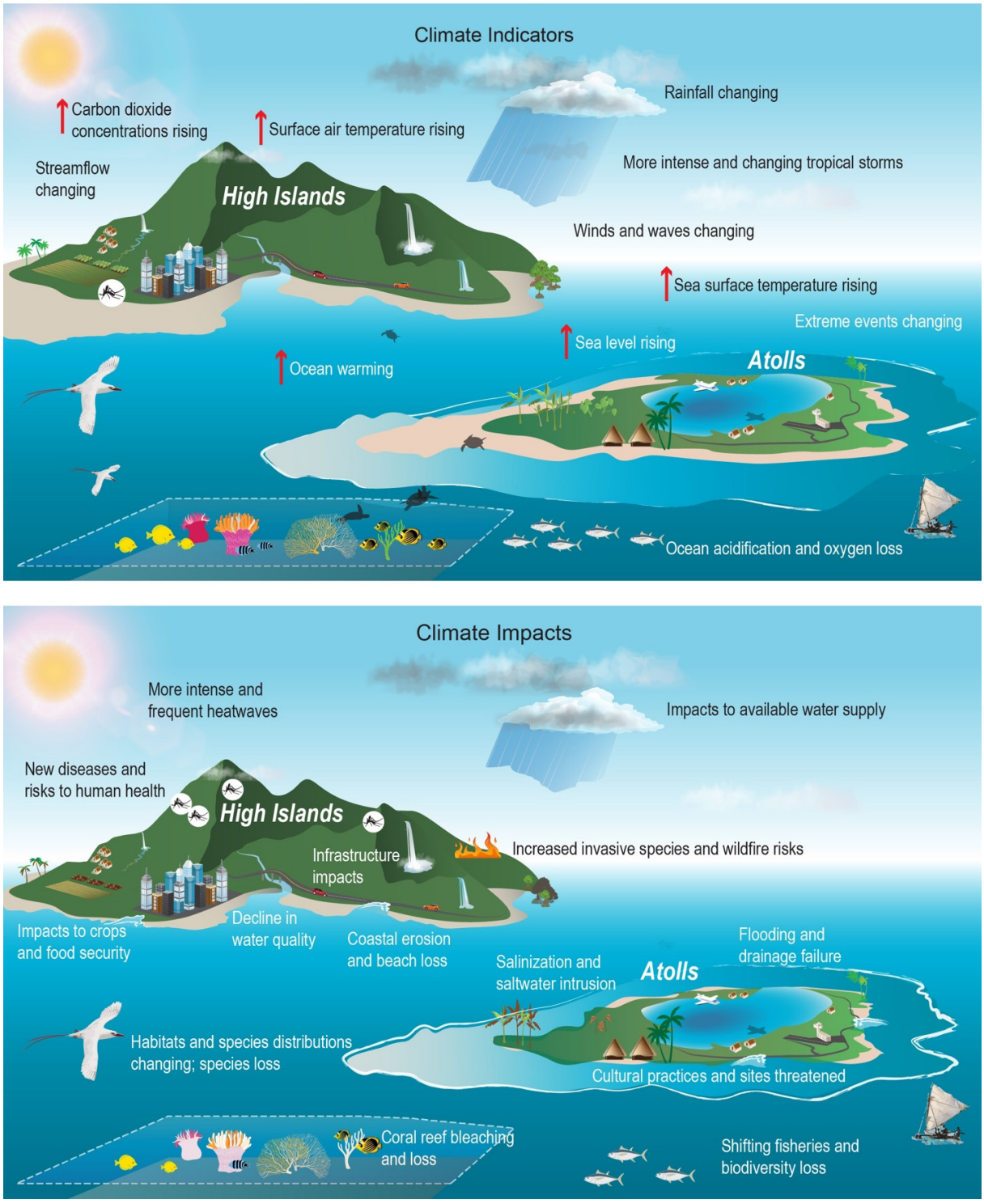
Future sea levels strongly depend on the scenario, and rates will vary across the region.

Figure 30.4. Sea level rise (SLR) projections for different scenarios are as follows: Low (1 foot of global SLR by 2100), Intermediate-Low (1.5 feet), Intermediate (3 feet), Intermediate-High (5 feet), and High (6.5 feet). (**top four panels**) Maps display regional variations in projected SLR by 2050 (top row) and 2100 (center row) in the Pacific under Intermediate (left) and High (right) scenarios. In general, sea levels are relatively higher in the northern and western Pacific than in the southern and eastern Pacific. Although patterns vary spatially due to various processes such as thermal expansion and subsidence, the greatest sources of variability are time and the scenario. (**bottom two panels**) SLR scenarios are shown for 2020–2100 at Honolulu, Hawai‘i (A), and Apra Harbor, Guam (B; locations noted in the upper-left panel). For information regarding the likelihood of these scenarios under possible future warming levels, see Appendix 3. Figure credit: US Geological Survey, University of Guam, Arizona State University, and NASA Jet Propulsion Laboratory.

Increasingly Severe Climate Impacts Are Causing Cascading Impacts for People

All Pacific Island communities are experiencing climate change impacts and, in some cases, facing existential risks (Figure 30.5). Sea level rise is compromising critical infrastructure and threatens to displace populations on low-lying atolls, forcing migration and disrupting social relationships (KMs 9.1, 9.2, 9.3). The vast majority of ports, airports, primary roads, power plants, and water treatment plants are located a few feet above sea level. Ports bring in 80%–100% of all consumer goods (including food and medical supplies) and 100% of fuel,[67] placing the islands at the end of long supply chains and making them extremely susceptible to disruptions (Ch. 23). Climate change increasingly affects the lands and waters of the region crucial for sustaining primary economic and cultural livelihoods, including tourism, agriculture, fishing, forestry, and artisan practices (KMs 10.2, 18.1, 19.1, 23.2). These effects exacerbate structural inequities (KMs 20.1, 31.2).[68,69] Climate change poses risks to the region's rich biodiversity, including many threatened and endangered species, that supports functioning ecosystems and cultural practices (KMs 8.2, 16.1). Table 30.1 illustrates examples of impacts across the region for each of the chapter's Key Messages related to water and food, human health, the built environment, ecosystems, and cultural and historical resources.

Climate Change Indicators and Impacts in the Pacific Islands



Monitoring key indicators of climate change is essential for understanding impacts and informing adaptation efforts.

Figure 30.5. Changes in climate, as measured through key indicators (**top panel**), including sea surface temperature, sea level, and tropical cyclone intensity, result in impacts and risks (**lower panel**) for Pacific Island environments and communities, both on high volcanic islands and atolls. Improved monitoring of indicators is essential for tracking the pace and extent of climate change. Understanding of the connections between indicators and impacts is expanding, which supports adaptation efforts. Adapted from Keener et al. 2018,[26] which was adapted from Keener et al. 2012.[15]

Table 30.1. Illustrative Climate Change–Related Impacts Across the Pacific Islands Region

Examples of historical, ongoing, and projected climate change impacts are given for each jurisdiction. Sea level rise is abbreviated as SLR.

Jurisdiction	KM 30.1: Water and Food	KM 30.2: Human Health	KM 30.3: Built Environment	KM 30.4: Ecosystems	KM 30.5: Cultural and Historical Resources
American Sāmoa	Increased extreme precipitation events degrade drinking water quality by stressing the water systems' filtration capacity (KM 4.2).[70,71]	Hot weather worsens chronic health conditions, including heart disease and diabetes, already at emergency levels (KM 15.1).[72]	Climate change threatens fisheries and impacts economic infrastructure, including canneries.[73]	Climate change promotes invasive species spread in native rainforests, home to rare and culturally important plants.[29]	Coastal flooding affects villages that contain burials of relatives and ancestors.[74]
Commonwealth of the Northern Mariana Islands (CNMI)	Access to safe drinking water is threatened as climate change exacerbates ongoing challenges of disposal of military, industrial, and municipal waste.[27]	Super Typhoon Yutu in 2018 negatively impacted mental health and healthcare providers.[75]	Two successive typhoons (2015 and 2018) damaged or destroyed significant portions of the built environment.[27]	Climate change aids species invasions, which threaten the high biodiversity in wetlands and forests, including endemic birds, threatened reptiles, and two species of bats.[27,76]	Coastal historical and cultural sites are exposed to SLR.[27]
Federated States of Micronesia (FSM)	Warmer temperatures and saltwater intrusion are projected to increase disease in staple crops such as taro, bananas, and breadfruit.[77]	Changes to marine and coastal habitats threaten artisanal fisheries, a key protein source.[78,79,80,81,82,83]	In FSM, 59% of infrastructure (89% of population) is within 0.3 miles (0.6 km) of the coast and vulnerable to coastal climate impacts.[84,85]	Highly valued mangrove forests in Pohnpei will be threatened by SLR.[86]	Coastal men's houses *(faluw)* are exposed to SLR and can benefit from historical adaptation measures.[87]
Guam	Northern Guam Lens Aquifer is at risk from hotter weather, drought, and possible increases in demand.[28,88]	In 2018–2019, compound extreme events (flash flooding followed by drought and wildfire) negatively impacted human health (safety, pathogens, and respiratory issues).[28]	Stronger tropical cyclones around Guam will increase the potential for severe damage to the built environment.[53]	Increased frequency of coral bleaching[89] and increased risk of wildfires are expected.[28]	Many cultural and historical resources located along the coast will be impacted by 3 feet of SLR.[90]
Hawai'i	Increasing drought is reducing available water supplies.[49]	Hot weather causes heat-related illness and increases hospitalizations (KM 15.1).[91]	3.2 feet of SLR would cause $23.1 billion in economic loss (in 2022 dollars).[92]	Warming at higher elevations will expand transmission of avian malaria, causing declines in endemic bird populations.[93,94]	Strong winds, large storm waves, SLR, and changes in groundwater impact fishponds throughout Hawai'i.[95,96,97]

Jurisdiction	KM 30.1: Water and Food	KM 30.2: Human Health	KM 30.3: Built Environment	KM 30.4: Ecosystems	KM 30.5: Cultural and Historical Resources
Pacific Remote Islands (PRI)	Decreasing precipitation and salinization from SLR are reducing freshwater availability.[98]	The possibility of disappearing islands contributes to distress due to loss of identity and relationship with place (solastalgia).[99]	US military installations and low-lying islets are at risk from SLR, which may impact exclusive economic zones.[98]	The 2014–2016 El Niño bleached over 90% of monitored reefs in Palmyra Atoll.[100]	Sea level rise threatens remote islands and megafauna connected to the Native Hawaiian culture and creation story.[101,102]
Republic of the Marshall Islands (RMI)	During the 2015–2016 extreme El Niño drought, the northern atolls established freshwater "filling stations" for water access.[103]	Sea level rise threatens health infrastructure,[104] and migration harms mental health.[105]	Highly urbanized atolls may not be able to adapt to future SLR, leading to land loss and potential uninhabitability.[98,106,107,108]	Tuna catch within the exclusive economic zone is projected to decline by 10%–40% by 2050 relative to the early 2000s under a very high scenario (RCP8.5).[109]	Graves in the Jenrōk neighborhood on Majuro were lost to coastal erosion.[110]
Republic of Palau	Climate change affects the timing of when crops are traditionally planted, which impacts food security.[111]	Mental health challenges arise from degradation of places and ecosystems essential to ocean-centered culture and livelihoods (Box 30.3; KM 15.1).[112]	Migration to and development in Koror's coastal zone exposes more people to SLR; king tides already flood urban areas.[113]	The strong 2015–2016 El Niño reduced the jellyfish population in Palau's Jellyfish Lake.[113]	High tides and SLR submerged and damaged Kukau el Bad, a historic healing ritual site in Ollei, Ngarchelong.[113]

Mitigation and Adaptation Through Indigenous Knowledge Systems, Collective Action, and Planning

Effective climate mitigation and adaptation measures for Pacific Islanders and Indigenous Peoples are grounded in local ecological knowledge, which promotes intergenerational and holistic stewardship approaches,[114,115] and best available Western science (KM 18.3). Indigenous ways of knowing can revitalize resilient practices and confront environmental injustices (KMs 16.3, 31.2).[14] Examples of Indigenous Knowledge–informed adaptation include agroforestry, wetland taro agriculture, fishponds, and fisheries rules such as rest periods.[116,117,118,119] Mangrove and seagrass conservation and regenerative agriculture demonstrate high potential for carbon sequestration (KM 30.4).[120,121,122]

Collective action in the region is codified in pursuit of the Sustainable Development Goals (SDGs) through the Local2030 Islands Network and Micronesia Challenge (Box 30.2; KM 20.2). Climate literacy may help spur collective action and build social capacity to address climate-driven changes (KM 32.5). Climate change–focused education and outreach programming in the Pacific Islands region is diverse and extends across federal, state, and county levels, nongovernmental organizations, and Indigenous-serving organizations (e.g., Bolden et al. 2018;[123] Frungillo et al. 2022;[124] HWMO 2021;[125] Longman et al. 2022;[126] USGS 2021[127]). Native Hawaiian and Pacific Islander epistemologies are woven into many programs (KM 16.2).[128,129]

Box 30.2. Sustainable Development Goals and Collective Action

Many Pacific Island states have adopted the 17 United Nations Sustainable Development Goals (SDGs)[130] as part of a place-based path toward climate resilience (KM 17.4). The Local2030 Islands Network is forming regional communities of practice around energy, data, tourism, and other topics of interest and is piloting SDG dashboards in Guam, Hawai'i, and Palau (KM 18.4). In Hawai'i, a scorecard provides annual progress summaries on SDGs for 2030.[131] Across sectors, Hawai'i has progressed toward meeting 6 of 36 local SDG metrics as of 2021 and is actively measuring progress in 17 more. While strong progress was made in measuring relevant goals, additional data and efforts are needed to meet more SDGs. Hawai'i Green Growth and Guam Green Growth[132] are diverse public–private partnerships formed to develop measurable economic, social, and environmental adaptations toward sustainability (Box 18.3). FSM's more formal commitment to the SDGs is evident in their national Strategic Development Plan 2004–2023.[133]

The Micronesia Challenge is a commitment by the Commonwealth of the Northern Mariana Islands, the Federated States of Micronesia, Guam, Palau, and the Republic of the Marshall Islands to conserve at least 20% of their terrestrial resources and 30% of their nearshore marine resources. With a regional endowment fund of approximately $23.1 million (in 2022 dollars)[134] providing a sustainable funding stream, the Micronesia Challenge has established over 150 protected areas throughout Micronesia, conserving biodiversity, protecting the environment, securing livelihoods and cultural practices, and enabling these islands to become more resilient to climate change.