Case Study: Charleston, South Carolina, Begins Planning and Reinvesting for Sea Level Rise

The main crosstown traffic artery in Charleston, South Carolina (U.S. 17 Septima Clark Parkway–crosstown), has historically been susceptible to flooding events (Figure 19.9). Charleston experienced all-time record high tide flood occurrences in 2015 (38 days) and 2016 (50 days).[52,58] By 2045, Charleston is projected to experience up to 180 high tide flood events a year.[1] The City of Charleston estimated that each flood event that affects the crosstown costs $12.4 million (in 2009 dollars). Over the past 50 years, the resultant gross damage and lost wages have totaled more than $1.53 billion (dollar year not specified). As a result, Charleston has developed a Sea Level Rise Strategy that plans for 50 years out based on moderate sea level rise scenarios (Figure 19.10) and that reinvests in infrastructure, develops a response plan, and increases readiness.[45] As of 2016, the City of Charleston has spent or set aside $235 million (in 2015 dollars) to complete ongoing drainage improvement projects (Figure 19.9) to prevent current and future flooding.

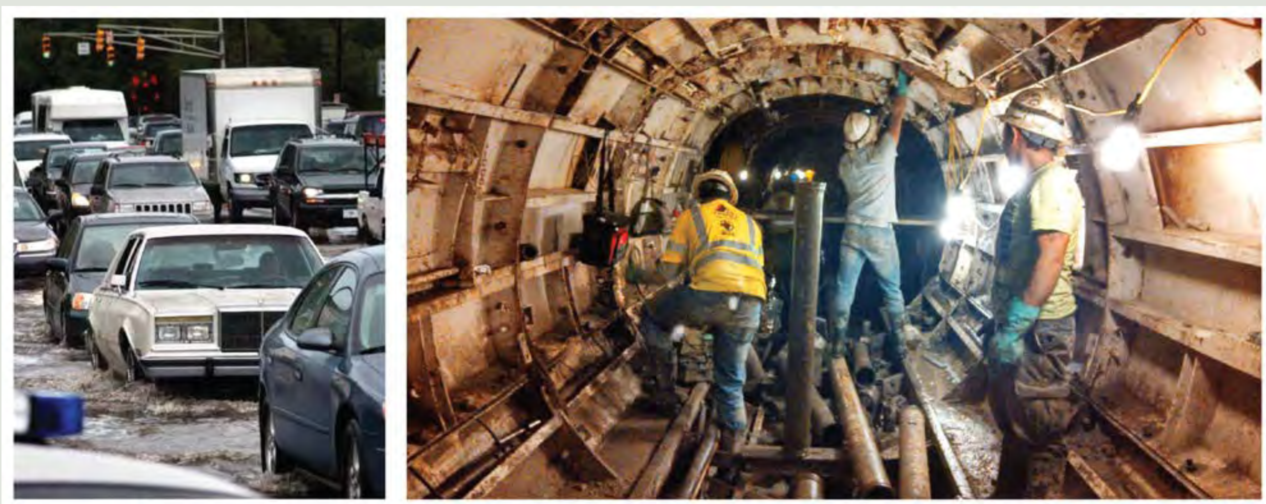

Figure 19.9: (left) U.S. Highway 17 (Septima Clark Parkway—crosstown) in Charleston, South Carolina, during a flood event. Floodwaters can get deep enough to stall vehicles. (right) Market Street drainage tunnel being constructed in Charleston, South Carolina, as part of a drainage improvement project to prevent current and future flooding. This tunnel crosses a portion of downtown Charleston 140 feet underground and is designed to rapidly convey storm water to the nearby Ashley River. Photo credit: City of Charleston 2015.[45]

Projected Sea Level Rise for Charleston, South Carolina

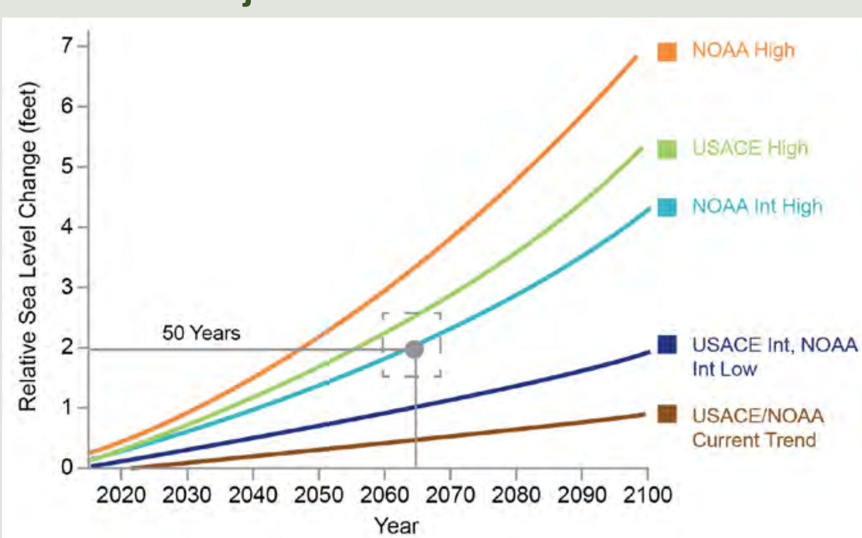

Figure 19.10: The City of Charleston Sea Level Rise Strategy calls for a 50-year outlook, based on existing federal sea level change projections in 2015 (colored curves), and calls for using a range of 1.5–2.5 feet of sea level rise (dashed box). A 1.5-foot increase will be used for short-term, less vulnerable investments, such as a parking lot. A 2.5-foot increase will be used for critical, longer-term investments, such as emergency routes and public buildings. This 1-foot range was chosen to approximate the average of these projections in 2065. Source: City of Charleston 2015.[45]

Many of the older historical coastal cities in the Southeast were built just above the current Mean Higher High Water (MHHW) level (the average height of the higher of the two daily high tides at a given location), with a gravity-driven drainage system designed to drain rainwater into the tidal estuaries. As sea levels have risen locally in the last one hundred years, the storm water systems in these areas are no longer able to perform as designed. When these cities experience high tide coastal flooding due to perigean tides, the tidewater enters the storm water system, which prevents rainwater from entering storm drains and causes increased impacts from flooding. In the future, the gravity-driven nature of many of these systems may cease to function as designed, causing rainwater to flood streets and neighborhoods until the tide lowers and water can drain normally. Cities such as Charleston and Miami have already begun to improve storm water infrastructure and explore natural and nature-based infrastructure design to reduce future flood risk.

Much of the Southeast region's coast is bordered by large expanses of salt marsh and barrier islands. Long causeways with intermittent bridges to connect the mainland to these popular tourism destinations were built decades ago at only a few feet above MHHW. Sea level rise has put these transportation connection points at risk. High tide coastal flooding has started to inundate these low-lying roads, restricting access during certain times of the day and causing public safety concerns. The U.S. East Coast, for example, already has 7,508 miles of roadways, including over 400 miles of interstate roadways, currently threatened by high tide coastal flooding (Ch. 12: Transportation, KM 1 and Figure 12.2).

Sea level rise is already causing an increase in high tide flood events in the Southeast region and is adding to the impact of more extreme coastal flooding events. In the future, this flooding is projected to become more serious, disruptive, and costly as its frequency, depth, and inland extent grow with time (Ch. 12: Transportation, KM 1).[52,63,67,68]

Case Study: A Lesson Learned for Community Resettlement: Isle de Jean Charles Band of Biloxi-Chitimacha-Choctaw Tribe

Coastal communities in the Southeast are already experiencing impacts from higher temperatures, sea level rise, increased flooding, and extreme weather events.[69,70,71,72] Several communities in the United States are already discussing the complexities of relocation; most are tribal and Indigenous communities.[73] Some have chosen to stay in their homelands, while others have few options but to relocate (Ch. 15: Tribes, KM 3).

Isle de Jean Charles is a narrow island in the bayous of South Terrebonne Parish, Louisiana, and home to the Isle de Jean Charles Band of Biloxi-Chitimacha-Choctaw, a tribal community already living the day-to-day impacts of land loss, sea level rise, and coastal flooding. The island has lost 98% of its landmass since 1955 and has only approximately 320 acres (approximately 1/2 square mile) remaining. The population living on the Island has fallen from 400 to 85 people. The decline is due in large part to land loss and flooding driven by climate change, extreme weather, and unsustainable development practices, which stem from oil and gas production, extraction, and water-management practices.[74] This process has resulted in family separation, spreading them across southern Louisiana.[75] In addition, the Tribe continues to lose parts of its livelihood and culture, including sacred places, cultural sites and practices, healing plants, traditional foods, and lifeways.[76]

Case Study: A Lesson Learned for Community Resettlement: Isle de Jean Charles Band of Biloxi-Chitimacha-Choctaw Tribe, *continued*

The Third National Climate Assessment[77] discussed the initial plans for resettlement of the Isle de Jean Charles community. Recently, after nearly 20 years of tribal persistence and two previous efforts, the U.S. Department of Housing and Urban Development (HUD) through the National Disaster Resilience Competition,[78] along with technical assistance from The Rockefeller Foundation, awarded the State of Louisiana $48 million (in 2016 dollars) to implement the Tribe's resettlement plan: a community-driven, culturally appropriate, sustainable development-based plan. It was developed in partnership with the Lowlander Center, a local nongovernmental organization with a long-standing relationship with the Tribe and other scientists, researchers, and planners. The award provides the Tribe with a historic opportunity to reunite a community.[79] While the application to relocate was initiated by the Tribe, the relocation funds now are for all residents of Isle de Jean Charles, according to the Louisiana State Office of Community Development.[75]

Figure 19.11: Chantel Comardelle, Isle de Jean Charles Tribe's Executive Secretary, leads a discussion at a community meeting for the Tribe's resettlement planning process in Pointe-aux-Chenes, Louisiana, on January 18, 2016. The meeting was supported by the Lowlander Center. Photo credit: The Lowlander Center Team.

The resettlement plan is expected to be implemented by 2022 with the inclusion of many facilities in the new location to revitalize the tribal community, including a tribal center and a healthcare facility. The Tribe's experience highlights how success can be achieved when at-risk communities are engaged in the resettlement planning process from the beginning to ensure long-term successful relocation and maintain community integrity.[80] It also highlights an opportunity for institutions to evolve in more flexible ways to accommodate the growing number of communities that may need to relocate.

Extreme Rainfall Events Are Contributing to Increased Inland and Coastal Flooding

Extreme rainfall events have increased in frequency and intensity in the Southeast, and there is *high confidence* they will continue to increase in the future (Figure 19.3).[19] The region, as a whole, has experienced increases in the number of days with more than 3 inches of precipitation (Figure 19.3) and a 16% increase in observed 5-year maximum daily precipitation (the amount falling in an event expected to occur only once every 5 years).[19] Both the frequency and severity of extreme precipitation events are projected to continue increasing in the region under both lower and higher scenarios (RCP4.5 and RCP8.5). By the end of the century under a higher scenario (RCP8.5), projections indicate approximately double the number of heavy rainfall events (2-day precipitation events with a 5-year return period) and a 21% increase in the amount of rain falling on the heaviest precipitation days (days with a 20-year return period).[19,81] These projected increases would directly affect the vulnerability of the Southeast's coastal and low-lying areas. Natural resources (see Key Message 3), industry, the local economy, and the population of the region are at increasing risk to these extreme events.

Across the Southeast since 2014, there have been numerous examples of intense rainfall events—many approaching levels that would be expected to occur only once every 500 years[82,83]—that have made state or national news due to the devastating impact they had on inland communities. Of these events, four major inland flood events have occurred in just three years (2014–2016) in the Southeast, causing billions of dollars in damages and loss of life (see Table 19.1 and Case Study "Coastal and Inland Impacts of Extreme Rainfall").[84]

A closer look at the August 2016 event in Louisiana provides an example of how vulnerable inland communities in the Southeast region are to these extreme rainfall events. Between August 11–15 2016, nearly half of southern Louisiana received at least 12–14 inches of rainfall. While urban areas such as Baton Rouge and Lafayette were hit the hardest, receiving upwards of 30 inches in a few days, coastal locations were also inundated with up to 20 inches of rain. Rainfall totals across the region exceeded amounts that would be expected to occur once every 1,000 years (or a less than 0.1% annual probability of occurrence), causing the Amite and Comite Rivers to surge past their banks and resulting in some 50,000 homes across the region filling with more than 18 inches of water.[85] Nearly 10 times the number of homes received major flooding (18 inches or more) during this event compared to a historic 1983 flood in Baton Rouge, and the damage resulted in more than 2 million cubic yards of curbside debris from cleaning up homes (enough to fill over 600 Olympic-sized pools).[86] A preceding event in northern Louisiana on March 8–12, 2016, caused $2.4 billion in damages (in 2017 dollars; $2.3 billion in 2015 dollars) and five casualties,[84] illustrating that inland low-lying areas in the Southeast region are also vulnerable to flooding impacts. Events of such magnitudes are projected to become more likely in the future due to a changing climate,[19,87] putting more people in peril from future floods. Existing flood map boundaries do not account for future flood risk due to the increasing frequency of more intense precipitation events, as well as new development that would reduce the floodplain's ability to manage storm water. As building and rebuilding in flood-prone areas continue, the risks of the kinds of major losses seen in these events will continue to grow.

The growing number of extreme rainfall events is stressing the deteriorating infrastructure in the Southeast. Many transportation and storm water systems have not been designed to withstand these events. The combined effects of rising numbers of high tide flooding and extreme rainfall events, along with deteriorating storm water infrastructure, are increasing the frequency and magnitude of coastal and lowland flood events.[45,88,89,90]

Billion-Dollar Flood Events in the Southeast, 2014–2016

Event	Date	Damages	Casualties
Southeast tornadoes and flooding (FL, AL, AR)	April 27–28, 2014	$1.8 Billion	33
South Carolina record flooding	October 1–5, 2015	$2.1 Billion	25
Hurricane Matthew	October 7–9, 2016	$10.1 Billion	49
Louisiana flooding (Baton Rouge)	August 11–15, 2016	$10.1 Billion	13

Table 19.1: Values are Consumer Price Index adjusted and are in 2017 dollars. Source: NOAA NCEI 2017.[84]

The recent increases in flood risk have led many cities and counties to take adaptive actions to reduce these effects. Four counties in Southeast Florida formed a climate compact in 2010 to address climate change impacts, including sea level rise and high tide flooding.[91] Recently updated in 2017, their climate action plan was one of the first intergovernmental collaborations to address climate change, adaptation, and mitigation in the country. Since then, cities like Charleston, South Carolina, have started to invest in flood management activities (see Case Study "Charleston, South Carolina, Begins Planning and Reinvesting"). Other examples include Miami Beach, Florida, which has a multiyear, $500-million program to raise public roads and seawalls and improve storm water drainage.[92] Norfolk, Virginia, has begun comprehensive planning to fix its high tide flooding issues.[93] Biloxi, Mississippi, has put in place several adaptation strategies to lessen the future impacts, including enacting a new building code that requires elevating structures an additional one foot above the base flood elevation.[94] Tybee Island, Georgia, has developed a sea level rise adaptation plan with recommendations to flood-proof a 5.5-mile stretch of their sole access causeway, replace two vulnerable bridges, and retrofit their existing storm water infrastructure to improve drainage.[95] In response to the 2016 flooding, eight parishes in the Acadiana region of Louisiana came together to collaborate at a watershed level, pooling their federal hazard mitigation grant funding to support projects across the Teche-Vermilion watershed. This is the only watershed-level hazard mitigation collaboration of this kind happening in the state and has the support of the Federal Emergency Management Agency (FEMA), the Governor's Office of Homeland Security and Emergency Preparedness, and the Louisiana Office of Community Development.[96]

Many communities in the Southeast also participate in FEMA's Community Rating System (CRS) program, which provides reduced flood insurance premiums to communities that go above and beyond the minimum National Flood Insurance Program regulation standards.[97] Many communities require a safety factor, also known as freeboard, expressed as feet above the base flood elevation, for construction in special flood hazard areas. Several Southeast communities—such as Hillsborough and Pinellas Counties, Florida; Biloxi, Mississippi; Chatham County, Georgia; and Myrtle Beach, South Carolina—have earned low CRS classes (5 on a scale of 1–10, with 1 being the best or most insurance premium discount) by implementing freeboard and other regulations that exceed the minimum standards.[97]

Case Study: Coastal and Inland Impacts of Extreme Rainfall

In October 2015, an extreme rainfall event impacted both inland and coastal South Carolina, leading to the largest flood-related disaster in the state since Hurricane Hugo struck in 1989. The October 2015 event is among a series of devastating precipitation events that have occurred across the Southeast in recent years. From October 1–5, 2015, deep tropical moisture combined with a slow-moving (stalled) upper-level low pressure system to pump moisture into South Carolina's coastal and interior regions. Much of the affected region received between 10 and 26 inches of rain over the 4-day event, breaking many all-time precipitation records (Figure 19.12). Mount Pleasant, located on South Carolina's coast, received 26.88 inches of rain, which is an extremely rare event. The rainfall sparked inland flooding that led to three dam breaches and the destruction of countless roads and homes (see Figure 19.13 showing flash flooding impacts to inland roads). Roughly 52,000 residents applied for disaster relief, and 160,000 homes sustained some type of damage. At the coast, a combination of high tide and heavy rain caused significant flooding in downtown Charleston. A high tide of 2.38 feet above Mean Higher High Water (MHHW) occurred in the afternoon of October 3. This was the seventh highest tide ever recorded in Charleston Harbor and the highest since Hurricane Hugo in 1989. Under future climate scenarios, the combination of extreme precipitation and higher tides due to local sea level rise will likely cause more frequent events of this intensity and magnitude.[98]

Case Study: Coastal and Inland Impacts of Extreme Rainfall, *continued*

October 2015 Extreme Rainfall Event

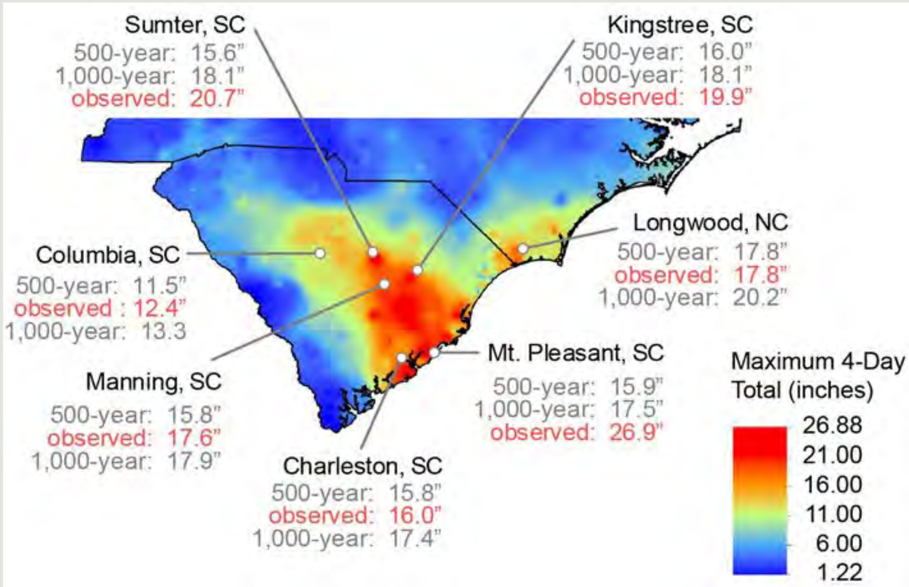

Figure 19.12: The map shows rainfall totals from the October 2015 South Carolina flood event. Red colors in the map indicate areas that received excessive rainfall totals that broke all-time records. Some of these totals exceeded the 500-year and 1,000-year return period amounts (rainfall amounts that would be expected to have only a 0.2% or 0.1% chance of occurring in a given year). Extreme precipitation events will likely increase in frequency in the Southeast. Source: CISA 2015.[98]

Figure 19.13: Many roads became impassable in the inland areas of South Carolina as a result of the October 2015 extreme rainfall event. This photo shows a neighborhood in North Charleston after the event with knee-deep flooding. Photo credit: Ryan Johnson (CC BY-SA 2.0).

Increases in extreme rainfall events and high tide coastal floods due to future climate change could impact the quality of life of permanent residents as well as tourists visiting the low-lying and coastal regions of the Southeast. Recent social science studies have indicated that people may migrate from many coastal communities that are vulnerable to the impacts of sea level rise, high tide flooding, saltwater intrusion, and storm surge.[71] Even though many communities are starting to develop adaptation strategies to address current flooding issues, many adaptation strategies are not being designed for longer time horizons and more extreme worst-case climate scenarios.[1,67]

The 2017 Hurricane Season

For the United States, 2017 was a historic year for weather and climate disasters, with widespread impacts and lingering costs. While 2017 tied the previous record year of 2011 for the total number of billion-dollar weather and climate disasters—16—the year broke the all-time previous record high costs by reaching $306.2 billion in damages (in 2017 dollars; $297 billion in 2015 dollars). The previous record year was 2005 with a total of $214.8 billion (in 2017 dollars; $208.4 billion in 2015 dollars), which included the impacts of Hurricanes Dennis, Katrina, Rita, and Wilma.[99]

In 2017, Hurricane Irma was one of three major hurricanes to make landfall in the United States and territories, with the most significant impacts occurring in the Southeast region. Irma was a Category 4 storm with 130 mph wind speeds when it made landfall at Cudjoe Key, Florida (20 miles north of Key West). Storm surge inundations at Cudjoe and the surrounding Keys were between 5 and 8 feet.[100] Prior to landfall in Florida, Irma caused significant damage in the U.S. Virgin Islands and parts of Puerto Rico as a Category 5 hurricane with 185 mph wind speeds (see Ch. 20: U.S. Caribbean, Box 20.1 and KM 5).[84]

Irma's intensity was impressive by any measure. According to the National Weather Service, Hurricane Irma was only the fifth hurricane with winds of 185 mph or higher in the whole of the Atlantic Basin since reliable record keeping began, and it was the strongest observed hurricane in the open Atlantic Ocean.[101] For three days, the storm maintained maximum sustained winds of 185 miles per hour, the longest observed duration in the satellite era.[101,102] Not only was Irma extremely strong, it was also very large with tropical storm force winds reaching as far away as 400 miles from the hurricane's center and driving hurricane force winds up to 80 miles away.[101] Two factors supported Irma's strength: the very warm waters it passed over, which exceeded 86°F,[102] and the light winds Irma encountered in the upper atmosphere (Figure 19.14).[101] High-intensity hurricanes such as Irma are expected to become more common in the future due to climate change.[103] Rapid intensification of storms is also more likely as the climate warms,[104] even though there is also some historical evidence that the same conditions that lead to this intensification also act to weaken hurricane intensity near the U.S. coast, but it is unclear whether this relationship will continue as the climate warms further (see Kossin et al. 2017,[103] Box 9.1).

The storm tracked up the west coast of Florida, impacting both coasts of the Florida peninsula with 3–5 feet of inundation from Cape Canaveral north to the Florida–Georgia border and even further, impacting coastal areas of Georgia and South Carolina with high tides and storm surge that reached 3–5 feet. Inland areas were also impacted by winds and heavy rains with river gauges and high-water marks showing upwards of 2–6 feet above ground level.[100] The winds eventually fell below tropical storm strength near Columbus, Georgia. Even though the wind speed fell below tropical storm strength, many communities along the coasts of Florida, Georgia, North and South Carolina, and Virginia experienced severe wind and storm surge damage with some near-historic levels of coastal flooding. A state of emergency was declared in four states from Florida north to Virginia and in Puerto Rico and the U.S. Virgin Islands, and, for the first time ever, Atlanta was placed under a tropical storm warning.[105,106,107,108] In Florida, a record 6.8 million people were ordered to evacuate, as were 540,000 coastal residents in Georgia and untold numbers in other coastal locations.[102,109,110] Nearly 192,000 evacuees were housed in approximately 700 emergency shelters in Florida alone.[109] According to NOAA's National Centers for Environmental Information (NCEI),[84] Irma significantly damaged 65% of the buildings in the Keys and destroyed 25% of them.

Warm Waters Contribute to the Formation of Hurricane Irma

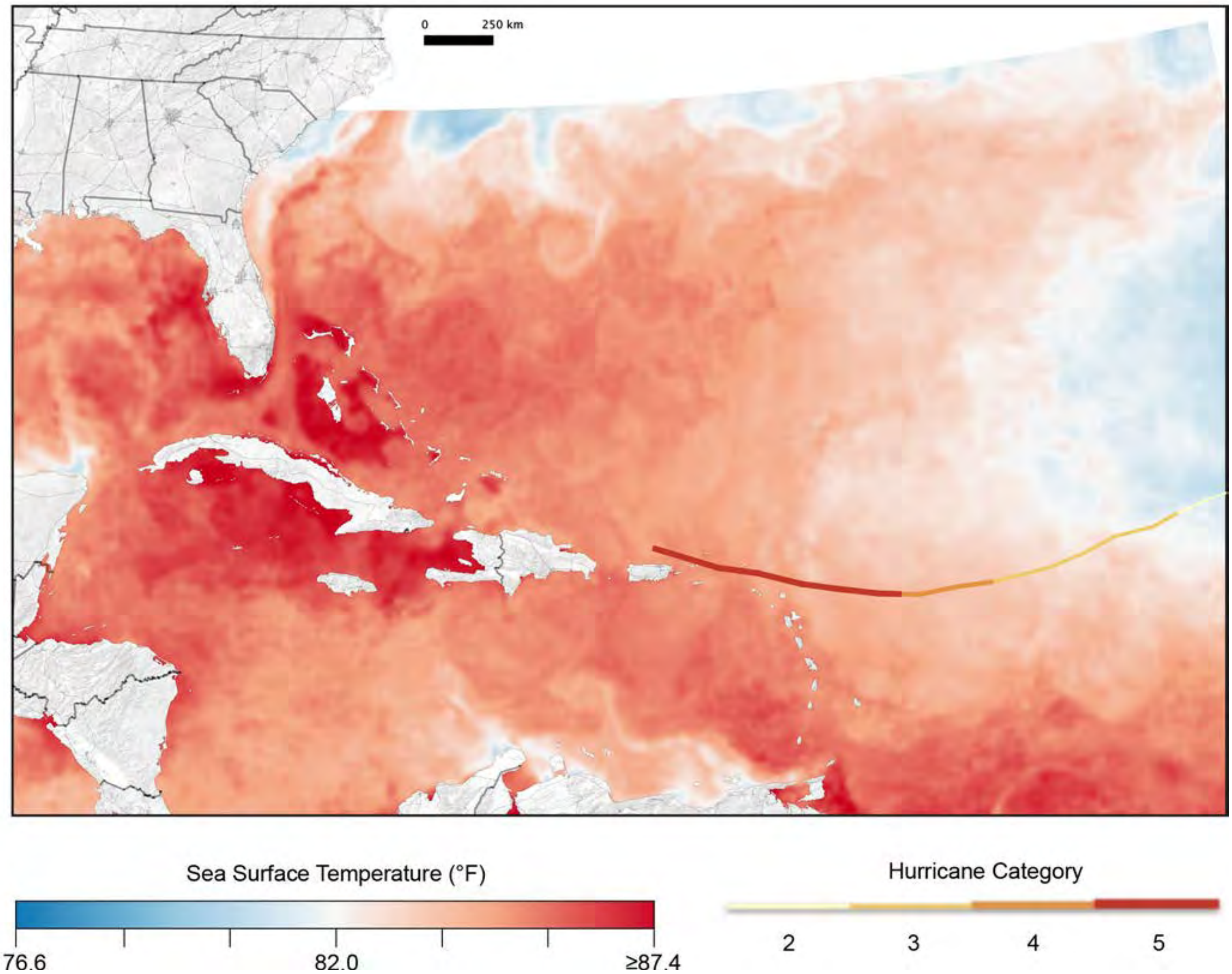

Figure 19.14: Two factors supported Hurricane Irma's strength as it reached the Southeast region: the very warm waters it passed over, depicted in this figure, and the light winds Irma encountered in the upper atmosphere.[101] High-intensity hurricanes such as Irma are expected to become more common in the future due to climate change.[103] Source: NASA 2017.[102]

High rainfall totals were experienced in many impacted areas, with Fort Pierce, Florida, receiving the highest rainfall of more than 21.5 inches[100] and the Florida Keys receiving 12 inches of rain.[84,102] Flooding occurred on most rivers in northern Florida and in many rivers in both Georgia and South Carolina to the point that rescues were required. In Jacksonville, Florida, heavy rains were the major issue causing rivers to reach major or record flood stage and flooded some city streets up to 5 feet deep in water. The heavy rainfall was noted even in Alabama, at 5 inches, and near 6 inches in the mountains of western North Carolina.[100] Twenty-five tornadoes were confirmed from Hurricane Irma, and many of them occurred along the east coast of central and northern Florida.[100] Even as Irma headed north, continuing to lose force, there were still 6.7 million people without electricity.[109]

According to NCEI,[84] the U.S. direct cost from Hurricane Irma is approximately $50 billion (in 2017 dollars), and the non-U.S. territory Caribbean Islands could add another $10–$15 billion to that total. Of the $50 billion, approximately $30–$35 billion accounts for wind and flood damage to a combination of residential and commercial properties, automobiles, and boats—with 80%–90% of this cost felt in Florida. The remainder of the costs include $5 billion for infrastructure repairs and $1.5–$2.0 billion for damage to the agricultural sector, also mainly in Florida. The remaining costs would address losses in the U.S. Virgin Islands and Puerto Rico.[84] The losses could have been worse except for the fact that Florida has implemented one of the strictest building codes in the country after the destruction caused by Hurricane Andrew in 1992.[111] Recent estimates using insured loss data show that implementing the Florida Building Code resulted in a 72% reduction of windstorm losses, and for every $1 in added cost to implement the building code, there is a savings of $6 in reduced losses, with the return or payback period being roughly 8 years (in 2010 dollars).[111]

Indirect impacts and costs are difficult to calculate and would add to the totals. In Central and South Florida, such things would include the closing of schools, colleges, and universities; the closing of tourist attractions and the cancellation of thousands of flights into and out of region; and the closing or restricting of the use of seaports including Canaveral, Key West, Miami, and Jacksonville, among others.[109,112] The Select Committee on Hurricane Response and Preparedness: Final Report[109] estimates that there were 84 U.S. deaths attributable to Hurricane Irma and other untold damage and human suffering. While the hurricane directly damaged portions of the Southeast, the impacts could be felt around the country in the form of business interruptions (such as tourism), transportation and infrastructure damages (such as ports, roadways, and airports), increases in fuel costs, and $2.5 billion (in 2018 dollars) in total estimated crop losses,[109] which had the potential to impact the cost of food and other products for all Americans.

Key Message 3

Natural Ecosystems Will Be Transformed

The Southeast's diverse natural systems, which provide many benefits to society, will be transformed by climate change. Changing winter temperature extremes, wildfire patterns, sea levels, hurricanes, floods, droughts, and warming ocean temperatures are expected to redistribute species and greatly modify ecosystems. As a result, the ecological resources that people depend on for livelihood, protection, and well-being are increasingly at risk, and future generations can expect to experience and interact with natural systems that are much different than those that we see today.

Ecosystems in the Southeast span the transition zone between tropical and temperate climates. The region's more temperate ecosystems include hardwood forests, spruce-fir forests, pine-dominated forests, and salt marshes. The region's more tropical ecosystems include mangrove forests, coral reefs, pine savannas, and the tropical freshwater wetlands of the Everglades. Ecological diversity in the Southeast is high,[113,114,115,116,117] and southeastern ecosystems and landscapes provide many benefits to society. In addition to providing habitat for fish and wildlife species, ecosystems in the Southeast provide recreational opportunities, improve water quality, provide seafood, reduce erosion, provide timber, support food webs, minimize flooding impacts, and support high rates of carbon sequestration (or storage).[118,119,120] These ecological resources that people depend on for livelihoods, protection, and well-being are increasingly at risk from the impacts of climate change.

Climate greatly influences the structure and functioning of all natural systems (Ch. 7: Ecosystems). An analysis of ecological changes that have occurred in the past can help provide some context for anticipating and preparing for future ecological changes. In response to past climatic changes, many ecosystems in the Southeast were much different than those present today. For example, since the end of the last glacial maximum (about 19,000 years ago—the most recent period of maximum ice extent),[121] forests in the region have been transformed by warming temperatures, sea level rise, and glacial retreat.[122,123] Spruce species that were once present in the region's forests have moved northward and have been replaced by oaks and other less cold-tolerant tree species that have expanded from the south.[124] And along the coast, freeze-sensitive mangrove forests and other tropical coastal species have been expanding northward and upslope since the last glacial maximum.[125,126,127,128,129]

In the coming decades and centuries, climate change will continue to transform many ecosystems throughout the Southeast,[6,130,131,132,133,134,135] which would affect many of the societal benefits these ecosystems provide. As a result, future generations can expect to experience, interact with, and potentially benefit from natural systems that are much different than those that we see today (Ch. 7: Ecosystems).[136,137]

Warming Winter Temperature Extremes

Changes in winter air temperature patterns are one aspect of climate change that will play an especially important role in the Southeast. By the late 21st century under the higher scenario (RCP8.5), the freeze-free season is expected to lengthen by more than a month. Winter air temperature extremes (for example, freezing and chilling events) constrain the northern limit of many tropical and subtropical species.[138,139,140,141,142,143,144] Certain ecosystems in the region are located near thresholds where small changes in winter air temperature regimes can trigger comparatively large and abrupt landscape-scale ecological changes (in other words, ecological regime shifts).[135,145] Reductions in the frequency and intensity of cold winter air temperature extremes can allow tropical and subtropical species to move northward and replace more temperate species. Where climatic thresholds are crossed, certain ecosystem and landscapes will be transformed by changing winter air temperatures.

Plant hardiness zone maps help convey the importance of winter air temperature extremes for species and natural systems in the Southeast. To help gardeners and farmers, the U.S. Department of Agriculture has produced plant hardiness zone maps that can be used to determine which species are most likely to survive and thrive in a given location. The plant hardiness zones are reflective of the frequency and intensity of winter air temperature extremes in a specific region. Already, in response to climate change, plant hardiness zones in certain areas are moving northward and are expected to continue their northward and upslope progression.[139,142,146,147] Continued reductions in the frequency and intensity of winter air temperature extremes are expected to change which species are able to survive and thrive in a given location (Figure 19.15). For example, citrus species are sensitive to freezing and chilling temperatures.[148] However, in the future, climate change is expected to enable the survival of citrus in areas that are north of the current tolerance zone.[142]

The effects of changing winters reach far beyond just agricultural and garden plants. Along the coast, for example, warmer winter temperatures are expected to allow mangrove forests to move northward and replace salt marshes (Figures 19.16 and 19.17).[135,149,150,151,152] Coastal wetlands, like mangrove forests and salt marshes, are abundant in the Southeast.[153,154] The societal benefits provided by coastal wetlands are numerous.[119] Hence, where coastal wetlands are abundant (for example, the Mississippi River Delta), their cumulative value can be worth billions of dollars each year and trillions of dollars over a 100-year period.[155] Coastal wetlands provide seafood, improve water quality, provide recreational opportunities, reduce erosion, support food webs, minimize flooding impacts, and support high rates of carbon sequestration.[118] Foundation species are species that create habitat and support entire ecological communities.[156,157] In coastal wetlands and many other ecosystems, foundation plant species play an especially important role. Hence, the loss and/or replacement of foundation plant species, like salt marsh grasses, will have ecological and societal consequences in certain areas.[135,145,157,158,159,160,161,162,163,164]

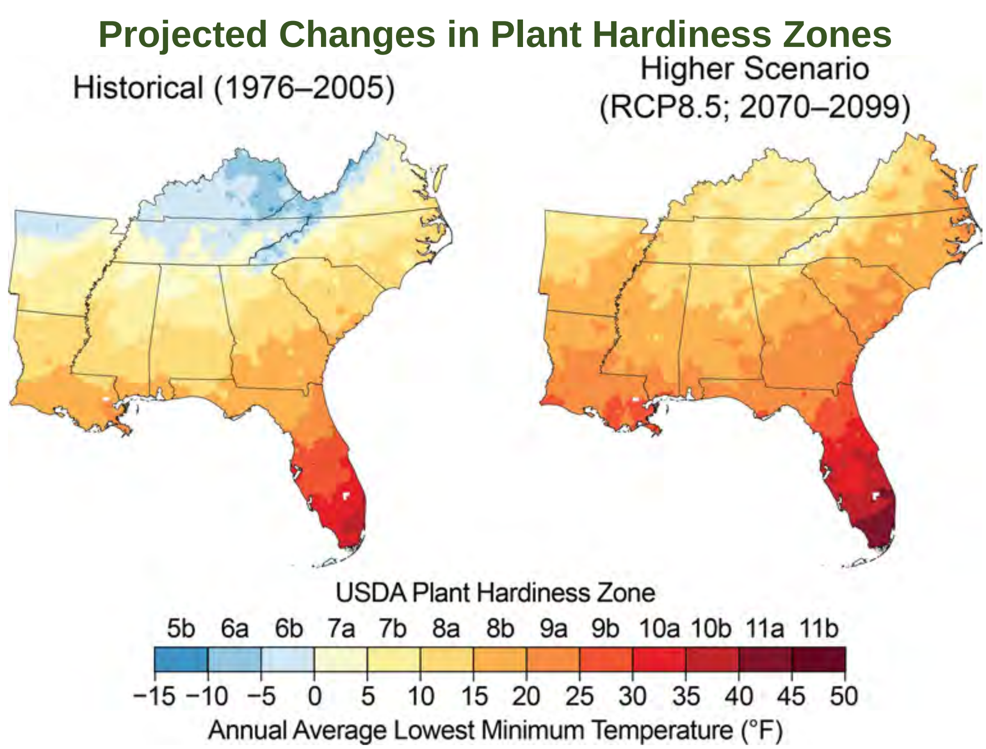

Figure 19.15: Increasing winter temperatures are expected to result in a northward shift of the zones conducive to growing various types of plants, known as plant hardiness zones. These maps show the mean projected changes in the plant hardiness zones, as defined by the U.S. Department of Agriculture (USDA), by the late 21st century (2070–2099) under a higher scenario (RCP8.5). The USDA plant hardiness zones are based on the average lowest minimum temperature for the year, divided into increments of 5°F. Based on these projected changes, freeze-sensitive plants, like oranges, papayas, and mangoes, would be able to survive in new areas.[142] Note that large changes are projected across the region, but especially in Kentucky, Tennessee, and northern Arkansas. Sources: NOAA NCEI and CICS-NC.

While salt marsh and mangrove wetlands both contain valuable foundation species, some of the habitat and societal benefits provided by existing salt marsh habitats will be affected by the northward expansion of mangrove forests.[145,158,160,161,164,165]

Salt Marsh Conversion to Mangrove Forest

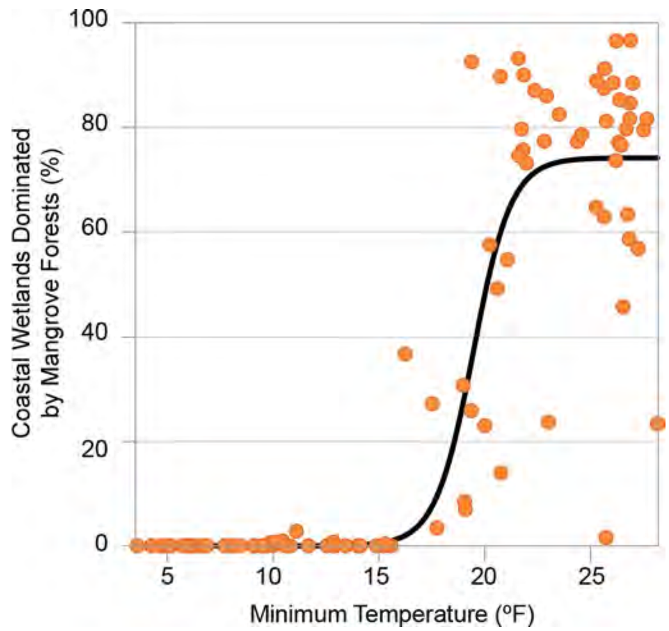

Figure 19.16: Where tropical and temperate ecosystems meet, warmer winter temperatures can lead to large ecological changes such as mangrove forest replacement of salt marshes along the Gulf and Atlantic Coasts. Mangrove forests are sensitive to freezing temperatures and are expected to expand northward at the expense of salt marshes. The figure shows the relationship between temperature and the percentage area dominated by mangrove forests. Mangrove expansion would entail a grassland-to-forest conversion, which would affect fish and wildlife habitat and many societal benefits. Source: adapted from Osland et al. 2013.[135] ©2012 Blackwell Publishing Ltd.

Transitioning Coastal Ecosystems

Figure 19.17: In Louisiana and parts of northern Florida, future coastal wetlands are expected to look and function more like the mangrove-dominated systems currently present in South Florida and the Caribbean. Like salt marshes (left), mangrove forests (right) provide coastal protection against wind and waves (Ch. 20: U.S. Caribbean, KM 2). Photo credit: Michael Osland.

In addition to plants, warmer winter air temperatures will also affect the movement and interactions between many different kinds of organisms. For example, certain insect species, including mosquitoes and tree-damaging beetles, are expected to move northward in response to climate change, which could affect human health and timber supplies.[30,144,166,167,168,169,170,171,172] And some bird species, including certain ducks, are not expected to migrate as far south in response to milder winters,[173] which could affect birding and hunting recreational opportunities. Many recreational fishery populations in tropical coastal areas are freeze-sensitive[138,174,175,176,177,178] and are, therefore, expected to move northward in response to warmer water and air temperatures. Although the appearance of tropical recreational fish, like snook for example, may be favorable for some anglers, the movement of tropical marine species is expected to greatly modify existing food webs and ecosystems (Ch. 7: Ecosystems, Figure 7.4).[179] Some problematic invasive species are expected to be favored by changing winters. For example, in South Florida, the Burmese python and the Brazilian pepper tree are two freeze-sensitive, nonnative species that have, respectively, decimated mammal populations and transformed native plant communities within Everglades National Park.[180,181,182,183,184,185,186,187,188] In the future, warmer winter temperatures are expected to facilitate the northward movement of these problematic invasive species, which would transform natural systems north of their current distribution.

Warm Winters Favor Invasive Species

Figure 19.18: Burmese pythons are apex predators (not preyed upon by other animals) that are sensitive to cold temperatures and are expected to be favored by warming winters. This photo is from Everglades National Park, where unintentionally introduced pythons have expanded and reduced native mammal populations. Photo credit: U.S. Geological Survey.

Changing Patterns of Fire

In the Southeast region, changing fire regimes (defined by factors including frequency, intensity, size, pattern, season, and severity) are expected to have a large impact on natural systems. Fire has historically played an important role in the region, and ecological diversity in many southeastern natural systems is dependent upon fire.[115,116,134,189] Although the total area burned by wildfire is greatest in the western United States, the Southeast has the largest area burned by prescribed fire (see Case Study "Prescribed Fire") and the highest number of wildfires.[134,190] In the future, rising temperatures and increases in the duration and intensity of drought are expected to increase wildfire occurrence and also reduce the effectiveness of prescribed fire.[3,4,5,6] Moreover, rapid urban expansion near managed forests has the potential to reduce opportunities to use prescribed fire, which could lead to native species declines, increased wildfire occurrence, and economic and health impacts.[134,191]

A recent example of the importance of fire lies in the forests of the southern Appalachians. Over the last century, invasive insects, logging, and pathogens have transformed forests in the region.[192] Warmer temperatures and insects have led to the loss of cold-adapted boreal communities, and flammable, fire-adapted tree species have been replaced by less flammable, fire-sensitive species—a process known as mesophication.[193,194] However, intense fires, like those observed in 2016, can halt the mesophication process. High temperatures, increases in accumulated plant material on the forest floor, and a four-month seasonal drought in the fall of 2016 collectively produced the worst wildfires the region has seen in a century. Intra-annual droughts, like the one in 2016, are expected to become more frequent in the future.[6] Thus, drought and greater fire activity[134] are expected to continue to transform forest ecosystems in the region (see Ch. 6: Forests, KM 1).

Case Study: Prescribed Fire

With wildfire projected to increase in the Southeast,[6,191] prescribed fire (the purposeful ignition of low-intensity fires in a controlled setting), remains the most effective tool for reducing wildfire risk.[4,195] Department of Defense (DoD) lands represent the largest reservoirs of biodiversity and native ecosystems in the region.[117] Military activities are a frequent source of wildfires, but increases in prescribed fire acres (Figure 19.19) show a corresponding decrease in wildfire ignitions for DoD.[4] Climate resilience by DoD is further achieved through restoration of native longleaf pine forests that occupy a wide range of site types, including wetland and well-drained soils—the latter leading many to characterize this forest as being drought resistant.[196,197,198,199] In addition to proactive adaptation through prescribed fire, DoD has been a leader in climate strategies that include regional conservation planning, ecosystem management, endangered species recovery, and research funding.

Wildlife and Prescribed Fire

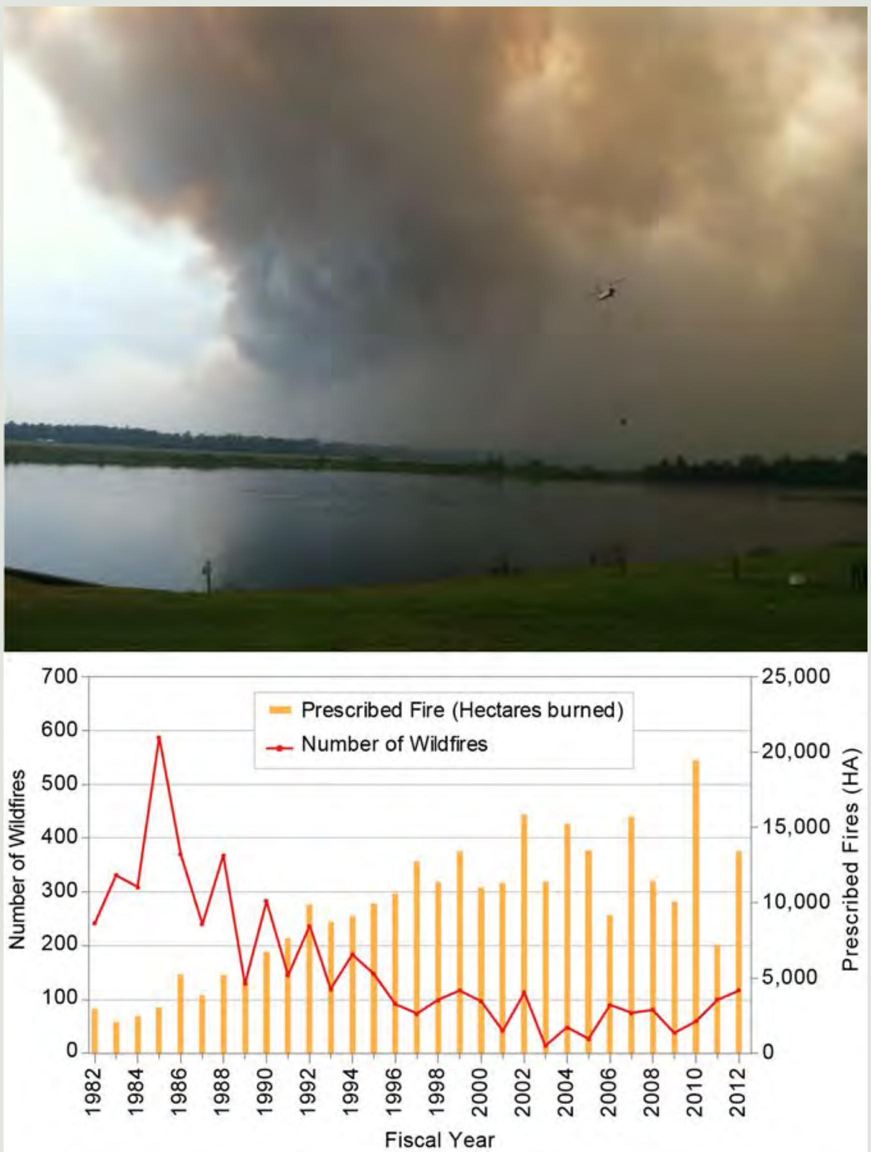

Figure 19.19: (top) A helicopter drops water on a 1,500-hectare wildfire on Hurlburt Field (Eglin Air Force Base) in Florida in June of 2012. (bottom) The increased use of prescribed fire at Ft. Benning, Georgia, led to a decrease in wildfire occurrence from 1982 to 2012. Photo credit: Kevin Hiers, Tall Timbers. Figure source: adapted from Addington et al. 2015.[4] Reprinted by permission of CSIRO Australia, ©CSIRO.

Rising Sea Levels and Hurricanes

Rising sea levels and potential changes in hurricane intensity are aspects of climate change that are expected to have a tremendous effect on coastal ecosystems in the Southeast (Ch. 8: Coastal, KM 2; Ch. 9: Oceans, KM 1). Since coastal terrestrial and freshwater ecosystems are highly sensitive to increases in inundation and salinity, sea level rise will result in the rapid conversion of these systems to tidal saline habitats. Historically, coastal ecosystems in the region have adjusted to sea level rise by vertical and horizontal movement across the landscape.[125,129,200,201] As sea levels rise in the future, some coastal ecosystems will be submerged and converted to open water, and saltwater intrusion will allow salt-tolerant coastal ecosystems to move inland at the expense of upslope and upriver ecosystems.[128,202,203,204,205,206,207,208] Where barriers are present (for example, levees and other coastal infrastructure), the potential for landward migration of natural systems will be reduced and certain coastal habitats will be lost (Ch. 20: U.S. Caribbean, KM 3).[204] With higher sea levels and increasing saltwater intrusion, the high winds, high precipitation rates, storm surges, and salts that accompany hurricanes will have large ecological impacts to terrestrial and freshwater ecosystems.[209,210]

An example of the effects of rising sea levels can be found in Louisiana, which faces some of the highest land loss rates in the world. The ecosystems of the Mississippi River Delta provide at least $12–$47 billion (in 2017 dollars) in benefits to people each year.[155] These benefits include hurricane storm protection, water supply, furs, habitat, climate stability, and waste treatment. However, between 1932 and 2016, Louisiana lost 2,006 square miles of land area (see Case Study "A Lesson Learned for Community Resettlement"),[211] due in part to high rates of relative sea level rise.[212,213,214,215] The rate of wetland loss during this period equates to Louisiana losing an area the size of one football field every 34 to 100 minutes.[211] To protect and restore the Louisiana coast, the Louisiana Coastal Protection and Restoration Authority (CPRA) has worked with local, state, and federal partners to iteratively develop a 2017 Coastal Master Plan that identifies investments that can provide direct restoration and risk reduction benefits.[216] The aim of the 50-year, $50-billion strategy is to sustain Louisiana's coastal ecosystems, safeguard coastal populations, and protect vital economic and cultural resources.[216]

Drought and Extreme Rainfall

Climate change is expected to intensify the hydrologic cycle and increase the frequency and severity of extreme events like drought and heavy rainfall. Drought and extreme heat can result in tree mortality and transform the region's forested ecosystems (Ch. 6: Forests, KM 1).[217,218,219,220,221,222,223] Drought can also affect aquatic and wetland ecosystems,[224] for example by contributing to mortality and ecological transformations in salt marshes,[225,226] mangrove forests,[227,228,229,230,231] and tidal freshwater forests.[232] In addition to drought, extreme rainfall events are also expected to become more frequent and severe in the future. The prolonged inundation and lack of oxygen that results from extreme rainfall can also result in mortality, such as the dieback of critical foundation plant species, and other large impacts to natural systems.[233] In combination, future increases in the frequency and severity of both extreme drought and extreme rainfall are expected to transform many ecosystems in the Southeast region. Natural systems in the region will have to become resistant and resilient to both too little water and too much water. The ecological transformations induced by these extreme events will affect many of the benefits that natural systems provide to society.

Warming Ocean Temperatures

Warming ocean temperatures due to climate change are expected to have a large effect on marine and coastal ecosystems (Ch. 9: Oceans, KM 3).[234,235,236] Many species are sensitive to small changes in ocean temperature; hence, the distribution and abundance of marine organisms are expected to be greatly altered by increasing ocean temperatures. For example, the distribution of tropical herbivorous fish has been expanding in response to warmer waters, which has resulted in the tropicalization of some temperate marine ecosystems and decreases in the cover of valuable macroalgal plant communities.[179] A decrease in the growth of sea turtles in the West Atlantic has been linked to higher ocean temperatures.[237] Due to climate change, warming ocean temperatures in the coming decades are expected to transform many marine and coastal ecosystems across the Southeast. However, the impacts to coral reef ecosystems in the region have been and are expected to be particularly dire. Coral reefs are biologically diverse ecosystems that provide many societal benefits, including coastal protection from waves, habitat for fish, and recreational and tourism opportunities.[238,239] However, coral reef mortality in the Florida Keys and across the globe has been very high in recent decades, due in part to warming ocean temperatures, nutrient enrichment, overfishing, and coastal development.[240,241,242,243,244] Small increases in ocean temperature can cause corals to expel the symbiotic algae upon which they depend for nourishment. When this happens, corals lose their color and die in a process known as coral bleaching (Ch. 9: Oceans, KM 1). Coral elevation and volume in the Florida Keys have been declining in recent decades,[245] and present-day temperatures in the region are already close to bleaching thresholds; hence, it is likely that many of the remaining coral reefs in the Southeast region will be lost in the coming decades.[246,247] In addition to warming temperatures, accelerated ocean acidification is also expected to contribute to coral reef mortality and decline.[248,249] When coral reefs are lost, coastal communities lose the many benefits provided by these valuable ecosystems, including lost tourism opportunities, a decline in fisheries, and a decrease in wave protection.[246,247]

Key Message 4

Economic and Health Risks for Rural Communities

Rural communities are integral to the Southeast's cultural heritage and to the strong agricultural and forest products industries across the region. More frequent extreme heat episodes and changing seasonal climates are projected to increase exposure-linked health impacts and economic vulnerabilities in the agricultural, timber, and manufacturing sectors. By the end of the century, over one-half billion labor hours could be lost from extreme heat-related impacts. Such changes would negatively impact the region's labor-intensive agricultural industry and compound existing social stresses in rural areas related to limited local community capabilities and associated with rural demography, occupations, earnings, literacy, and poverty incidence. Reduction of existing stresses can increase resilience.

In the Southeast, over 56% of land remains rural (nonmetropolitan) and home to approximately 16 million people, or about 17% percent of the region's population.[250] These rural areas are important to the social and economic well-being of the Southeast. Many in rural communities are maintaining connections to traditional livelihoods and relying on natural resources that are inherently vulnerable to climate change. The Southeast has the second highest number of farmworkers hired per year compared to other National Climate Assessment (NCA) regions.[251] Climate trends and possible climate futures show patterns that are already impacting—and are expected to further impact—rural sectors, from agriculture and forestry to human health and labor productivity (Ch. 10: Ag & Rural, KM 3). For example, shrimping, oystering, and fishing along the coast are long-standing traditions in the coastal economy that are expected to face substantial challenges. For example, by the end of the century, annual oyster harvests in the Southeast are projected to decline between 20% (19%–22%) under a lower scenario (RCP4.5) and 46% (44%–48%) under a higher scenario (RCP8.5), leading to projected price increases of 48% (RCP4.5) to 140% (RCP8.5).[35] Projected warming ocean temperatures, sea level rise, and ocean and coastal acidification are raising concern over future harvests (Ch. 9: Oceans, KM 2).[35,252] While adaptation and resilience can moderate climate change impacts, rural areas generally face other stressors, such as poverty and limited access to healthcare, which will make coping to these climate-related challenges more difficult.

Heat-related stresses are presently a major concern in the Southeast. Future temperature increases are projected to pose challenges for human health. While recent regional temperature trends have not shown the same consistent rate of daytime maximum temperature increase as observed in other parts of the United States, climate model simulations strongly suggest that daytime maximum temperatures are likely to increase as humans continue to emit greenhouse gases into the atmosphere.[13] The resulting temperature increases are expected to add to the heat health burden in rural, as well as urban, areas.[35] Projected temperature increases also pose challenges for crop production dependent on periods of lower temperatures to reach full productivity. Drought has been a recurrent issue in the Southeast affecting agriculture, forestry, and water resources.[253] With rapid growth in population and overall demand, drought is increasingly a concern for water resource management sectors such as cities, ecosystems, and energy production.

Diverse Rural Regions

Urban and rural areas exist along a continuum from major metro areas to suburbs, small towns, and lightly populated places. These areas are linked through many processes, commuting patterns, and shared central services, such as airports and hospitals, that connect the risks. Rapid population growth with associated urbanization and suburbanization over the last several decades has resulted in a more fine-grained forest landscape with smaller and more numerous forest patches.[254] Agriculture, manufacturing, tourism, and other major economic sectors are spread across the Southeast region. Rural counties in the region generally have a diversified economy with a relatively low percentage being heavily dependent on one sector. While well known for agriculture and forestry, rural areas also support manufacturing and tourism.[250]

In 2013, approximately 34% of the U.S. manufacturing output, or about $700 billion (dollar year not reported), came from the Southeast and Texas, including rural areas.[255] While manufacturing growth has been particularly strong in the Southeast in recent years, future climate changes would pose challenges for economic competitiveness. For companies involved in food processing, there are additional secondary economic risks associated with climate impacts on crops and livestock that could alter price or availability.[64,255] Facilities that are energy- or water-intensive are more likely to face increases in the costs and decreases in the availability of these resources, with potential impacts to their economic competitiveness.[246,255]

Energy production, and its dependence on water availability, is a key concern in the Southeast, given the region's growing population and large, diversified economy. An increasing number of high heat and dry days as the climate warms poses a risk to efficient power generation, particularly under conditions where the mode of primary generation moves towards natural gas and water-intensive nuclear power.[256]

Risks to Agriculture and Forestry

Agriculture, livestock rearing, and forestry activities are widespread and varied through the Southeast region.[7] Climate change is expected to have an overall negative impact on agricultural productivity in the United States,[35] although some crops could also become newly viable alternatives (Key Message 3, Figure 19.15). Increases in temperatures, water stress, freeze-free days, drought, and wildfire risks, together with changing conditions for invasive species and the movement of diseases, create a number of potential risks for existing agricultural systems (Ch. 10: Ag & Rural, KM 1).[7] In particular, precipitation trends for the Southeast region show an inclination towards slightly drier summers, which could reduce productivity, and wetter fall seasons, which can make it difficult to harvest the full crop. Multimodel averages of climate model simulations (CMIP3 [SRES A2] and CMIP5 [RCP8.5] higher scenarios) show that there is a greater risk of drier summers by the middle of the century in the western portion of the Southeast and in southern Florida, while wetter fall seasons are more likely in the eastern portion of the region.[257]

The conditions for raising and harvesting crops and livestock are projected to change. Higher temperatures can result in decreasing productivity of some cultivated crops, including cotton, corn, soybeans, and rice.[7] Livestock, which includes hogs and pigs, horses, ponies, mules, burros, and donkeys as well as poultry and processed poultry for consumption (for example, chicken nuggets), is a large component of the agricultural sector for these states and the Nation.[258] Livestock are all vulnerable to heat stress, and their care under projected future conditions would require new or enhanced adaptive strategies (Ch. 10: Ag & Rural, KM 3).

Recent changes in seasonal temperatures that are critical for plant development will continue to impact regionally important crops. Plants collected from the wild may become less available as the ideal conditions for their growth shift to other areas (see Case Study "Mountain Ramps"). Peaches—an important crop in the Southeast—require an adequate period of cool temperatures, called the chill period, to produce yields that are economically viable. Peaches also require warm temperatures at specific times during their development.[259] If the warm temperatures come too early, the chill periods could be too short or the peach blossoms can flower too soon and be in danger of late freeze impacts. A late freeze in March 2017 caused over a billion dollars of damages to peaches and other fruit crops.[84] To assist peach growers in adapting to such changes, researchers are working to develop peach varieties that can produce quality fruits in warmer winters and are developing winter chill models that can assist in adaptation planning efforts.[260,261]

Forests, both natural and plantation, in the Southeast are vulnerable to climate variability and change. Southeastern forests represent almost 27% of the U.S. total[262] and are the highest-valued crop in the region.[7] The vast majority of forest is held in private hands, primarily corporate. Forest cover ranges from almost 50% to 80% in these states, creating large areas of interface between populations and forests.[262] Jobs in timber, logging, and support for agriculture and forestry totaled approximately 458,000.[263] (See Ch. 6: Forests, KM 3 for additional discussion on forest change impacts on rural landscapes.)

The Southeast is one of the most dynamic regions for forest change on the globe,[269] though much of the change owes to intensive rotations of pine production and economic forces that drive frequent conversion between forest and agricultural uses in rural areas.[270,271] Climate is expected to have an impact on the region's forests primarily through changes in moisture regimes.[272] Species migration westward across the eastern United States in response to changing precipitation patterns has already been noted.[273] Drought is likely to alter fire regimes and further interact with species distributions (see Key Message 3). The interactions of altered precipitation and natural disturbances will be important in understanding impacts to the forests not dominated by industrial forestry (Ch. 6: Forests, KM 1 and KM 3).[274]

Wildfire is a well-known risk in the Southeast region, where it occurs with greater frequency than any other U.S. region.[275] However, mitigation strategies, particularly the use of prescribed fire, can significantly reduce wildfire risk and have been widely adopted across rural communities in the Southeast.[190] A doubling of prescribed fire at the landscape scale has been found to reduce wildfire ignitions by a factor of four,[4] while it is well documented that prescribed fire reduces the potential for crown fire in treated forest stands.[276] With greater projected fire risks,[191,277] more attention on how to foster fire-adapted communities offers opportunities for risk reduction (see Case Study "Prescribed Fire" and Key Message 3).[278,279]

Case Study: Mountain Ramps

The Cherokee have been harvesting ramps, a wild onion (*Allium tricoccum*), in the southern Appalachians, their ancestral homelands, for thousands of years.[264,265] Collecting ramps for food sustenance is only one aspect of this cultural tradition. The family-bound harvesting techniques are equally as important and make up part of the deeply held tribal lifeways (Ch. 15: Tribes, KM 2). Ramps emerge in springtime and provide important nutrients after a long winter with a dearth of fresh vegetables. These plants grow in moist forest understory areas that are sensitive to temperature and soil moisture.[266]

Figure 19.20: This up-close image of a ramp (*Allium tricoccum*), harvested from the wild, shows leaves and the bulb/corm of the plant. Photo credit: Gary Kaufman, USDA Forest Service Southern Research Station.

In the southern Appalachians, ramps are threatened by two major processes: overharvesting pressures and a changing climate that could expose these plants to higher temperatures and lower soil moisture conditions during sensitive growth periods (Ch. 10: Ag & Rural, KM 1).[267,268] Although ramps are found all along the Appalachian mountain range, on Cherokee ancestral lands, they are already in their southernmost range. Climate change thus acts to increase the vulnerability of this plant to the existing stressors.

Heat, Health, and Livelihoods

Heat-related health threats are already a risk in outdoor jobs and activities. While heat illness is more often associated with urban settings, rural populations are also at risk. For example, higher rates of heat-related illness have been reported in rural North Carolina compared to urban locations.[280] However, strategies to reduce health impacts on hot days, such as staying indoors or altering times outdoors, are already contributing to reducing heat-related illness in the Southeast.[281]

Workers in the agriculture, forestry, hunting, and fishing sectors together with construction and support, waste, and remediation services work are the most highly vulnerable to heat-related deaths in the United States, representing almost 68% of heat-related deaths nationally.[282] Six of the ten states with the highest occupational heat-related deaths in these sectors are in the Southeast region, accounting for 28.6% of occupational heat-related deaths between 2000 and 2010.[282] By 2090, under a higher scenario (RCP8.5), the Southeast is projected to have the largest heat-related impacts on labor productivity in the country, resulting in average annual losses of 570 million labor hours, or $47 billion (in 2015 dollars, undiscounted), a cost representing a third of total national projected losses, although these figures do not include adaptations by workers or industries (Figure 19.21).[35]

Investing in increased cooling is one likely form of adaptation. Among U.S. regions, the Southeast is projected to experience the highest costs associated with meeting increased electricity demands in a warmer world.[35]

Compounding Stresses and Constraints to Adaptation

The people of the rural Southeast confront a number of social stresses likely to add to the challenges posed by increases in climate stresses.[283] Rural communities tend to be more vulnerable due to factors such as demography, occupations, earnings, literacy, poverty incidence, and community capacities (Ch. 10: Ag & Rural, KM 4).[8,9,10] Reducing stress associated with these factors can increase household and community resilience.[9,284]

Projected Changes in Hours Worked

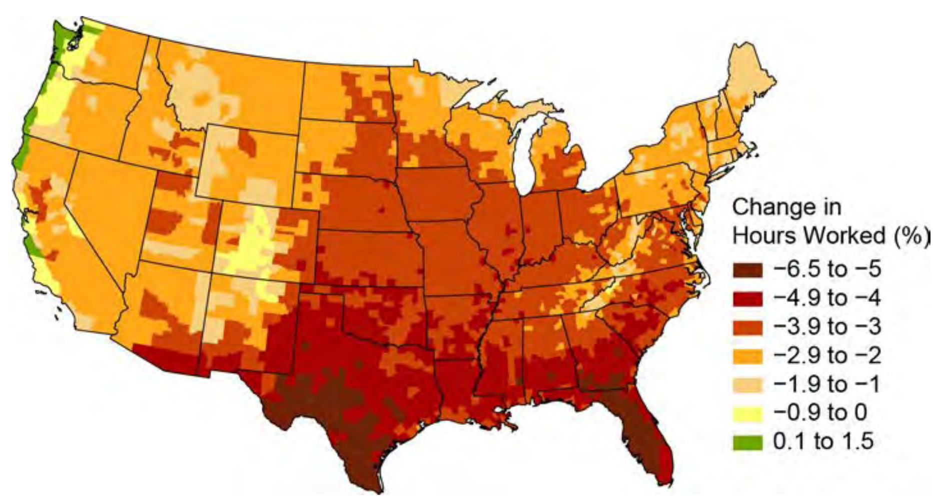

Figure 19.21: This map shows the estimated percent change in hours worked in 2090 under a higher scenario (RCP8.5). Projections indicate an annual average of 570 million labor hours lost per year in the Southeast by 2090 (with models ranging from 340 million to 820 million labor hours).[35] Estimates represent a change in hours worked as compared to a 2003–2007 average baseline for high-risk industries only. These industries are defined as agriculture, forestry, and fishing; hunting, mining, and construction; manufacturing, transportation, and utilities. Source: adapted from EPA 2017.[35]

Persistent rural poverty stands out in the Southeast (Figure 19.22). The rural counties in the region are experiencing higher levels of population loss (13% of rural counties lost population) and low educational attainment (38% of rural counties), with 35% of rural counties experiencing poverty rates of more than 20% persisting over approximately 30 years.[10] The Southeast is expected to experience the highest costs associated with meeting increased energy demands; an estimated $3.3 billion each year under a higher scenario (RCP8.5) and $1.2 billion annually under a lower scenario (RCP4.5) by the end of the century.[35] Energy poverty is a situation "where individuals or households are not able to adequately heat or provide other required energy services in their homes at affordable cost."[285] A case study from rural eastern North Carolina further explains energy poverty as a function of the energy efficiency of the home, energy provision infrastructure, physical health, low incomes, and support of social networks, which collectively influence households' choices about the amount of heating and cooling they can afford.[286] The National Weather Service (NWS) calculates degree days,[287] a way of tracking energy use. NWS starts with the assumption that when the average outside temperature is 65°F, heating or cooling is not needed in order to be comfortable. The difference between the average daily temperature and 65°F is the number of cooling or heating degrees for that day. These days can be added up over time—a month or a year—to give a combined estimate of energy needed for heating or cooling. Although heating costs are expected to decrease as the climate warms in the Southeast, the number of cooling degree days is expected to increase and the length of the cooling season expected to expand, increasing energy demand and exacerbating rural energy poverty (Figure 19.22).

The ability to cope with current and potential impacts, such as flooding, is further reduced by limited county resources. A study of hazard management plans (2004–2008) in 84 selected rural southeastern counties found these plans scored low across various criteria.[288] The rural, geographically remote locations contributed to more difficult logistics in reaching people. Interviewees also identified low-income and minority communities, substandard housing, lack of access to vehicles for evacuation, limited modes of communication, and limited local government capacity as contributing factors to difficulties in emergency planning.[288]

The healthcare system in the Southeast is already overburdened and may be further stressed by climate change. Between 2010 and 2016, more rural hospitals closed in the Southeast than any other region, with Alabama, Georgia, Mississippi, and Tennessee being among the top five states for hospital closures.[289] This strain, when combined with negative health impacts from climate change stressors (such as additional patient demand due to extreme heat and vector-borne diseases and greater flood risk from extreme precipitation events), increases the potential for disruptions of health services in the future. The Green River District Health Department recently did an assessment of ways to reduce vulnerability to negative health impacts of climate change in a mostly rural region of western Kentucky.[290] As a result, the local health department plans to enhance existing epidemiology, public health preparedness, and community health assessment services.[290]

Projected Changes in Cooling Degree Days

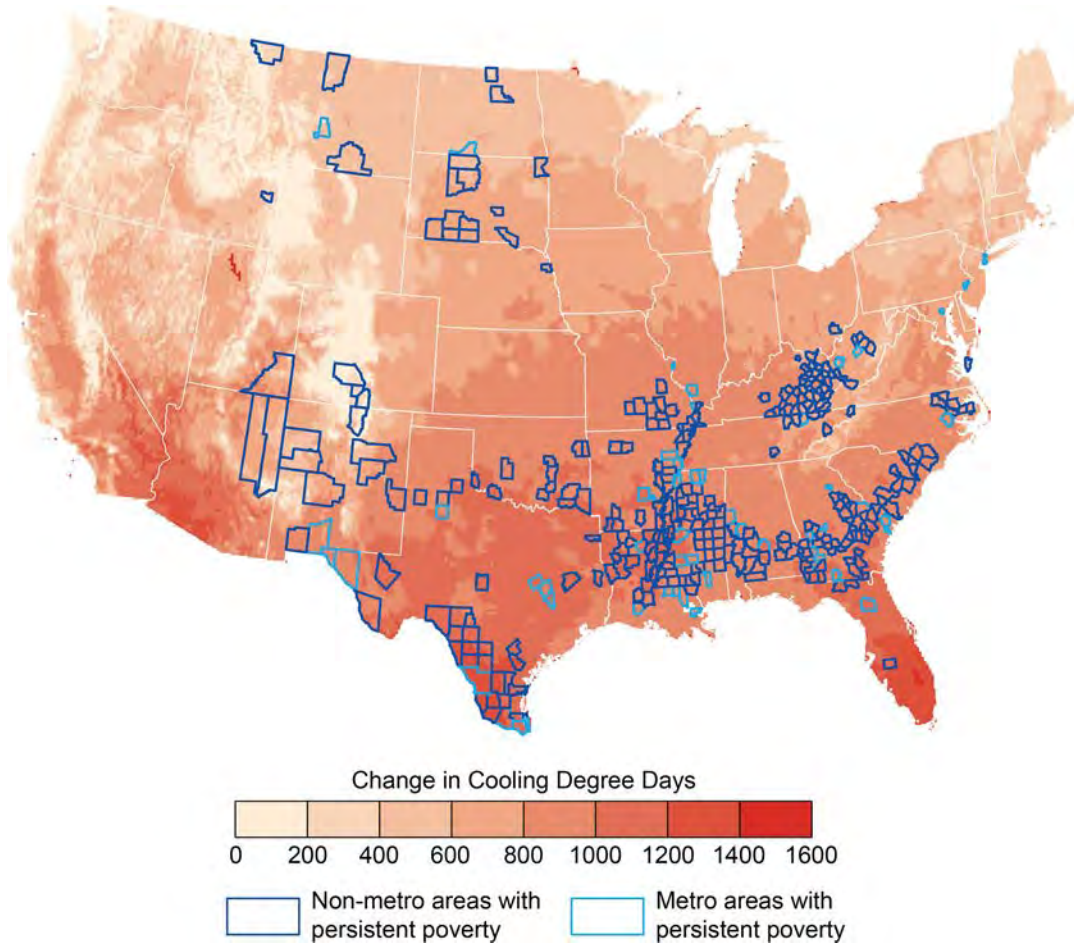

Figure 19.22: The map shows projected changes in cooling degree days by the mid-21st century (2036–2065) under the higher scenario (RCP8.5) based on model simulations. Rural counties experiencing persistent poverty are concentrated in the Southeast, where the need for additional cooling is expected to increase at higher rates than other areas of the country by mid-century. Sources: NOAA NCEI, CICS-NC, and ERT, Inc.

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Opening Image Credit

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Traceable Accounts

Process Description

Prior to identifying critical issues for the Southeast assessment focuses for the Fourth National Climate Assessment (NCA4), the Chapter Lead (CL) contacted numerous professional colleagues representing various geographic areas (e.g., Florida, Louisiana, and South Carolina) for expert opinions on critical climate change related issues impacting the region, with a particular emphasis on emerging issues since the Third National Climate Assessment (NCA3) effort.[77] Following those interviews, the CL concluded that the most pressing climate change issues to focus on for the NCA4 effort were extreme events, flooding (both from rainfall and sea level rise), wildfire, health issues, ecosystems, and adaptation actions. Authors with specific expertise in each of these areas were sought, and a draft outline built around these issues was developed. Further refinement of these focal areas occurred in conjunction with the public Regional Engagement Workshop, held on the campus of North Carolina State University in March 2017 and in six satellite locations across the Southeast region. The participants agreed that the identified issues were important and suggested the inclusion of several other topics, including impacts on coastal and rural areas and people, forests, and agriculture. Based on the subsequent authors' meeting and input from NCA staff, the chapter outline and Key Messages were updated to reflect a risk-based framing in the context of a new set of Key Messages. The depth of discussion for any particular topic and Key Message is dependent on the availability of supporting literature and chapter length limitations.

Key Message 1

Urban Infrastructure and Health Risks

Many southeastern cities are particularly vulnerable to climate change compared to cities in other regions, with expected impacts to infrastructure and human health (*very likely*, *very high confidence*). The vibrancy and viability of these metropolitan areas, including the people and critical regional resources located in them, are increasingly at risk due to heat, flooding, and vector-borne disease brought about by a changing climate (*likely*, *high confidence*). Many of these urban areas are rapidly growing and offer opportunities to adopt effective adaptation efforts to prevent future negative impacts of climate change (*very likely*, *high confidence*).

Description of evidence base

Multiple studies have projected that urban areas, including those in the Southeast, will be adversely affected by climate change in a variety of ways. This includes impacts on infrastructure[41,42,43,291,292,293] and human health.[30,31,38,294] Increases in climate-related impacts have already been observed in some Southeast metropolitan areas (e.g., Habeeb et al. 2015, Tzung-May Fu et al. 2015[12,39]).

Southeastern cities may be more vulnerable than cities in other regions of the United States due to the climate being more conducive to some vector-borne diseases, the presence of multiple large coastal cities at low elevation that are vulnerable to flooding and storms, and a rapidly growing urban and coastal population.[22,295,296]

Many city and county governments, utilities, and other government and service organizations have already begun to plan and prepare for the impacts of climate change (e.g., Gregg et al. 2017; FTA 2013; City of Fayetteville 2017; City of Charleston 2015; City of New Orleans 2015; Tampa Bay Water 2014; EPA 2015; City of Atlanta 2015, 2017; Southeast Florida Regional Climate Change Compact 2017[44,45,46,50,91,246,297,298,299]). A wide variety of adaptation options are available, offering opportunities to improve the climate resilience, quality of life, and economy of urban areas.[77,300,301,302,303,304]

Major uncertainties

Population projections are inherently uncertain over long time periods, and shifts in immigration or migration rates and shifting demographics will influence urban vulnerabilities to climate change. The precise impacts on cities are difficult to project. The scope and scale of adaptation efforts, which are already underway, will affect future vulnerability and risk. Technological developments (such as a potential shift in transportation modes) will also affect the scope and location of risk within cities. Newly emerging pathogens could increase risk of disease in the future, while successful adaptations could reduce public health risk.

Description of confidence and likelihood

There is *very high confidence* that southeastern cities will *likely* be impacted by climate change, especially in the areas of infrastructure and human health.

Key Message 2

Increasing Flood Risks in Coastal and Low-Lying Regions

The Southeast's coastal plain and inland low-lying regions support a rapidly growing population, a tourism economy, critical industries, and important cultural resources that are highly vulnerable to climate change impacts (*very likely*, *very high confidence*). The combined effects of changing extreme rainfall events and sea level rise are already increasing flood frequencies, which impacts property values and infrastructure viability, particularly in coastal cities. Without significant adaptation measures, these regions are projected to experience daily high tide flooding by the end of the century (*likely*, *high confidence*).

Description of evidence base

Multiple lines of research have shown that global sea levels have increased in the past and are projected to continue to accelerate in the future due to increased global temperature and that higher local sea level rise rates in the Mid-Atlantic and Gulf Coasts have occurred.[51,52,53,54,55,56,57,59,61,62]

Annual occurrences of high tide flooding have increased, causing several Southeast coastal cities to experience all-time records of occurrences that are posing daily risks.[1,52,58,60,61,63,67,68]

There is scientific consensus that sea level rise will continue to cause increases in high tide flooding in the Southeast as well as impact the frequency and duration of extreme water level events, causing an increase in the vulnerability of coastal populations and property.[1,60,63,67,68]

In the future, coastal flooding is projected to become more serious, disruptive, and costly as the frequency, depth, and inland extent grow with time.[1,2,35,64,65,67,68]

Many analyses have determined that extreme rainfall events have increased in the Southeast, and under higher scenarios, the frequency and intensity of these events are projected to increase.[19,21,88]

Rainfall records have shown that since NCA3, many intense rainfall events (approaching 500-year events) have occurred in the Southeast, with some causing billions of dollars in damage and many deaths.[68,82,84]

The flood events in Baton Rouge, Louisiana, in 2016 and in South Carolina in 2015 provide real examples of how vulnerable inland and coastal communities are to extreme rainfall events.[81,85,86]

The socioeconomic impacts of climate change on the Southeast is a developing research field.[65,71]

Major uncertainties

The amount of confidence associated with the historical rate of global sea level rise is impacted by the sparsity of tide gauge records and historical proxies as well as different statistical approaches for estimating sea level change. The amount of unpredictability in future projected rates of sea level rise is likely caused by a range of future climate scenarios projections and rate of ice sheet mass changes. Flooding events are highly variable in both space and time. Detection and attribution of flood events are difficult due to multiple variables that cause flooding.

Description of confidence and likelihood

There is *high confidence* that flood risks will *very likely* increase in coastal and low-lying regions of the Southeast due to rising sea level and an increase in extreme rainfall events. There is *high confidence* that Southeast coastal cities are already experiencing record numbers of high tide flooding events, and without significant adaptation measures, it is *likely* they will be impacted by daily high tide flooding.

Key Message 3

Natural Ecosystems Will Be Transformed

The Southeast’s diverse natural systems, which provide many benefits to society, will be transformed by climate change (*very likely*, *high confidence*). Changing winter temperature extremes, wildfire patterns, sea levels, hurricanes, floods, droughts, and warming ocean temperatures are expected to redistribute species and greatly modify ecosystems (*very likely*, *high confidence*). As a result, the ecological resources that people depend on for livelihood, protection, and well-being are increasingly at risk, and future generations can expect to experience and interact with natural systems that are much different than those that we see today (*very likely*, *high confidence*).

Description of evidence base

Winter temperature extremes, fire regimes, sea levels, hurricanes, rainfall extremes, drought extremes, and warming ocean temperatures greatly influence the distribution, abundance, and performance of species and ecosystems.

Winter air temperature extremes (for example, freezing and chilling events) constrain the northern limit of many tropical and subtropical species.[30,48,127,132,135,138,139,140,141,142,143,144,145,148,149,150,152,166,167,168,169,170,172,173,174,175,176,177,178] In the future, warmer winter temperatures are expected to facilitate the northward movement of cold-sensitive species, often at the expense of cold-tolerant species.[132,135,142,145,149,150,152,166,169,173,179] Certain ecosystems are located near thresholds where small changes in winter air temperature regimes can trigger comparatively large and abrupt landscape-scale ecological changes (i.e., ecological regime shifts).[135,145,152]

Changing fire regimes are expected to have a large impact on natural systems. Fire has historically played an important role in the region, and ecological diversity in many southeastern natural systems is dependent upon fire.[115,116,134,189] In the future, rising temperatures and increases in the duration and intensity of drought are expected to increase wildfire occurrence and also reduce the effectiveness of prescribed fire.[3,4,5,6]

Hurricanes and rising sea levels are aspects of climate change that will have a tremendous effect on coastal ecosystems in the Southeast. Historically, coastal ecosystems in the region have adjusted to sea level rise via vertical and/or horizontal movement across the landscape.[125,129,200,201] As sea levels rise in the future, some coastal ecosystems will be submerged and converted to open water, and some coastal ecosystems will move inland at the expense of upslope and upriver ecosystems.[203,204] Since coastal terrestrial and freshwater ecosystems are highly sensitive to increases in inundation and/or salinity, sea level rise will result in the comparatively rapid conversion of these systems to tidal saline habitats. In addition to sea level rise, climate change is expected to increase the impacts of hurricanes; the high winds, storm surges, inundation, and salts that accompany hurricanes will have large ecological impacts to terrestrial and freshwater ecosystems.[209,210]

Climate change is expected to intensify the hydrologic cycle and increase the frequency and severity of extreme events. Extreme drought events are expected to become more frequent and severe. Drought and extreme heat can result in tree mortality and transform southeastern forested ecosystems.[217,218,219,220,221,222,223] Drought can also affect aquatic and wetland ecosystems.[224,225,226,227,228,229,232] Extreme rainfall events are also expected to become more frequent and severe in the future. The prolonged inundation and lack of oxygen that result from extreme rainfall events can also result in mortality and large impacts to natural systems.[233] In combination, future increases in both extreme drought and extreme rainfall are expected to transform many southeastern ecosystems.

Warming ocean temperatures due to climate change are expected to have a large effect on marine and coastal ecosystems.[234,235,236] Many species are sensitive to small changes in ocean temperature; hence, the distribution and abundance of marine organisms are expected to be greatly altered by increasing ocean temperatures. For example, the distribution of tropical herbivorous fish has been expanding in response to warmer waters, which has resulted in the tropicalization of some temperate marine ecosystems and decreases in the cover of valuable macroalgal plant communities.[179] A decrease in the growth of sea turtles in the West Atlantic has been linked to higher ocean temperatures.[237] The impacts to coral reef ecosystems have been and are expected to be particularly dire. Coral reef mortality in the Florida Keys and across the globe has been very high in recent decades, due in part to warming ocean temperatures, nutrient enrichment, overfishing, and coastal development.[240,241,242,243,244] Coral elevation and volume in the Florida Keys have been declining in recent decades,[245] and present-day temperatures in the region are already close to bleaching thresholds; hence, it is likely that many of the remaining coral reefs in the Southeast will be lost in the coming decades.[246,247] In addition to warming temperatures, accelerated ocean acidification is also expected to contribute to coral reef mortality and decline.[248,249]

Major uncertainties

In the Southeast, winter temperature extremes, fire regimes, sea level fluctuations, hurricanes, extreme rainfall, and extreme drought all play critical roles and greatly influence the distribution, structure, and function of species and ecosystems. Changing climatic conditions (particularly, changes in the frequency and severity of climate extremes) are, however, difficult to replicate via experimental manipulations; hence, ecological responses to future climate regimes have not been fully quantified for all species and ecosystems. Natural ecosystems are complex and governed by many interacting biotic and abiotic processes. Although it is possible to make general predictions of climate change effects, specific future ecological transformations can be difficult to predict, especially given the number of interacting and changing biotic and abiotic factors in any specific location. Uncertainties in the range of potential future changes in multiple and concurrent facets of climate and land-use change also affect our ability to predict changes to natural systems.

Description of confidence and likelihood

There is *high confidence* that climate change (e.g., changing winter temperatures extremes, changing fire regimes, rising sea levels and hurricanes, warming ocean temperatures, and more extreme rainfall and drought) will *very likely* affect natural systems in the Southeast region. These climatic drivers play critical roles and greatly influence the distribution, structure, and functioning of ecosystems; hence, changes in these climatic drivers will transform ecosystems in the region and greatly alter the distribution and abundance of species.

Key Message 4

Economic and Health Risks for Rural Communities

Rural communities are integral to the Southeast's cultural heritage and to the strong agricultural and forest products industries across the region. More frequent extreme heat episodes and changing seasonal climates are projected to increase exposure-linked health impacts and economic vulnerabilities in the agricultural, timber, and manufacturing sectors (*very likely*, *high confidence*). By the end of the century, over one-half billion labor hours could be lost from extreme heat-related impacts (*likely*, *medium confidence*). Such changes would negatively impact the region's labor-intensive agricultural industry and compound existing social stresses in rural areas related to limited local community capabilities and associated with rural demography, occupations, earnings, literacy, and poverty incidence (*very likely*, *high confidence*). Reduction of existing stresses can increase resilience (*very likely*, *high confidence*).

Description of evidence base

Analysis of the sensitivity of some manufacturing sectors to climate changes anticipates secondary risks associated with crop and livestock productivity.[64,255]

Multiple analyses anticipate that energy- or water-intensive industries could face water stress and increased energy costs.[8,64,255,256]

A large body of evidence addresses the sensitivity of many crops grown in the Southeast to changing climate conditions including increased temperatures, decreased summer rainfall, drought, and change in the timing and duration of chill periods.[7,35] Extensive research documents livestock sensitivity to heat stress.[7]

Multiple lines of evidence indicate that forests are likely to be impacted by changing climate, particularly moisture regimes and potential changes in wildfire activity.[191,195,272,274] There is extensive research on heat-related illness and mortality among those living and working in the Southeast. While there is more evidence focused on urban areas, limited research has identified higher levels of heat-related illness in rural areas.[280,281] Research on occupational heat-related mortality identifies some of the Nation's highest levels in southeastern states.[282] Computer model simulations of heat-related reductions in labor productivity anticipate the greatest losses will occur in the Southeast. However, these models do not account for adaptations that may reduce estimated losses.[35,64] By the end of the century, mean annual electricity costs are estimated at $3.3 billion each year under RCP8.5 (model range: $2.4 to $4.2 billion; in 2015 dollars, undiscounted) and mean $1.2 billion each year under RCP4.5 (model range $0.9 to $1.9 billion; in 2015 dollars, undiscounted).[35]

Rural communities tend to be vulnerable due to factors such as demography, occupations, earnings, literacy, and poverty incidence.[8,9,10,250,283,284,305] Reducing the stress created by such factors can improve resilience.[9,284] The availability and accessibility of planning and health services to support coping with climate-related stresses are limited in the rural Southeast.[288,289]

Major uncertainties

There are limited studies documenting direct connections between climate changes and economic impacts. Models are limited in their ability to incorporate adaptation that may reduce losses. These factors restrict the potential to strongly associate declines in agricultural and forest productivity with the level of potential economic impact.

Projections of potential change in the frequency and extent of wildfires depend in part on models of future population growth and human behavior, which are limited, adding to the uncertainty associated with climate and forest modeling.

Many indicators of vulnerability are dynamic, so that adaptation and other changes can affect the patterns of vulnerability to heat and other climate stressors over time. Limited studies indicate concerns over the planning and preparedness of capacity at local levels; however, information is limited.

Projected labor hours lost vary by global climate model, time frame, and scenario, with a mean of 0.57 and a model range of 0.34–0.82 billion labor hours lost each year for RCP8.5 by 2090. The annual mean projected losses are roughly halved (0.28 billion labor hours) and with a model range from 0.19 to 0.43 billion labor hours lost under RCP4.5 by 2090.[35]

Description of confidence and likelihood

There is *high confidence* that climate change (e.g., rising temperatures, changing fire regimes, rising sea levels, and more extreme rainfall and drought) will *very likely* affect agricultural and forest products industries, potentially resulting in economic impacts. There is *high confidence* that increases in temperature are *very likely* to increase heat-related illness, deaths, and loss of labor productivity without greater adaptation efforts.

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On the Web: https://nca2018.globalchange.gov/chapter/caribbean

20 U.S. Caribbean

San Juan, Puerto Rico

Key Message 1

Freshwater

Freshwater is critical to life throughout the Caribbean. Increasing global carbon emissions are projected to reduce average rainfall in this region by the end of the century, constraining freshwater availability, while extreme rainfall events, which can increase freshwater flooding impacts, are expected to increase in intensity. Saltwater intrusion associated with sea level rise will reduce the quantity and quality of freshwater in coastal aquifers. Increasing variability in rainfall events and increasing temperatures will likely alter the distribution of ecological life zones and exacerbate existing problems in water management, planning, and infrastructure capacity.

Key Message 2

Marine Resources

Marine ecological systems provide key ecosystem services such as commercial and recreational fisheries and coastal protection. These systems are threatened by changes in ocean surface temperature, ocean acidification, sea level rise, and changes in the frequency and intensity of storm events. Degradation of coral and other marine habitats can result in changes in the distribution of species that use these habitats and the loss of live coral cover, sponges, and other key species. These changes will likely disrupt valuable ecosystem services, producing subsequent effects on Caribbean island economies.

Key Message 3

Coastal Systems

Coasts are a central feature of Caribbean island communities. Coastal zones dominate island economies and are home to critical infrastructure, public and private property, cultural heritage, and natural ecological systems. Sea level rise, combined with stronger wave action and higher storm surges, will worsen coastal flooding and increase coastal erosion, likely leading to diminished beach area, loss of storm surge barriers, decreased tourism, and negative effects on livelihoods and well-being. Adaptive planning and nature-based strategies, combined with active community participation and traditional knowledge, are beginning to be deployed to reduce the risks of a changing climate.

Key Message 4

Rising Temperatures

Natural and social systems adapt to the temperatures under which they evolve and operate. Changes to average and extreme temperatures have direct and indirect effects on organisms and strong interactions with hydrological cycles, resulting in a variety of impacts. Continued increases in average temperatures will likely lead to decreases in agricultural productivity, changes in habitats and wildlife distributions, and risks to human health, especially in vulnerable populations. As maximum and minimum temperatures increase, there are likely to be fewer cool nights and more frequent hot days, which will likely affect the quality of life in the U.S. Caribbean.

Key Message 5

Disaster Risk Response to Extreme Events

Extreme events pose significant risks to life, property, and economy in the Caribbean, and some extreme events, such as flooding and droughts, are projected to increase in frequency and intensity. Increasing hurricane intensity and associated rainfall rates will likely affect human health and well-being, economic development, conservation, and agricultural productivity. Increased resilience will depend on collaboration and integrated planning, preparation, and responses across the region.

Key Message 6

Increasing Adaptive Capacity Through Regional Collaboration

Shared knowledge, collaborative research and monitoring, and sustainable institutional adaptive capacity can help support and speed up disaster recovery, reduce loss of life, enhance food security, and improve economic opportunity in the U.S. Caribbean. Increased regional cooperation and stronger partnerships in the Caribbean can expand the region's collective ability to achieve effective actions that build climate change resilience, reduce vulnerability to extreme events, and assist in recovery efforts.

Executive Summary

Historically, the U.S. Caribbean region has experienced relatively stable seasonal rainfall patterns, moderate annual temperature fluctuations, and a variety of extreme weather events, such as tropical storms, hurricanes, and drought. However, the Caribbean climate is changing and is projected to be increasingly variable as levels of greenhouse gases in the atmosphere increase.

The high percentage of coastal area relative to the total island land area in the U.S. Caribbean means that a large proportion of the region's people, infrastructure, and economic activity are vulnerable to sea level rise, more frequent intense rainfall events and associated coastal flooding, and saltwater intrusion. High levels of exposure and sensitivity to risk in the U.S. Caribbean region are compounded by a low level of adaptive capacity, due in part to the high costs of mitigation and adaptation measures relative to the region's gross domestic product, particularly when compared to continental U.S. coastal areas.[1] The limited geographic and economic scale of Caribbean islands means that disruptions from extreme climate-related events, such as droughts and hurricanes, can devastate large portions of local economies and cause widespread damage to crops, water supplies, infrastructure, and other critical resources and services.[1]

The U.S. Caribbean territories of Puerto Rico and the U.S. Virgin Islands (USVI) have distinct differences in topography, language, population size, governance, natural and human resources, and economic capacity. However, both are highly dependent on natural and built coastal assets; service-related industries account for more than 60% of the USVI economy. Beaches, affected by sea level rise and erosion, are among the main tourist attractions. In Puerto Rico, critical infrastructure (for example, drinking water pipelines and pump stations, sanitary pipelines and pump stations, wastewater treatment plants, and power plants) is vulnerable to the effects of sea level rise, storm surge, and flooding. In the USVI, infrastructure and historical buildings in the inundation zone for sea level rise include the power plants on both St. Thomas and St. Croix; schools; housing communities; the towns of Charlotte Amalie, Christiansted, and Frederiksted; and pipelines for water and sewage.

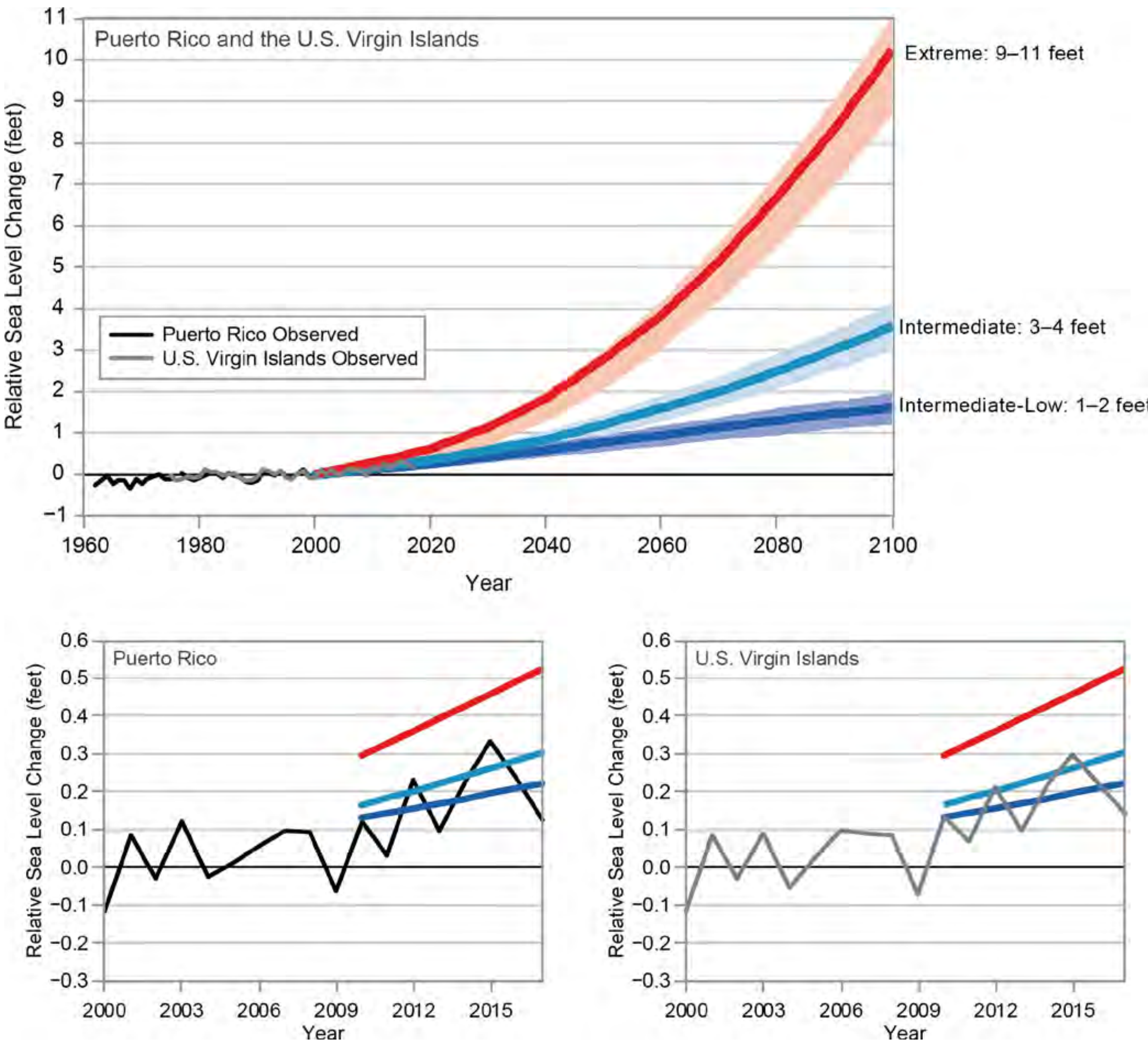
Climate change will likely result in water shortages due to an overall decrease in annual rainfall, a reduction in ecosystem services, and increased risks for agriculture, human health, wildlife, and socioeconomic development in the U.S. Caribbean. These shortages would result from some locations within the Caribbean experiencing longer dry seasons and shorter, but wetter, wet seasons in the future.[2,3,4,5,6,7,8] Extended dry seasons are projected to increase fire likelihood.[9,10] Excessive rainfall, coupled with poor construction practices, unpaved roads, and steep slopes, can exacerbate erosion rates and have adverse effects on reservoir capacity, water quality, and nearshore marine habitats.

Ocean warming poses a significant threat to the survival of corals and will likely also cause shifts in associated habitats that compose the coral reef ecosystem. Severe, repeated, or prolonged periods of high temperatures leading to extended coral bleaching can result in colony death. Ocean acidification also is likely to diminish the structural integrity of coral habitats. Studies show that major shifts in fisheries distribution and changes to the structure and composition of marine habitats adversely affect food security, shoreline protection, and economies throughout the Caribbean.

In Puerto Rico, the annual number of days with temperatures above 90°F has increased over the last four and a half decades. During that period, stroke and cardiovascular disease, which are influenced by such elevated temperatures, became the primary causes of death.[11,12] Increases in average temperature and in extreme heat events will likely have detrimental effects on agricultural operations throughout the U.S. Caribbean region.[13,14] Many farmers in the tropics, including the U.S. Caribbean, are considered small-holding, limited resource farmers and often lack the resources and/or capital to adapt to changing conditions.[15]

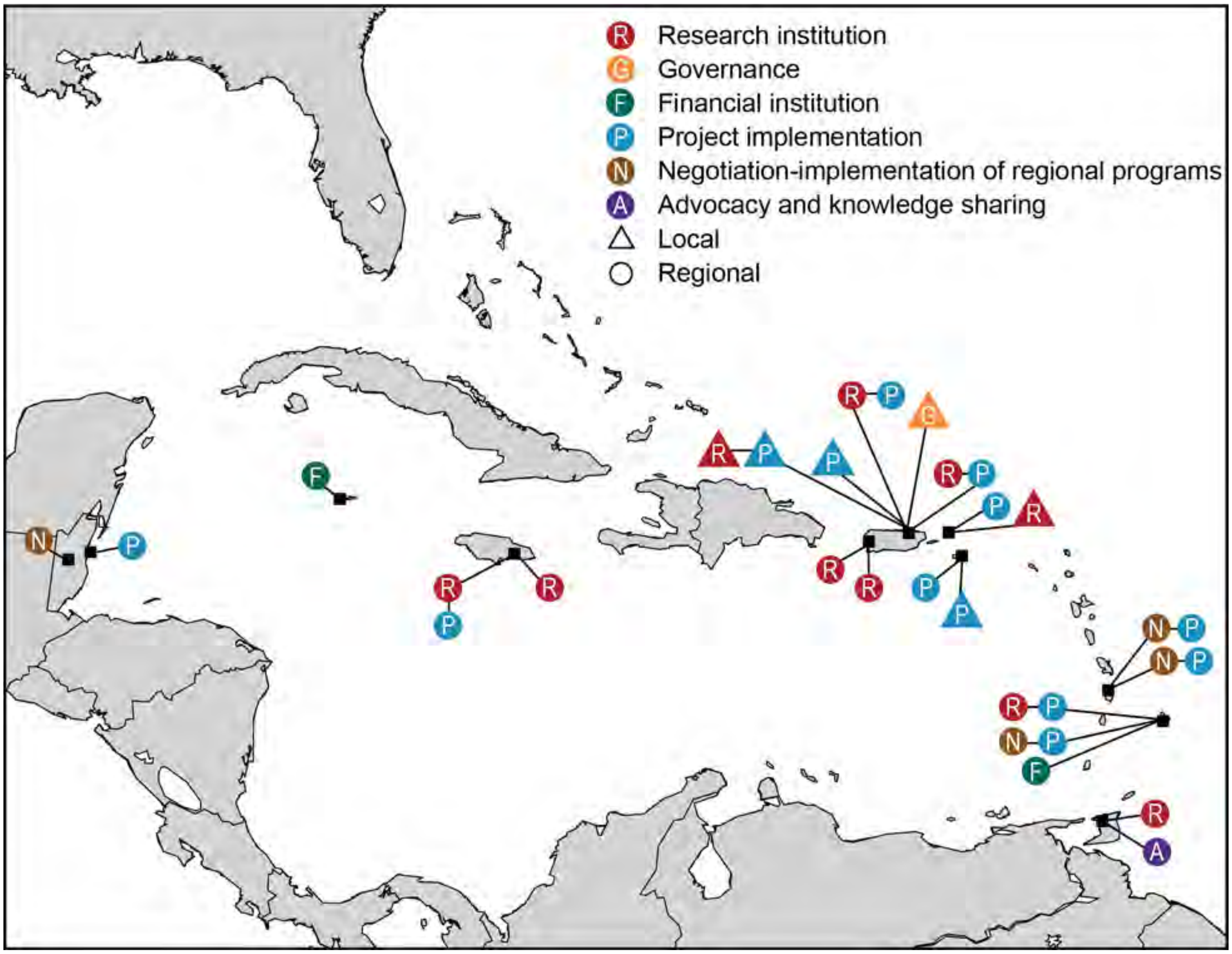
Most Caribbean countries and territories share the need to assess risks, enable actions across scales, and assess changes in ecosystems to inform decision-making on habitat protection under a changing climate.[16,17] U.S. Caribbean islands have the potential to improve adaptation and mitigation actions by fostering stronger collaborations with Caribbean initiatives on climate change and disaster risk reduction.

Observed and Projected Sea Level Rise



(top) Observed sea level rise trends in Puerto Rico and the U.S. Virgin Islands reflect an increase in sea level of about 0.08 inches (2.0 mm) per year for the period 1962–2017 for Puerto Rico and for 1975–2017 for the U.S. Virgin Islands. The bottom panels show a closer look at more recent trends from 2000 to 2017 that measure a rise in sea level of about 0.24 inches (6.0 mm) per year. Projections of sea level rise are shown under three different scenarios of Intermediate-Low (1–2 feet), Intermediate (3–4 feet), and Extreme (9–11 feet) sea level rise. The scenarios depict the range of future sea level rise based on factors such as global greenhouse gas emissions and the loss of glaciers and ice sheets. *From Figure 20.6. (Sources: NOAA NCEI and CICS-NC).*

Climate Risk Management Organizations



Some of the organizations working on climate risk assessment and management in the Caribbean are shown. Joint regional efforts to address climate challenges include the implementation of adaptation measures to reduce natural, social, and economic vulnerabilities, as well as actions to reduce greenhouse gas emissions. See the online version of this figure at http://nca2018.globalchange.gov/chapter/20#fig-20-18 for more details. *From Figure 20.18 (Sources: NOAA and the USDA Caribbean Climate Hub)*.

Background

Puerto Rico and the U.S. Virgin Islands (USVI) are rich in biodiversity, cultural heritage, and natural resources. More than 3.5 million inhabitants depend on the region's natural resources and environmental services for their well-being, livelihoods, local economies, and cultural identities. Changing climate and weather patterns interacting with human activities, are affecting land use, air quality, and resource management and are posing growing risks to food security, the economy, culture, and ecosystems services.

The U.S. Caribbean (Figure 20.1) includes the inhabited commonwealth islands of Puerto Rico, Vieques, and Culebra (with a combined population of 3.4 million), along with the inhabited territorial islands of St. Croix, St. Thomas, St. John, and Water Island (with a combined population of 104,000). In addition to the principal islands, the U.S. Caribbean includes over 800 smaller islands and cays, diverse cultural and historical resources, and a rich matrix of marine and terrestrial ecosystems. The region's physical geography includes nearshore and open ocean marine areas; coastal wetlands, hills, and plains; limestone (or karst) hills; and interior mountains. Average rainfall amounts vary widely across the region, and social and ecological systems are diverse. Puerto Rico and the USVI share many vulnerabilities with coastal states and the Pacific Islands but lack much of the capacity available to the continental United States.

Shared Vulnerabilities of U.S. Caribbean and Pacific Islands

The U.S. Caribbean islands face many of the same climate change related challenges as Hawai'i and the U.S.-Affiliated Pacific Islands (Ch. 27: Hawai'i & Pacific Islands), including

- isolation and dependence on imports, making islands more vulnerable to climate-related impacts;
- critical dependence on local sources of freshwater (Ch. 27, KM 1);
- temperature increases that will further reduce supply and increase demand on freshwater (Ch. 27, KM 1);
- vulnerability to drought in ways that differ from mainland regions (Ch. 27, KM 1);
- a projected significant decrease in rainfall in all (Caribbean) or parts (Hawai'i and Pacific Islands) of these regions (Ch. 27, KM 1);
- sea level rise, coastal erosion, and increasing storm impacts that threaten lives, critical infrastructure, and livelihoods on islands (Ch. 27, KM 2–4);
- prominent concerns about the economic consequences of coastal threats (Ch. 27, KM 3);
- coral bleaching and mortality due to warming ocean surface waters and ocean acidification (Ch. 27, KM 4); and
- threats to critical economic marine resources, including fisheries (Ch. 27, KM 4).

U.S. Caribbean Region

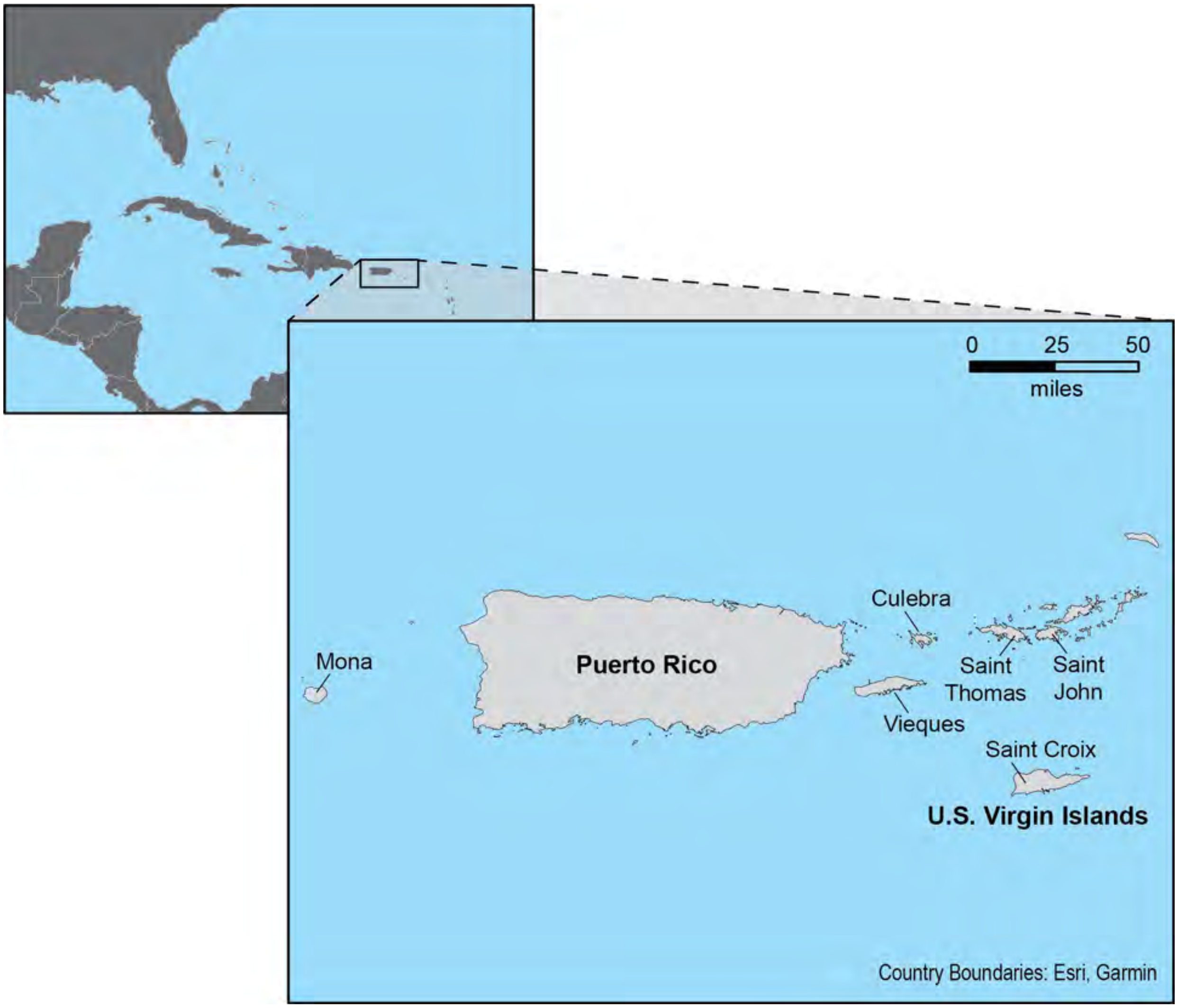


Figure 20.1: The U.S. Caribbean includes the Commonwealth of Puerto Rico and the territory of the U.S. Virgin Islands. The region includes seven inhabited islands and nearly 800 smaller islands and cays.

The islands also have unique issues related to data availability and the capacity to develop datasets comparable to those available for the continental United States. For example, the small size of the islands, particularly the USVI, affects the availability and accuracy of downscaled climate data and projections, similar to the Pacific Islands (Ch. 27: Hawaiʻi & Pacific Islands). Additionally, differences in the natural and social systems, and in information availability for Puerto Rico and the USVI, affect the degree of vulnerability to climate change and extreme climate events. This is reflected in different needs, priorities, and approaches to reducing vulnerability between Puerto Rico and the USVI. Historically, the U.S. Caribbean region has experienced relatively stable seasonal rainfall patterns, moderate annual temperature fluctuations, and a variety of extreme weather events, such as tropical storms, hurricanes, and drought. However, these patterns are changing and are projected to be increasingly variable as atmospheric greenhouse gas concentrations increase. Having evolved with these historic climate conditions, and given the small size and relatively isolated nature of these islands, Caribbean social, economic, and ecological systems are likely to be more sensitive to changes in temperature and precipitation than similar systems in the mainland United States (Figure 20.2).[18,19]

Climate Indicators and Impacts

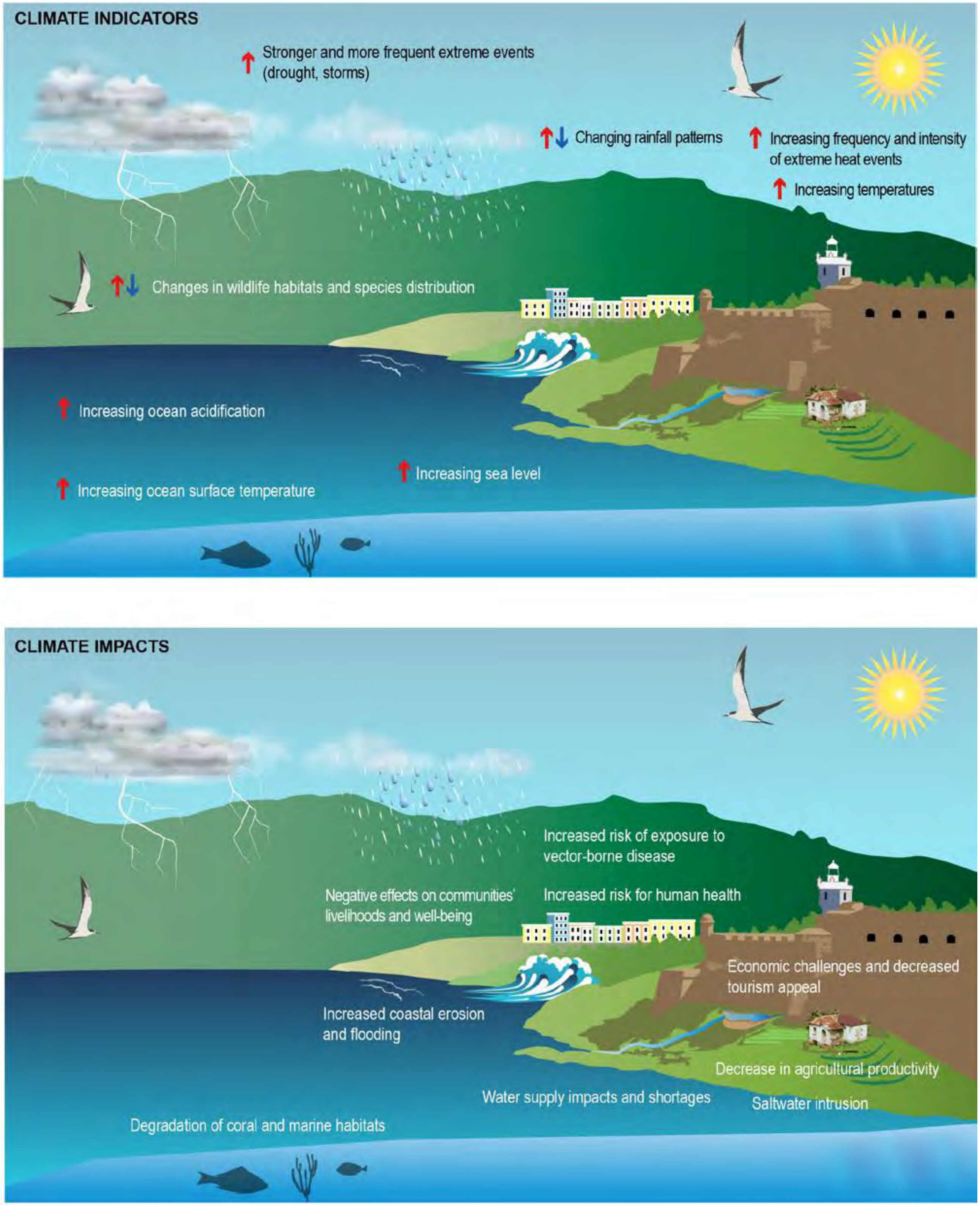


Figure 20.2: (top) Key indicators for monitoring climate variability and change in the U.S. Caribbean include sea level rise, ocean temperature and acidity, air temperature, rainfall patterns, frequency of extreme events, and changes in wildlife habitats. (bottom) Changes in these climate indicators result in environmental and social impacts to natural ecosystems, infrastructure, and society, including degradation of coral and marine habitats, increased coastal flooding and erosion, decrease in agricultural productivity, water supply shortages, negative effects on communities' livelihoods and on human health, as well as economic challenges and decreased tourism appeal. Source: Puerto Rico Department of Natural and Environmental Resources.

The vulnerability of the U.S. Caribbean region is influenced by global, regional, and local factors. The region is sensitive to large-scale patterns of natural variability in both the Atlantic and Pacific tropical basins, such as the El Niño–Southern Oscillation and the Atlantic Multidecadal Oscillation.[20] Climate variations due to these large-scale patterns directly impact the U.S. Caribbean because the islands largely rely on surface waters and consistent annual rainfall to meet freshwater demands. The high percentage of coastal areas relative to the total island land area means that a large proportion of the region's people, infrastructure, and economic activity are vulnerable to sea level rise, more frequent intense rainfall events and associated coastal flooding, and saltwater intrusion. As on islands worldwide, there are strong socioeconomic and cultural ties to diminishing marine resources and services, as well as economic dependence on tourism and imported goods.[1,13,14,21] High levels of exposure and sensitivity to risk in the region are compounded by a low level of adaptive capacity, due in part to the high costs of mitigation and adaptation measures relative to the region's gross domestic product, particularly when compared to continental U.S. coastal areas.[1]

The people of the U.S. Caribbean rely heavily on imported food and other goods and services, leaving them critically exposed to climate-related disruptions in transportation systems as well as vulnerabilities associated with source geographies.[22] Crop species key to regional economies and food security—such as coffee, plantains, and mangoes—have evolved in narrower climatic niches relative to temperate crops and are often detrimentally affected by relatively small shifts in temperature, humidity, and rainfall.[13,23,24] The limited geographic and economic scale of Caribbean islands means that disruptions from extreme climate-related events, such as droughts and hurricanes, can devastate large portions of local economies and cause widespread damage to crops, water supplies, infrastructure, and other critical resources and services.[1,25]

Observed and Projected Climate Change

The *Climate Science Special Report* (CSSR)[26] provides an in-depth assessment of observed and projected climate change in the continental United States. Because this level of assessment was not available for the U.S. Caribbean region, this section provides a brief overview of observed trends and future projections of five climate variables that are relevant to assessing climate change risk in the region: temperature, precipitation, sea surface temperature, ocean acidification, and sea level rise.

Temperature. Annual average temperatures in the U.S. Caribbean have fluctuated over the last century. However, since 1950, temperatures have increased by about 1.5°F in Puerto Rico.[27] Projected increases under both a lower and higher scenario (RCP4.5 and RCP8.5) are expected in both average and extreme temperatures, which will lead to more days per year over 95°F and more nights per year over 85°F.[28] Global climate models project about a 1.5°F to 4°F increase in average temperatures for the U.S. Caribbean by 2050. End-of-century estimates show temperature increases as high as about 9°F under a higher scenario (RCP8.5; Figure 20.3).[7]

Observed and Projected Temperature Change for Puerto Rico

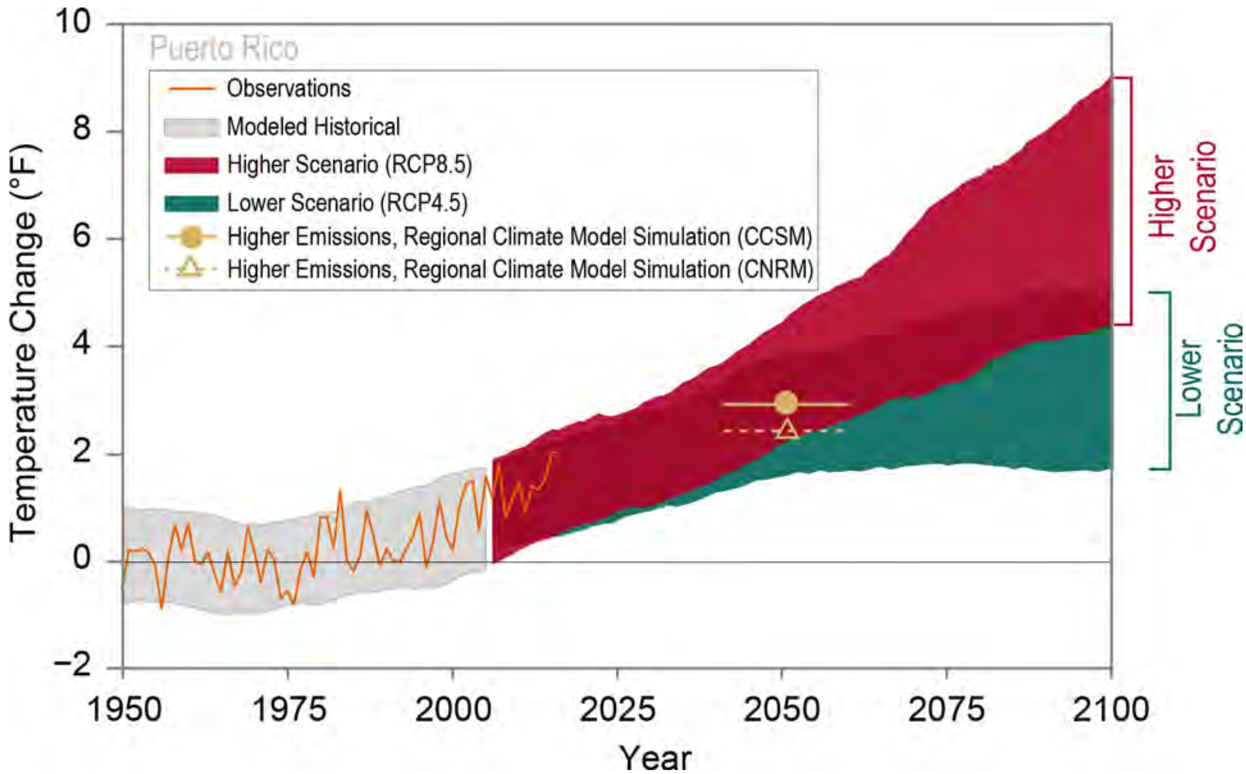


Figure 20.3: Observed and projected temperature changes are shown as compared to the 1951–1980 average. Observed data are for 1950–2017, and the range of model simulations for the historical period is for 1950–2005. The range of projected temperature changes from global climate models is shown for 2006–2100 under a lower (RCP4.5) and a higher (RCP8.5) scenario (see the Scenario Products section of App. 3). Projections from two regional climate models are shown for 2036–2065, and they align with those from global models for the same period.[29,30] Sources: NOAA NCEI, CICS-NC, and USGS.

Precipitation. Globally, subtropical regions are expected to become drier in the future, especially in regions such as the U.S. Caribbean where oceans have the largest influence on local precipitation patterns.[31] Climate model results consistently project significant drying in the U.S. Caribbean region by the middle of this century, specifically, a decline of more than 10% in annual precipitation under the higher scenario (RCP8.5; Figure 20.4).[7,28,30,32] The magnitude of this projected drying, particularly for climate scenarios with the highest amounts of warming, is in general lower in the most recently developed climate models.[28] The region is likely to experience more intense rainfall events associated with tropical cyclones;[33] however, uncertainty remains regarding various aspects of extreme rainfall within the region, such as the frequency and duration of extreme rainfall events associated with tropical cyclones.[28,34] For instance, one study[34] finds less frequent extreme rainfall events on average in the future at sub-daily and daily timescales, while another[28] finds more frequent extreme rainfall events that exceed 3 inches of rain in a day, as well as more intense rainfall associated with tropical cyclones.[28,33]

Sea surface temperature and ocean acidification. Globally, surface ocean waters have warmed by about 1.3°F per century between 1900 and 2016.[35] Over the period 1955–2016, the waters of the northeast Caribbean increased in temperature at a rate of 0.23°F per decade,[36] and over the last two decades, the sea surface warming rate has reached 0.43°F per decade (Figure 20.5).

Projected Precipitation Change for Puerto Rico

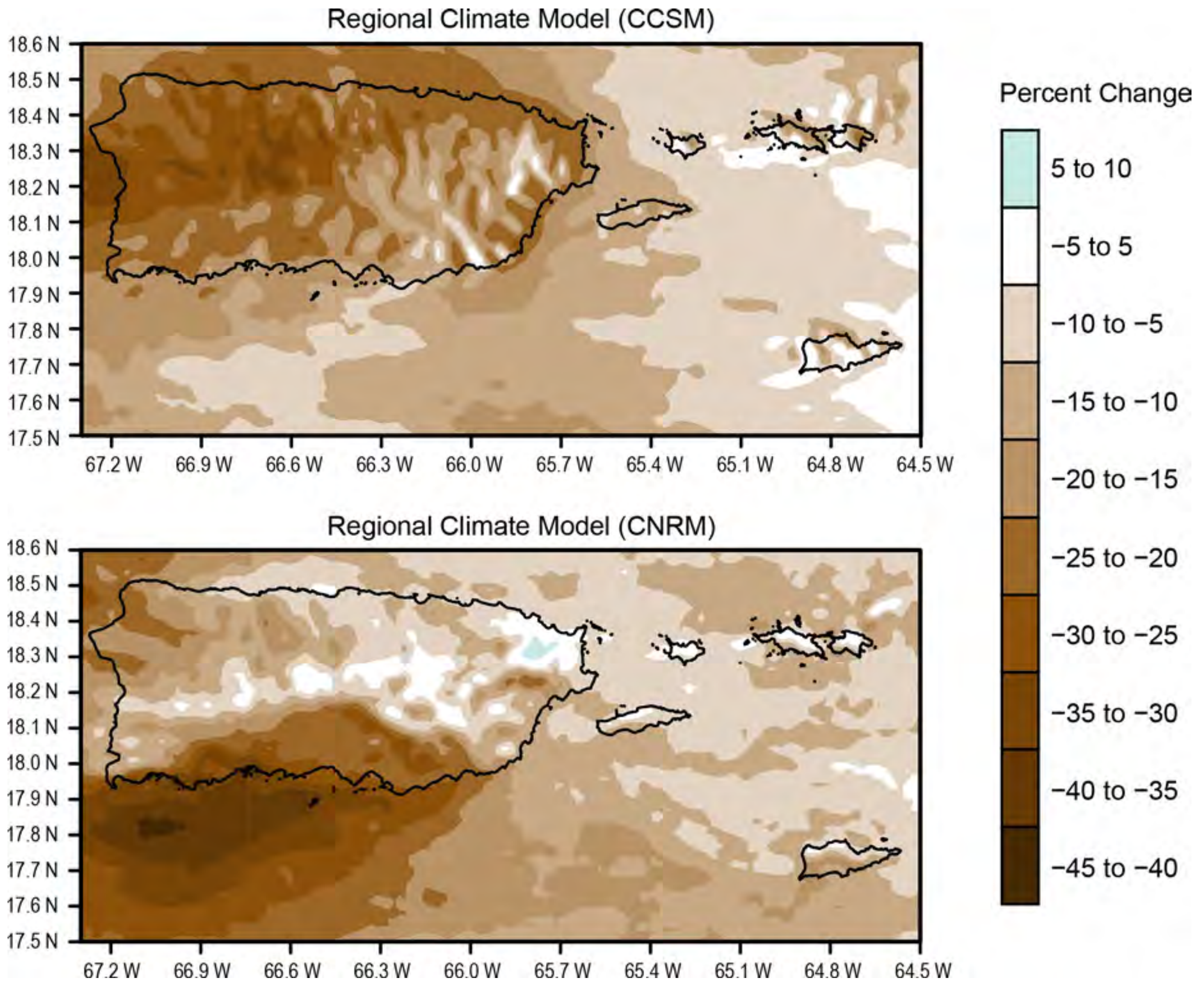


Figure 20.4: This figure shows the projected percent change in annual precipitation over the U.S. Caribbean region for the period 2040–2060 compared to 1985–2005 based on the results of two regional climate model simulations.[29,30] These simulations downscale two global models for the higher scenario (RCP8.5)[26] and show that within-island changes are projected to exceed a 10% reduction in annual rainfall. Uncertainty remains as to the location of the largest reductions within the islands. Projections of precipitation change for the U.S. Virgin Islands are particularly uncertain because of model limitations related to resolving these smaller islands. Source: Bowden et al. 2018.[30]

Ocean Chemistry and Temperature

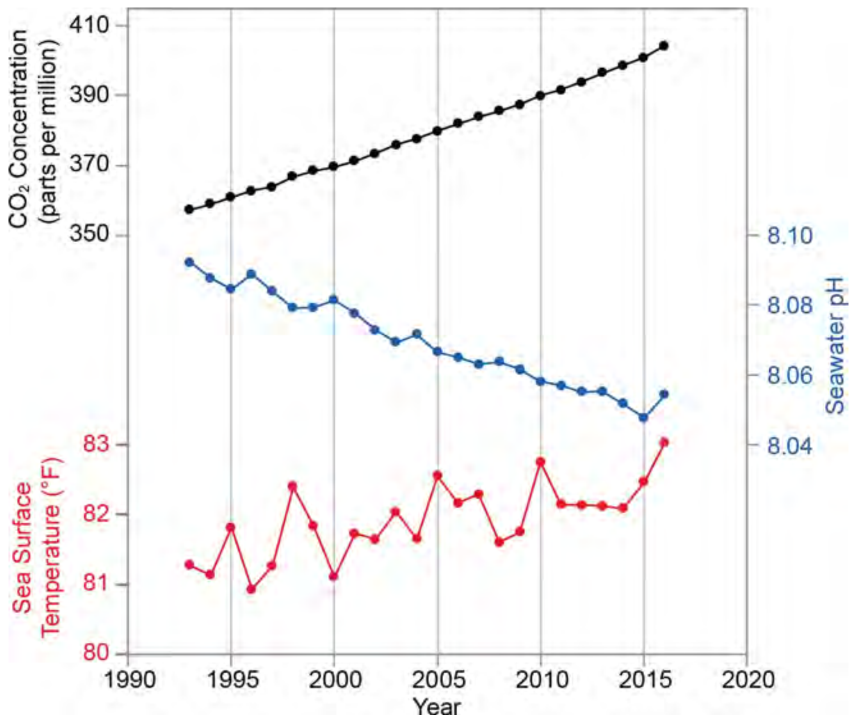


Figure 20.5: This figure represents an annual time series from 1993 to 2016 of atmospheric carbon dioxide (CO_2; black line), sea surface temperature (red line), and seawater pH (blue line) for the Caribbean region. The Caribbean ocean is subject to changes in surface pH and temperature due to the increase in atmospheric CO_2 concentrations. The oceans have the capacity to not only absorb heat from the air (leading to ocean warming) but also to absorb some of the CO_2 in the atmosphere, causing more acidic (lower pH) oceans. Continued ocean acidification and warming have potentially detrimental consequences for marine life and dependent coastal communities in the Caribbean islands. Source: University of Puerto Rico.

Sea level rise. Since the middle of 20th century, relative sea levels have risen by about 0.08 inches (2 mm) per year on average along the coasts of Puerto Rico and the USVI.[37,38] However, rates have been slowly accelerating since the early 2000s and show noticeable acceleration (by a factor of about 3) starting in about 2010–2011. This recent accelerating trend is in agreement with what has been observed along the southeastern U.S. seaboard, and rates of global and regional relative sea level rise are projected to continue to increase substantially this century, largely dependent on the amount of future greenhouse gas emissions. Under the Intermediate-Low, Intermediate, and Extreme scenarios, relative sea levels are projected to rise by about 0.8 feet, 1.2 feet, or 2.8 feet (24 cm, 37 cm, or 84 cm), respectively, by 2050 across the region compared to levels in 2000 and by about 1.6 feet, 3.6 feet, or 10.2 feet (0.5 m, 1.1 m, or 3.1 m), respectively, by 2100 (Figure 20.6).[38] Additionally, the region may experience more than the global average increase under the higher scenarios in response to changes in the Earth's gravitational field and rotation due to melting of land ice, ocean circulation, and vertical land motion.

Observed and Projected Sea Level Rise

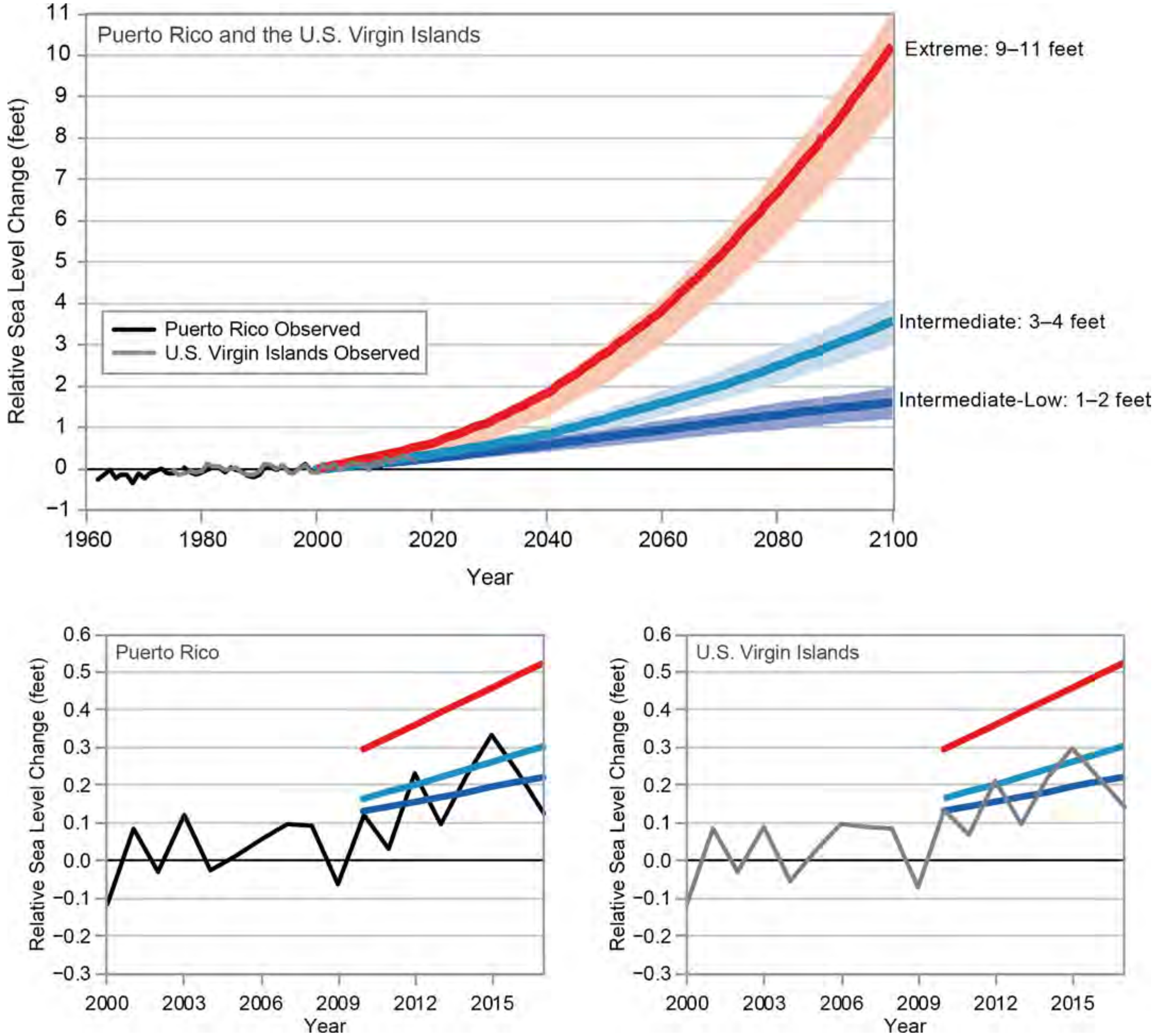


Figure 20.6: (top) Observed sea level rise trends in Puerto Rico and the U.S. Virgin Islands reflect an increase in sea level of about 0.08 inches (2.0 mm) per year for the period 1962–2017 for Puerto Rico and for 1975–2017 for the U.S. Virgin Islands. The bottom panels show a closer look at more recent trends from 2000 to 2017 that measure a rise in sea level of about 0.24 inches (6.0 mm) per year. Projections of sea level rise are shown under three different scenarios of Intermediate-Low (1–2 feet), Intermediate (3–4 feet), and Extreme (9–11 feet) sea level rise. The scenarios depict the range of future sea level rise based on factors such as global greenhouse gas emissions and the loss of glaciers and ice sheets. Sources: NOAA NCEI and CICS-NC.

Key Message 1

Freshwater

Freshwater is critical to life throughout the Caribbean. Increasing global carbon emissions are projected to reduce average rainfall in this region by the end of the century, constraining freshwater availability, while extreme rainfall events, which can increase freshwater flooding impacts, are expected to increase in intensity. Saltwater intrusionassociated with sea level rise will reduce the quantity and quality of freshwater in coastal aquifers. Increasing variability in rainfall events and increasing temperatures will likely alter the distribution of ecological life zones and exacerbate existing problems in water management, planning, and infrastructure capacity.

Linkage Between Climate Change and Regional Risks

Freshwater availability is a function of rainfall, temperature, evapotranspiration (evaporation and transpiration from plants), land cover, watershed characteristics, water use and management, and water quality, and is dependent on the intensity, duration, frequency, and distribution of rainfall within the island. Availability is also affected by seasonal and annual variability in rainfall as well as long-term climate trends. Climate change will likely result in water shortages (due to an overall decrease in annual rainfall), a reduction in ecosystem services, and increased risks for agriculture, human health, wildlife, and socioeconomic development in the U.S. Caribbean.

Rainfall in the U.S. Caribbean is highly variable across space and time, complicating analyses of trends.[39] However, past occurrences of drought or excessive rainfall provide insights into vulnerabilities that may be indicative of the future. Droughts and extreme rainfall events in recent years have resulted in economic loss and social disruption. The most recent drought of 2014–2016 in Puerto Rico and the USVI resulted in severe losses to the agriculture sector, implementation of water rationing by the Puerto Rico Aqueduct and Sewer Authority, drying of wetlands, and reduced habitat quality for freshwater biota, including threatened and endangered species such as the Antillean manatee.[40]

Freshwater resources are primarily surface waters. In the USVI, desalination plants provide some of the public water supply. In Puerto Rico, management and sustainable use of water resources and infrastructure have been problematic for decades, particularly in terms of storage, distribution, and quality of the public water supply.[41,42] In 2013, 57.4% of all water produced was lost in distribution.[42] Recurring droughts and sedimentation-induced reductions in reservoir storage present a challenge to freshwater availability.[43] One of the principal sources of potable water for Puerto Rico, Loíza reservoir, has lost nearly 40% of its original storage capacity due to sedimentation.[44,45]

Future Climate Change Relevant to Regional Risks

The greatest risk to freshwater resources may be reduced availability due to drying trends.[46] Large uncertainty remains in terms of projected rainfall intensity, duration, and frequency. However, hydrologic model simulations indicate that major reservoirs in Puerto Rico could enter permanent supply deficit as early as 2025 under a higher emissions scenario (SRES A2) (see the Scenario Products section of App. 3) and by 2040 under a lower emissions scenario (SRES B1; Figure 20.7).[46]

Projected Change in Annual Streamflow

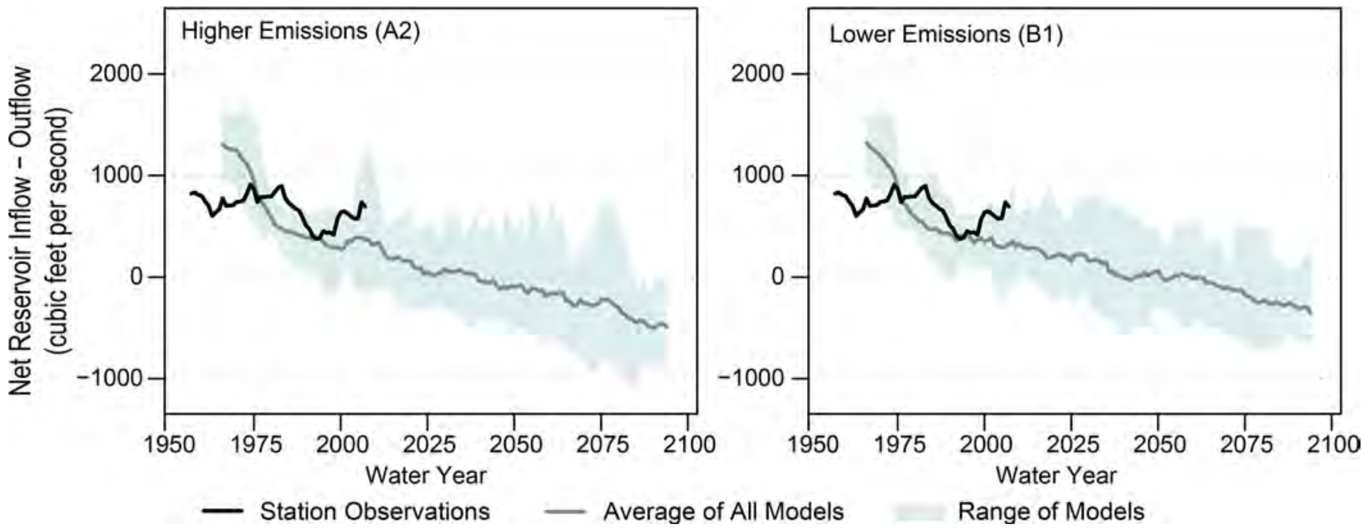


Figure 20.7: This figure shows ten-year moving averages of projected annual streamflow leaving Lago La Plata and Lago Loíza. Projections were developed using an estimation of water supply entering the reservoirs and an estimation of withdrawals. The former was developed using a range of global climate models (GCMs; shading indicates averages from all GCMs used in the study) and the mean of that range (gray line). The latter was developed using a conservative population growth rate. Annual streamflow is modeled under a higher emissions scenario (SRES A2; left panel) and a lower emissions scenario (SRES B1; right panel). The solid black line is the historical streamflow through 2012.[46] It is important to note these are the best estimates available for projected streamflow and use the older generation of GCMs, which project more drying for the region.[28] Source: adapted from Van Beusekom et al. 2016.[46]

Studies indicate that some locations within the Caribbean may experience longer dry seasons and shorter, but wetter, wet seasons in the future.[2,3,4,5,6,8] Extended dry seasons are projected to increase fire likelihood[9,10] and affect plant phenology (the timing of important biological events), as well as wildlife dependent on fruiting and flowering.[47] Excessive rainfall coupled with poor construction practices, unpaved roads, and steep slopes, which are typical of the Caribbean islands, can exacerbate erosion rates and reduce reservoir capacity, water quality, and nearshore habitat quality.

Rainfall also drives the distribution of ecological life zones in the U.S. Caribbean.[48] Projected decreases in rainfall foreshadow relative increases in dry life zones and the shrinkage and disappearance of wetter life zones. Ecological implications of these shifts include changes in biodiversity, carbon cycling, forest composition and structure, and nutrient and water cycling.[7] Vulnerable life zones include the unique rainforest habitats in the Luquillo Mountains of Puerto Rico (Figure 20.8).[8,49,50] Montane species are shifting their ranges upslope and may reach upper elevational limits as temperatures continue to climb.[51] Studies find that cloud levels in the dry season are consistently as low as, or lower than, in the wet season in the Luquillo Mountains, indicating that the cloud forest ecosystem may be more vulnerable to wet-season drought periods than previously assumed.[10]

Cloud Forests Are Vulnerable to Climate Change

Figure 20.8: Tropical montane cloud forests in the Luquillo Mountains of Puerto Rico are characterized by the frequent presence of clouds, reduced tree height, a high number of endemic and endangered species, and high water content of the soil due to reduced sunlight. Cloud forests around the world are vulnerable due to the warming and drying conditions that are expected with climate change.[52] Cloud forests on low mountains are especially vulnerable, as drying and warming conditions can increase the elevation at which clouds form, thereby reducing or possibly eliminating the cloud cover shrouding the mountain peaks.[53,54,55] Photo credit: Grizelle González, USDA Forest Service International Institute of Tropical Forestry.

Challenges, Opportunities, and Success Stories for Reducing Risk

Climate change projections provide new impetus to establish practices that reduce current risks to drought and excessive rain and, by inference, reduce future risks to new conditions. The United Nations Environment Programme has promoted rainwater harvesting in Caribbean Small Island Developing States (SIDS).[56,57] The Puerto Rico Technical Scientific Drought Committee also recommended the use of cisterns and other structural measures to capture rainwater in residential areas of the territory, encouraged their use on existing homes, and recommended making them mandatory for new projects.[40] These systems not only serve as sources for drinking water but also help in storm water management.[58,59,60] Citizens of the USVI are required by law to be directly responsible for their own domestic water supply. The majority of USVI's residents depend on cistern water and use the public source only when they run out of their cistern water.[57]

Application of new technologies is vital if losses from water supply distribution systems are to be reduced. Public freshwater supplies are jeopardized by reservoir sedimentation, which can also be harmful to downstream ecosystems as sedimentation rates are reduced downstream. Improving sediment management practices, such as those identified from prior experiences,[61] can help sustain reservoir capacities and minimize environmental impacts.

Emerging Issues

Managing freshwater and balancing water use among sectors are emerging as two of the most important issues to the U.S. Caribbean islands. Increasing agricultural production will improve food security and the economy but will be challenging, as water availability is likely to decrease over much of the Caribbean.[62] Options for improving water-use efficiency in the agricultural sector include optimizing the management of water infrastructure, applying scientific methods for scheduling irrigation, determining crop water requirements for local crops, using crop suitability modeling to evaluate potential responses to climate change and extreme weather scenarios, plant-breeding for extreme conditions, and implementing methods to improve soil fertility, reduce erosion, and increase carbon storage (Ch. 27: Hawai'i & Pacific Islands, KM 1).[62,63]

Key Message 2

Marine Resources

Marine ecological systems provide key ecosystem services such as commercial and recreational fisheries and coastal protection. These systems are threatened by changes in ocean surface temperature, ocean acidification, sea level rise, and changes in the frequency and intensity of storm events. Degradation of coral and other marine habitats can result in changes in the distribution of species that use these habitats and the loss of live coral cover, sponges, and other key species. These changes will likely disrupt valuable ecosystem services, producing subsequent effects on Caribbean island economies.

Linkage Between Climate Change and Regional Risks

Corals are a major component of the coastal protection, fisheries, and tourism economy of Caribbean islands. Key Message 3 discusses the importance of coastal systems to island economies and the potential effects of climate change on these economies. As in many tropical island systems, coral reefs anchor one end of the ridge-to-reef continuum—a concept that recognizes the linkage of social, ecological, terrestrial, and marine components associated with island systems (Ch. 27: Hawai'i & Pacific Islands). Recognizing that the coral reef ecosystem includes mangrove and seagrass habitats, this section briefly discusses the role these habitats play in fisheries and the potential impacts climate change is likely to have on this role.

Ocean warming poses significant threats to the survival of coral species and may also cause shifts in associated habitats that compose the coral reef ecosystem (Ch. 9: Oceans, KM 1 and 3).[35] The primary observable response to ocean warming is bleaching of adult coral colonies, wherein corals expel their symbiotic algae in response to stress. Severe, repeated, or prolonged periods of high temperatures leading to extended coral bleaching can result in colony death. Ocean warming can also harm hard corals that form coral reefs by decreasing successful sexual reproduction, causing abnormal development, impairing coral larvae's attempts to attach to and grow on hard substrate, and affecting hard corals' ability to create their calcium carbonate skeleton. Ocean warming also increases the susceptibility of corals to diseases and is expected to increase the impact of pathogens that cause disease.[64] In 2005, a mass bleaching event, driven by 12 weeks of temperatures above the normal local seasonal maximum, affected the entire Caribbean region, resulting in the loss of 40%–80% of the coral cover in the region.[65]

Ocean acidification associated with rises in carbon dioxide (CO_2) levels also is likely to diminish the structural integrity of coral habitats, affecting fisheries and other marine resources (Figure 20.9).[35] One study concluded that calcification rates have decreased by about 15% based on examination of different species of calcification in planktonic foraminifera.[66] Uncertainty remains about the magnitude of decreases in calcification on coral reefs and some crustaceans and mollusks (such as queen conch). However, a small decline in calcification rates has the potential to alter the growth–erosion balance of reefs if the erosion of the hard structure of reefs becomes more frequent.[67] Ocean acidification effects could be further exacerbated by local processes in coastal zones, such as land-based transport of nutrients to nearshore waters.

The compounded risk of climate change with human-caused stressors increases vulnerability and accelerates habitat loss and degradation.[68] Where fringing (nearshore) and barrier reef systems have eroded, mangroves and seagrass may also decline due to the loss of protection from wave action afforded by reefs. The potential decline in seagrass and mangrove habitats would be compounded by the effects of coastal and in-water development on these habitats and on coral reefs, resulting in overall declines in nursery habitat for important fishery species like spiny lobster, queen conch, snappers, and groupers. The impacts of climate change, in general, on seagrass in the Caribbean is uncertain, but some studies suggest that photosynthesis could be inhibited at high temperatures.[69] Sea level rise may lead to a reduction in the area occupied by seagrass if waters become too deep for the plants to obtain enough light to photosynthesize. Sea level rise is also projected to result in a loss of mangrove habitat if low-lying coastal areas are not present or have already been developed on islands such that mangroves cannot colonize these areas as coastal waters get deeper.[70] Additionally, increases in the magnitude and frequency of storms result in impacts caused not only by waves and surge but also by increased rainfall and the associated transport of sediment and other land-based pollutants into nearshore waters. Mangrove and seagrass habitats filter storm water runoff, but large volumes of sediment transported downstream can overwhelm these systems, leading to burial of seagrass beds and partial burial of mangrove roots, thus affecting the ability of these habitats to reduce pollutant transport to coral reefs.

Caribbean reefs have experienced declines in important fishery species—such as the Caribbean spiny lobster and queen conch; predatory species, such as snappers and groupers; and important herbivores, like parrotfish—due to overexploitation.[71,72] Overexploitation is demonstrated by the exceedance of commercial annual catch limits (established by the Caribbean Fishery Management Council to protect depleted stocks) in 2013 in Puerto Rico and the USVI and in 2014 in Puerto Rico, leading to the establishment of additional regulatory measures.[73] In terms of annual economies, commercial fishing of reef fish provides an average of $9 million to Puerto Rico, $2.4 million to St. Thomas and St. John, and $3 million to St. Croix (in 2014 dollars).[73]

Studies show that major shifts in fisheries distribution, coupled with structural and compositional changes in marine habitats such as coral reefs due to climate change, adversely affect food security, shoreline protection, and economies throughout the Caribbean.[5,69,74,75,76] In the U.S. Caribbean region, where fishery resources are shared with other Caribbean islands, competition for fisheries resources are likely to increase as stock distribution changes due to climate change (Ch. 16: International, KM 4). Figure 20.10 shows the connections between climate change, marine habitats and species, and human communities. In the case of Puerto Rico, the coral reef ecosystems off the east coast of the main island (Fajardo area) and the islands of Culebra and Vieques were estimated as generating $192 million per year for recreation and tourism and $1 million in coastal protection services annually (in 2007 dollars, or $217 million and $1 million in 2015 dollars, respectively).[68] For the territory of USVI, reef-related tourism was estimated as generating $96 million per year, and coastal protection was estimated as providing $6 million annually to the local economy (in 2007 dollars, or $108 million and $7 million in 2015 dollars, respectively).[68]`

Climate Change Effects on Coral Reefs

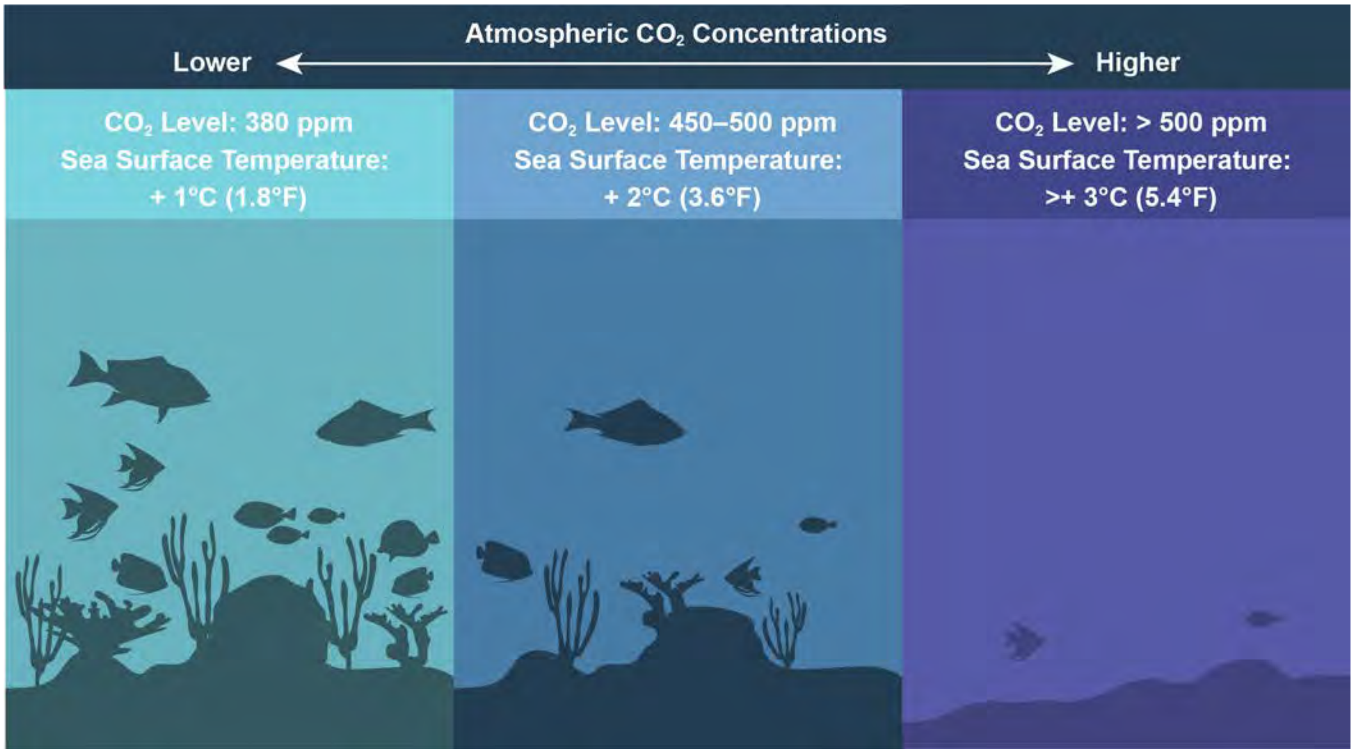


Figure 20.9: The diagram demonstrates how coral reef ecosystems in the U.S. Caribbean are likely to change in potentially warmer and more acidic waters caused by climate change, including elevated sea surface temperatures and elevated carbon dioxide (CO_2) levels. The severity of these impacts increases as CO_2 levels and sea surface temperatures rise. If conditions stabilized with concentrations of atmospheric CO_2 at 380 ppm (parts per million), coral would continue to be carbonate accreting, meaning reefs would still form and have corals. At 450–500 ppm, reef erosion could exceed calcification, meaning that reef structure is likely to erode and coral cover is likely to decline dramatically. Beyond 500 ppm, corals are not expected to survive.[77] Sources: NOAA and USFS.

Climate Change Impacts on Coral Reef Ecosystems and Societal Implications

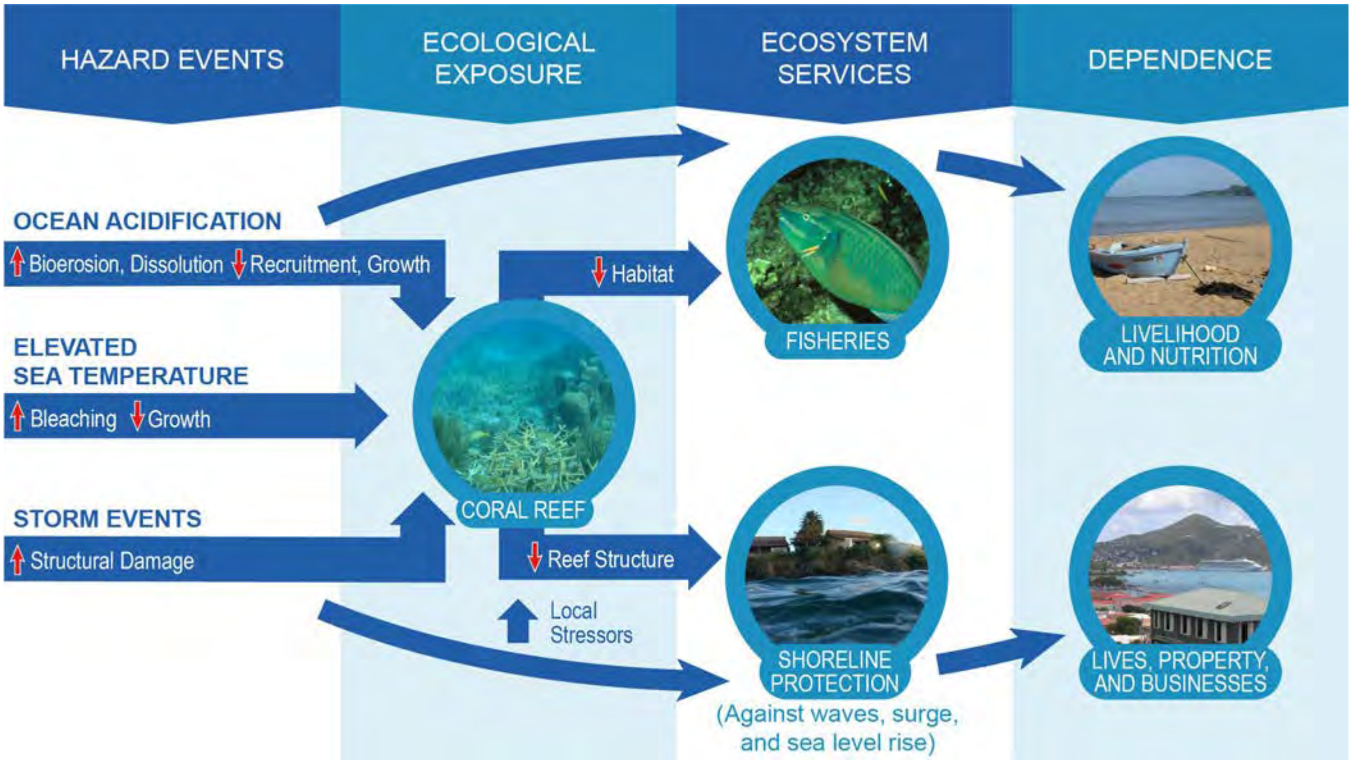


Figure 20.10: The figure shows the connections between climate-related impacts (ocean acidification and warming as well as severe storms), responses of marine habitats and species to these impacts, and, ultimately, the effects to ecosystem services (such as fisheries and shoreline protection) and, in turn, the human community. Specifically, the figure depicts how degradation of coral reefs due to climate change is expected to affect fisheries and the economies that depend on them as habitat is lost. The figure also shows how reef degradation decreases shoreline protection for local communities, which affects the economy and human populations more generally. Source: adapted from Pendleton et al. 2016.[78] Photo credits: NOAA.

Future Climate Change Relevant to Regional Risks

With high levels of greenhouse gas emissions (in other words, business as usual), mass coral bleaching in the Caribbean may occur at least twice a year within the next decade.[79] The increasing frequency of extreme heat events is highly likely to preclude reef recovery, considering that the region's reefs have yet to fully recover from the 2005 event. Moreover, the increase in average temperature will make corals more susceptible to extreme heat events and to coral disease, further contributing to declines in live coral cover in marine habitats.[64] One study suggests that coral reefs in Puerto Rico are expected to pass a critical ecosystem threshold in the first several decades of the century with coral cover loss of 95% by 2090 under a higher scenario (RCP8.5).[80]

Sea level rise is another climate-related stressor in the Caribbean. The rate of sea level rise in the region is expected to follow or exceed global projections. Sea level rise will likely have effects not only on marine communities by diminishing the amount of sunlight they receive but also on low-lying cays, which provide important habitat for seabirds and sea turtles. Coastlines on the larger islands and mainlands of the U.S. Caribbean will be submerged or greatly reduced in extent as sea levels rise. Coastal mangroves, squeezed between rising seas and coastal development, may be reduced in extent, diminishing the natural protection they provide against the action of waves and storm surge and limiting their role as wildlife habitat. Sea level rise is also expected to lead to a loss of seagrass if waters become too deep for them to photosynthesize. Photosynthesis will also be inhibited as sea surface temperatures continue to rise, which is likely to affect both seagrass and mangroves in addition to corals, as noted above.

The combined stress of sea level rise, increases in sea surface temperatures, and ocean acidification, along with increases in the severity and frequency of storms and associated transport of land-based pollutants into coastal and marine habitats, will likely lead to loss and degradation of these habitats. Future climate change effects on marine habitats will likely impact island economies due to changes in the availability of key fishery species such as queen conch, Caribbean spiny lobster, and species in the snapper and grouper complexes; declines in natural shoreline protection and associated impacts to coastal infrastructure and communities, as well as wildlife habitat; and loss of tourism associated with habitats such as coral reefs. Fisheries productivity is projected to decline while catch-per-unit effort increases as fishers travel longer distances and spend more time on the water.[75] Potential losses of up to 90% of the coral reef recreation value in Puerto Rico are projected under most scenarios considered by the end of the century, due to the expected loss of coral reef habitat associated with climate change impacts.[80]

Challenges, Opportunities, and Success Stories for Reducing Risk

Climate change directly influences marine species' physiology, behavior, growth, reproductive capacity, mortality, and distribution, while indirectly influencing marine ecosystem productivity, structure, and composition.[74] As a result, fishery resources and essential habitats for commercially, recreationally, and ecologically important species are likely to be less resilient.

Several strategies meant to increase ecosystem resilience to local stressors (such as declines in water quality, overexploitation of fisheries, recreational use, and coastal and marine development) are being implemented in the Caribbean to lessen the potential impacts of climate change on marine resources. One such strategy is the establishment of protected areas in coastal and marine areas. Management of these areas may include limiting or prohibiting extractive uses, implementing conservation and restoration of coastal and marine habitats, and designating usage zones to minimize the impacts of recreational use on ecosystems. Another strategy is watershed planning to minimize the transport of land-based pollutants to nearshore waters, thus protecting marine habitats from declines in water quality caused by influxes of sediment, nutrients, and other contaminants. The NOAA Coral Reef Conservation Program, in partnership with federal and local agencies and local nongovernmental organizations, has sponsored the development and implementation of several watershed management plans in Puerto Rico and the USVI.[81]

Building the resilience of marine organisms, such as corals, is another strategy aimed at lessening the potential impacts of climate change on the marine ecosystem. Coral population enhancement through propagation (or coral farming) is a strategy meant to improve the reef community and ecosystem function, including for fish species that use this ecosystem (Figure 20.11). The selection and propagation of fragments and samples from coral colonies that have survived stressors such as bleaching events are emphasized as part of these efforts in an attempt to accelerate the otherwise uncertain recovery of these species.[82] This strategy has been used in the U.S. Caribbean and South Florida to recover species such as elkhorn and staghorn corals and species from the star coral complex—all of which are listed as threatened under the Endangered Species Act—without negatively affecting native populations of corals.

Coral Farming Can Increase the Extent and Diversity of Coral Reefs

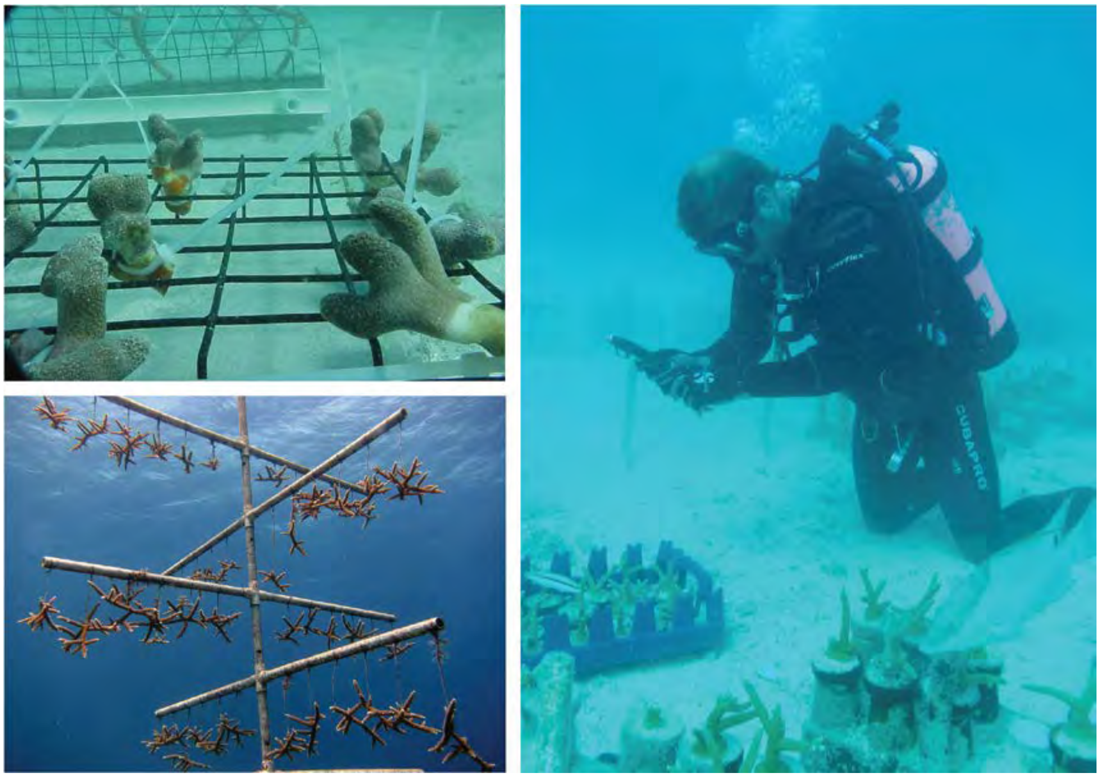


Figure 20.11: Examples of coral farming in the U.S. Caribbean and Florida demonstrate different types of structures used for growing fragments from branching corals. Coral farming is a strategy meant to improve the reef community and ecosystem function, including for fish species. The U.S Caribbean Islands, Florida, Hawai'i, and the U.S.-Affiliated Pacific Islands face similar threats from coral bleaching and mortality due to warming ocean surface waters and ocean acidification. Degradation of coral reefs is expected to negatively affect fisheries and the economies that depend on them as habitat is lost in both regions. While coral farming may provide some targeted recovery, current knowledge and efforts are not nearly advanced enough to compensate for projected losses from bleaching and acidification. Photo credits: (top left) Carlos Pacheco, USFWS; (bottom left) NOAA; (right) Florida Fish and Wildlife (CC BY-ND 2.0).

Emerging Issues

Integrating international monitoring networks of marine species and environmental conditions is critical to understanding the status and trends of wide-ranging marine resources. Areas like the Caribbean and the Pacific (Ch. 27: Hawai'i & Pacific Islands), where marine resources are key to socioeconomic well-being, benefit from monitoring programs that assess threats to reef health, ecosystem services, and reef-dependent communities. Research into the linkages between climate change and marine ecosystems is critical to enhancing the ability to predict future ecosystem responses to climate change and the associated socioeconomic consequences, as well as finding ways to mitigate those consequences.

Key Message 3

Coastal Systems

Coasts are a central feature of Caribbean island communities. Coastal zones dominate island economies and are home to critical infrastructure, public and private property, cultural heritage, and natural ecological systems. Sea level rise, combined with stronger wave action and higher storm surges, will worsen coastal flooding and increase coastal erosion, likely leading to diminished beach area, loss of storm surge barriers, decreased tourism, and negative effects on livelihoods and well-being. Adaptive planning and nature-based strategies, combined with active community participation and traditional knowledge, are beginning to be deployed to reduce the risks of a changing climate.

Linkage Between Climate Change and Regional Risks

A high concentration of population and critical infrastructure in low-lying coastal areas increases vulnerability to sea level rise and storm surge and magnifies the effects of coastal flooding and beach erosion. For example, most of the population in Puerto Rico (62%, or more than 2.2 million) lives in the 44 coastal municipalities, where a total of 1,019,300 housing units are also located.[83,84] It is also estimated that 401,145 people (11.5% of Puerto Rico's total population) live in areas subject to inundation, and 56,114 people live in areas susceptible to storm surge, also known as the coastal high hazard areas.[83] As sea level rises, storm surge and high energy wave action may cause shorelines to recede inland.[85] Approximately 60% of 3,808 beach transects studied along the coasts of Puerto Rico (799 miles) experienced erosion from the 1970s to 2010. Of those transects, 5% suffered very high erosion, with a beach loss of 3.97 feet to 6.56 feet per year.[86] Major loss of sand was identified in various municipalities of the north coast, including San Juan—the capital city and a center of economic activity, ports, and tourism—as well as Loíza and Dorado, which are cultural and tourist destinations. (For more information on effects from extremes and disaster events, see Key Message 5.)

The response of coastal systems to sea level rise is dependent on local natural and human factors.[87] Natural ecological systems can protect coastlines from erosion but can also be affected by sea level rise and other environmental changes. Coral reefs, mangroves, and sand dunes buffer coastlines from erosion and inundation, providing protective services. They reduce risk to people and infrastructure from wave damage and flooding. The coral reef–mangrove systems can reduce risk and provide fishery services if space is available for landward mangrove migration; however, this process can be hampered by coastal development. Beaches and coastal dunes provide wave energy dissipation and coastal asset protection yet are highly susceptible to wave action and erosion.

The U.S. Caribbean Economy

The U.S. Caribbean territories of Puerto Rico and the U.S. Virgin Islands have distinct differences in topography, language, population size, governance, natural and human resources, and economic capacity. However, both are highly dependent on natural and built coastal assets. Service-related industries account for more than 60% of the USVI's economy and cater to more than 570,000 tourists, as well as an additional 2.1 million cruise ship passengers who arrive to the island each year.[88] In 2013 in the USVI, tourists and cruise ship passengers spent $851 million and $381 million, respectively (in 2013 dollars; $877 and $392 million, respectively, in 2015 dollars). Approximately 3.7 million people visited Puerto Rico in 2016 as tourists, and an additional 1.3 million people arrived via cruise ships. Tourist and cruise ship passenger expenditures amounted to $3.8 billion and $202 million, respectively (in 2016 dollars; $3.8 billion and $200 million, respectively, in 2015 dollars).[89]

Beaches, affected by sea level rise and erosion, are among the main tourist attractions; consequently, these revenues from tourism are at risk due to limitations of access and deterioration to the coastal landscape. In addition, residents' recreational activities will likely be disrupted, as about 63% of Puerto Rican residents enjoy recreational activities such as swimming, bathing, or sunbathing on the beach.[90]

Operations of Puerto Rico's ports, the Luis Muñoz Marín (LMM) international airport, and the city of San Juan are currently at risk from extreme weather and climate-related events and will likely be even more vulnerable under projected sea level rise scenarios (Figure 20.12). In 2016, 93% of all passengers entering Puerto Rico through airports did so through the LMM airport.[91] The U.S. Caribbean's economy is also tied to climate impacts on Florida ports, as raw material for industries, food, clothes, and essential goods are shipped from Jacksonville, Florida, to the San Juan port and Isla Verde airport. As such, Florida's infrastructure vulnerability also affects the U.S. Caribbean.

Critical Infrastructure at Risk, San Juan Metro Area

Figure 20.12: Puerto Rico's Luis Muñoz Marín (LMM) international airport is already at risk from extreme weather and climate-related events and is expected to become more vulnerable in the future as a result of continuing sea level rise. Photo credit: Ernesto Díaz, Puerto Rico Department of Natural and Environmental Resources.

Cultural Heritage

Cultural and historic sites in the U.S. Caribbean region are threatened by sea level rise and storm surge. In the USVI, two significant early prehistoric sites, the Aklis and Great Pond archaeological sites, are directly threatened by sea level rise.[92] In Puerto Rico, effects on cultural heritage resources at risk due to climate change include impaired access to coastal resources like fishing, degraded ecotourism attractions, and loss of public access to beaches.[93] One of Puerto Rico's most notable cultural sites, the San Juan National Historic Site (El Morro), faces challenges from climate change, including sea level rise and coastal erosion.[94]

Critical Infrastructure, Property, and Real Estate

Sea level rise will likely increase threats to private, commercial, and residential property, as well as associated service infrastructure. Over 8,000 structures in Puerto Rico's low-lying areas would be affected by an increase in sea level of 1.6 feet (0.5 m). A sea level increase of 6.5 feet (2 m) would affect more than 50,000 structures located along the coast, causing approximately $11.8 billion in losses (in 2017 dollars).[83]

Critical infrastructure in the region is vulnerable to the effects of sea level rise, storm surge, and flooding. As an example, if sea levels rise 6.5 feet (2 m), which could occur during this century under the Intermediate-High to Extreme scenarios,[38,95] Puerto Rico and the USVI are projected to lose 3.6% and 4.6% of total coastal land area, respectively. Were such a rise to take place, Puerto Rico's critical infrastructure near the coast would be negatively impacted, including drinking water pipelines and pump stations, sanitary pipelines and pump stations, one wastewater treatment plant, and six power plants and associated substations.[96] In the USVI, infrastructure and historical buildings in the inundation zone for sea level rise include the power plants on both St. Thomas and St. Croix; schools; housing communities; the towns of Charlotte Amalie, Christiansted, and Frederiksted; and pipelines for water and sewage.

Challenges, Opportunities, and Success Stories for Reducing Risk

In Puerto Rico, the Department of Natural and Environmental Resources (DNER) commissioned the development of five climate change community-based adaptation plans for selected coastal municipalities.[97] Through an active community participation process, which included surveys and participatory mapping, these plans evaluated the risks and vulnerabilities posed by climate change and developed recommendations and adaptation strategies that will serve as guidance for municipal governments, communities, and local businesses (Figure 20.13).[97]

The USVI has released a guidance document to promote resilient coastal and marine communities through Ecosystem-based Adaptation (EbA). EbA reduces risk through the protection and restoration of natural areas like mangroves, dunes, and wetlands. High-risk areas were identified through analysis of social vulnerability, risk exposure, and adaptive capacity. Eleven areas throughout the USVI were selected as optimal to implement EbA options, as they faced high-risk exposure, high sensitivity, and low adaptive capacity. When considering climate effects and adaptation in the Caribbean, traditional knowledge from those members of the community maintaining the most intimate relationships with the land and natural systems is key to the early stages of the planning process. Traditional fishing, subsistence agriculture, and plant harvesting practices may provide a better understanding of how Caribbean Indigenous knowledge systems have sustained generations in the past and can benefit future generations.[98]

Assessing Vulnerability with Communities

Figure 20.13: Culebra's Mayor and community members worked on the participatory maps to identify risks, important natural resources, infrastructure, and important services to the community in Culebra. This exercise allowed them to gather information about issues in the territory that are important to the community but not commonly reflected in maps. Photo credit: Vanessa Marrero, Puerto Rico Department of Natural and Environmental Resources.

Natural and nature-based shoreline responses are used as stabilization techniques against erosion and can provide habitat for coastal species. Wetlands, dunes, and mangroves experience less damage from severe storms and are more resilient than hardened shorelines, and they also provide multiple benefits such as habitat for fish and other living organisms, as well as support recreational and commercial activities.[88] Mangroves alone can help reduce wave energy, erosion, and damage caused by large storms.[99] The U.S. Fish and Wildlife Service and the Puerto Rico DNER have funded wetland and dune restoration projects at various sites along the coast of Puerto Rico as nonstructural solutions to reduce coastal flooding and beach erosion.

Emerging Issues

Adaptive planning and nature-based strategies are gaining increased attention in Puerto Rico, as they are more accessible to coastal communities and can be cost effective. Also, stabilization and excavation of vulnerable cultural sites throughout the USVI can serve to protect or salvage cultural resources from the effects of climate change.[92]

Key Message 4

Rising Temperatures

Natural and social systems adapt to the temperatures under which they evolve and operate. Changes to average and extreme temperatures have direct and indirect effects on organisms and strong interactions with hydrological cycles, resulting in a variety of impacts. Continued increases in average temperatures will likely lead to decreases in agricultural productivity, changes in habitats and wildlife distributions, and risks to human health, especially in vulnerable populations. As maximum and minimum temperatures increase, there are likely to be fewer cool nights and more frequent hot days, which will likely affect the quality of life in the U.S. Caribbean.

Linkage Between Climate Change and Regional Risks

Records from weather stations in Puerto Rico indicate that the annual number of days with temperatures above 90°F has increased over the last four and a half decades (Figure 20.14). A number of extreme temperature events occurred in Puerto Rico during the summers of 2012–2014, when most days exceeded 90°F. This period included the hottest months on record and the longest continuous period of days over 90°F.[11] Higher temperatures drive increased energy demand to cool buildings and indoor environments. San Juan's record heat episode in 2012 drove record-level energy consumption. During that time, stroke and cardiovascular disease were the primary causes of death due, in part, to the elevated summer temperatures in the municipalities of San Juan and Bayamón (Ch. 14: Human Health, KM 1).[11,12]

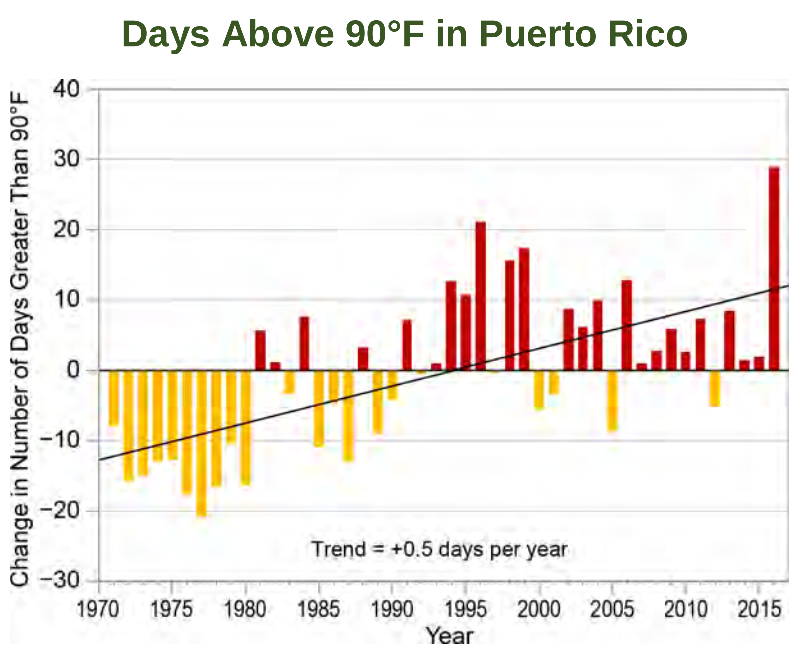


Figure 20.14: This figure illustrates the deviation from the long-term (1970–2016) average annual number of days exceeding 90°F, based on data from eight climate stations in Puerto Rico. Source: University of Puerto Rico.

Heat stress can exacerbate preexisting health conditions and lead to an increase in human mortality.[100,101] Time of year, repetition, duration, time between events, and adaptation of individuals are important determinants of the health outcomes during extreme heat episodes. Vulnerability to heat is a function of exposure and personal sensitivity, which depends on an array of individual factors and may influence the ability to cope with extreme temperatures.[102]

Urban areas are particularly vulnerable to extreme heat events, given the concentration of built structures, traffic, and other factors that drive the urban heat island (UHI) effect.[103,104] Since the middle of the last century, urbanization and population growth have increased the UHI effects in San Juan. Such effects are becoming even more life threatening with a growing and more vulnerable aging population. Heat vulnerability index maps show that the hottest and most vulnerable areas correspond to highly built areas, including within and around the LMM Airport, seaports, parking lots, and high-density residential areas, while cooler areas correspond to vegetated landscapes and urban bodies of water (such as lagoons and wetlands).[102]

The role of agriculture in Puerto Rico and the USVI is both economic and cultural. The economic role of agriculture has diminished in recent decades compared to the mid-20th century. Currently, less than 1% of Puerto Rico's gross domestic product (GDP) and approximately 1% of the USVI's GDP is due to agriculture.[13,89] Recent revitalizations in agricultural productivity are vulnerable to climate change. At risk are food security, rural livelihoods, and agroecological services. Increases in average temperature and extreme heat events will likely have detrimental effects on agricultural operations throughout the U.S. Caribbean region.[13,14] Climate change affects cattle ranchers and dairy farmers in the U.S. Caribbean by reducing productivity of rangeland, causing a shortage of nutritional feed, increasing heat stress on animals, and increasing energy costs for cooling.[105] High temperatures and resultant heat stress reduce animal productivity and increase the proliferation and survival of parasites and disease pathogens. Warming reduces the ability of dairy cattle to produce milk and gain weight and can lower conception rates.[105]

Tropical cropping systems are often more vulnerable to climatic shifts and anomalies for a number of reasons. Many farmers throughout the tropics, including in the U.S. Caribbean, are considered small-holding, limited resource farmers.[1,15] This terminology refers to farmers who own small parcels of land (fewer than 2–5 acres) and often lack the resources and/or capital to adapt to changing conditions.[15] Many important tropical crop species, such as coffee, evolved within relatively narrow temperature bands and are more sensitive to variation in rainfall and temperature than are crop species native to temperate regions.[24]

Finally, rising temperatures will generally increase regional sea surface temperatures, which tends to increase the maximum intensity that hurricanes in the region can achieve.[33] This can lead to stronger hurricanes and more active hurricane seasons in general, which the Caribbean region is especially vulnerable to, as evidenced by the 2017 hurricane season (see Box 20.1).

Future Climate Change Relevant to Regional Risks

Cooling degree days (CDDs), used as a proxy for future air conditioning energy demands, are projected to increase over time and to more than double in Puerto Rico by the end of century (Ch. 4: Energy, KM 1).[7] The warmer south coast is projected to have the highest increase in CDDs in the first half of the century, while the San Juan metropolitan area is projected to have its highest increases in the second half of the century, suggesting higher energy demands in the island's largest metropolitan area by the end of the century.[7]

Warming, along with drying, is projected to affect the terrestrial ecosystems in the region. The ecological life zones of Puerto Rico are projected to shift from rain and wet zones to moist and dry zones based on the projected drying. By the middle of this century, under most scenarios considered, all life zones in Puerto Rico are projected to shift to tropical zones.[7] Environmental suitability for species in the region would be altered by life zone shifts, which may lead to biodiversity redistribution in the region. Environmental factors, especially climatic variables, were shown to have higher importance than land-use history on forest species composition in Puerto Rico and the USVI.[106] The projected changes in the amount and spatial variability of climatic variables will likely affect the composition and spatial redistribution of species.

Climate change adaptation strategies and national (as well as international) discussions and agreements have focused more on direct socioeconomic implications and less on changes in natural ecosystems; nonetheless, climate-induced species redistribution affects ecosystem functioning, human well-being, and the dynamics of the climate change itself and represents a substantial challenge for human society.[107] Species respond to changes in environmental conditions by tolerating the changes, adapting to the new conditions, facing extinction, or moving, which changes their distributions.[108] Warming forces species to move toward higher latitudes and altitudes.[109] On small islands in the Caribbean with limited latitudinal ranges, species' adaptive movement is limited to tracking changing temperatures toward higher altitudes.

Challenges, Opportunities, and Success Stories for Reducing Risk

Green and blue infrastructure are, respectively, the natural terrestrial vegetation and water-related components of an urban or other landscape. They provide many beneficial ecosystem services for surrounding microclimates.[102,110,111] Urban planning efforts in coastal cities are placing greater emphasis on the use of green infrastructure and water bodies for cooling urban environments. Planners in low-lying cities are also incorporating adaptable spaces that can accommodate occasional flood waters while providing services such as parks or urban open space[112] that can also help mitigate the UHI effect. In agriculture, the rapid expansion of electronic and worldwide communications is bringing old and new adaptation practices to a new generation of practitioners as they deal with multigenerational problems of water management and heat stress in crops and livestock.[13]

Emerging Issues

Cumulative effects on urban populations, agricultural sectors, and the natural environment add complexity to developing scenarios and prioritizing actions to reduce risks related to climate change. New alliances, collaborations, and governmental structures may be necessary to address these complex challenges.

Key Message 5

Disaster Risk Response to Extreme Events

Extreme events pose significant risks to life, property, and economy in the Caribbean, and some extreme events, such as flooding and droughts, are projected to increase in frequency and intensity. Increasing hurricane intensity and associated rainfall rates will likely affect human health and well-being, economic development, conservation, and agricultural productivity. Increased resilience will depend on collaboration and integrated planning, preparation, and responses across the region.

The Caribbean is highly vulnerable to disaster-related risks.[113] The U.S. Caribbean region experiences hurricanes, extreme rainfall, and droughts. The most extreme of these events have caused significant disruptions in Caribbean island livelihoods, including casualties and substantial economic losses. Current demographic and economic characteristics of Puerto Rico and the USVI—and their innate vulnerabilities as islands—result in greater sensitivity to these events, therefore imposing greater burdens in terms of response and recovery compared to many places in the continental United States.

Tropical cyclones (hurricanes and tropical storms), floods, and droughts are the most frequent and damaging extreme events in Puerto Rico. More than 50 extreme events related to floods, droughts, tropical storms, and winter swells have been declared emergencies and disasters since the mid-1990s.[114] Disaster declarations have occurred on a yearly basis since 2001.

Over the years, extreme events have caused billions of dollars in property and crop damages in Puerto Rico and the USVI. Tropical cyclones cause the most severe disruption and economic damage. In 2017, damages caused by Hurricanes Irma and Maria prompted a humanitarian crisis in the U.S. Caribbean by causing the collapse of the region's main energy, water, transport, and communication infrastructures (see Box 20.1). The estimated damages for Hurricane Maria alone totaled between $27 and $48 billion for the Caribbean region, with Puerto Rico estimates ranging from $25 to $43 billion (in 2017 dollars).[115] Total casualties caused by these hurricanes have proven difficult to establish. In Puerto Rico, estimates range from 64 to more than 1,000 deaths, although the evidence base is still evolving in this area.

Box 20.1: 2017 Atlantic Hurricane Season Impacts

The 2017 Atlantic hurricane season had devastating impacts across the Caribbean region (Figure 20.15) and reemphasized the exposure and vulnerabilities of the Small Island Developing States (SIDS) in the region.[116] During the unusually active 2017 hurricane season, there were 17 named storms (wind speeds of 39 mph or higher), 9 of which impacted one or more Caribbean SIDS. Twenty-two of the 29 Caribbean SIDS (including islands that are United Nation members and non-U.N. Associate Members of Regional Commissions) were impacted by at least one named storm, and a large number of SIDS experienced catastrophic impacts from major hurricanes (wind speeds of 111 mph or more). Five SIDS were impacted by three storms, 13 by two storms, and 4 by one storm. Eleven SIDS experienced tropical storm force winds (39 mph or higher wind speeds), 11 experienced hurricane force winds (74 mph or higher wind speeds), and 9 experienced direct landfall of a major hurricane.[116]

Of the 29 SIDS, only 7 were not significantly affected by the 2017 storms: Guyana, Jamaica, Suriname, Aruba, Bermuda, Cayman Islands, and Curaçao. Antigua and Barbuda, Cuba, Dominica, Saint Kitts and Nevis, Anguilla, British and U.S. Virgin Islands, Guadeloupe, Puerto Rico, Saint Maarten, and Turks and Caicos were all affected by Saffir-Simpson Category 4 and 5 hurricanes (winds of 130 mph or higher). The impacts and costs, in terms of lives and property damage, during the 2017 Atlantic hurricane season are still being calculated. In this age of satellite technology, hurricane warnings are generally timely, and mortality rates during local hurricane passage have been minimized, but post-event mortality numbers can grow quickly due to lack of electrical power, potable water, food, and access to adequate healthcare, among other factors (Ch. 14: Human Health, KM 1 and 2).[116,117] The death toll in Puerto Rico, for example, has been estimated to have grown by a factor of about 1700% in the three months following Maria's landfall on the island,[116] due in part to the lack of electricity and potable water, as well as access to medical facilities and medical care.

The health impacts across the Caribbean SIDS span a large range, including physical injury from wind and water during hurricane passage and during post-event rescue and cleanup efforts, heat-related injury due to loss of access to air conditioning and fans, inability to manage chronic disease due to loss of access to electrical power or medical services, and increased exposure to vector-borne diseases and diseases from contaminated water. Mental health impacts are also notable, as most survivors experience a high degree of psychological trauma during and after hurricane events (Ch. 14: Human Health, KM 1).[116]

Critical infrastructure in the region suffered catastrophic damages as a consequence of Hurricanes Irma and Maria. These hurricanes caused the complete failure of Puerto Rico's power grid[118] and the loss of power throughout the USVI. Telecommunication infrastructure suffered major damages in the aftermath of the 2017 hurricanes, severely disrupting the communication capabilities of both Puerto Rico and the USVI.[119] Over 70% of potable water infrastructure was also severely affected in Puerto Rico due to Hurricane Maria's impacts, primarily from direct damages to infrastructure and loss of electricity.[118]

Hurricanes Irma and Maria caused catastrophic damage to crops and infrastructure across farms in Puerto Rico and the USVI. In Puerto Rico, losses surpassed $2 billion in crops alone (in 2018 dollars), with damages to infrastructure adding much more to the total.[120] In the USVI, farms, ranches, and infrastructure, including government agriculture offices, experienced sizable damages; however, there are no official estimates of the economic value of the losses caused by the storms.

Box 20.1: 2017 Atlantic Hurricane Season Impacts, *continued*

Hurricane Maria caused severe damage to the milk and poultry industries in Puerto Rico. Over $4 million (in 2018 dollars) was lost in the poultry industry due to chicken mortality during the storm or conditions afterward (lack of water, shelter, or feed).[120] Similarly, many in the milk industry lost barns, food for cows, or power, leading to an inability to sustain operations.[121] Further, due to a lack of electricity, many residents were reluctant to purchase fresh chicken or milk, which affected the markets. Hundreds of thousands of residents are estimated to have left the islands in the aftermath of Hurricane Maria,[122] which is likely to affect the long-term demand for agricultural products.

Based on information in NOAA's ResponseLink, in the USVI, 479 vessels were displaced, and almost 4,000 orphaned containers, propane cylinders, marine batteries, and other waste from these vessels had to be removed from coastal waters after the hurricanes. In Puerto Rico, 376 vessels were displaced, and approximately 27,000 gallons of waste oil had to be recovered from these vessels and coastal waters after the hurricanes. Coral reefs and other marine habitats suffered impacts from transport of these vessels and associated debris into these habitats, as well as from debris transported in rivers and streams into nearshore waters. Hurricanes Irma and Maria also caused impacts to corals and other marine habitats due to bottom swells and wave action. Coral farms being used to grow Endangered Species Act–listed corals as part of reef restoration efforts were largely lost from sites around Puerto Rico and St. Croix, where they had been in place for years.

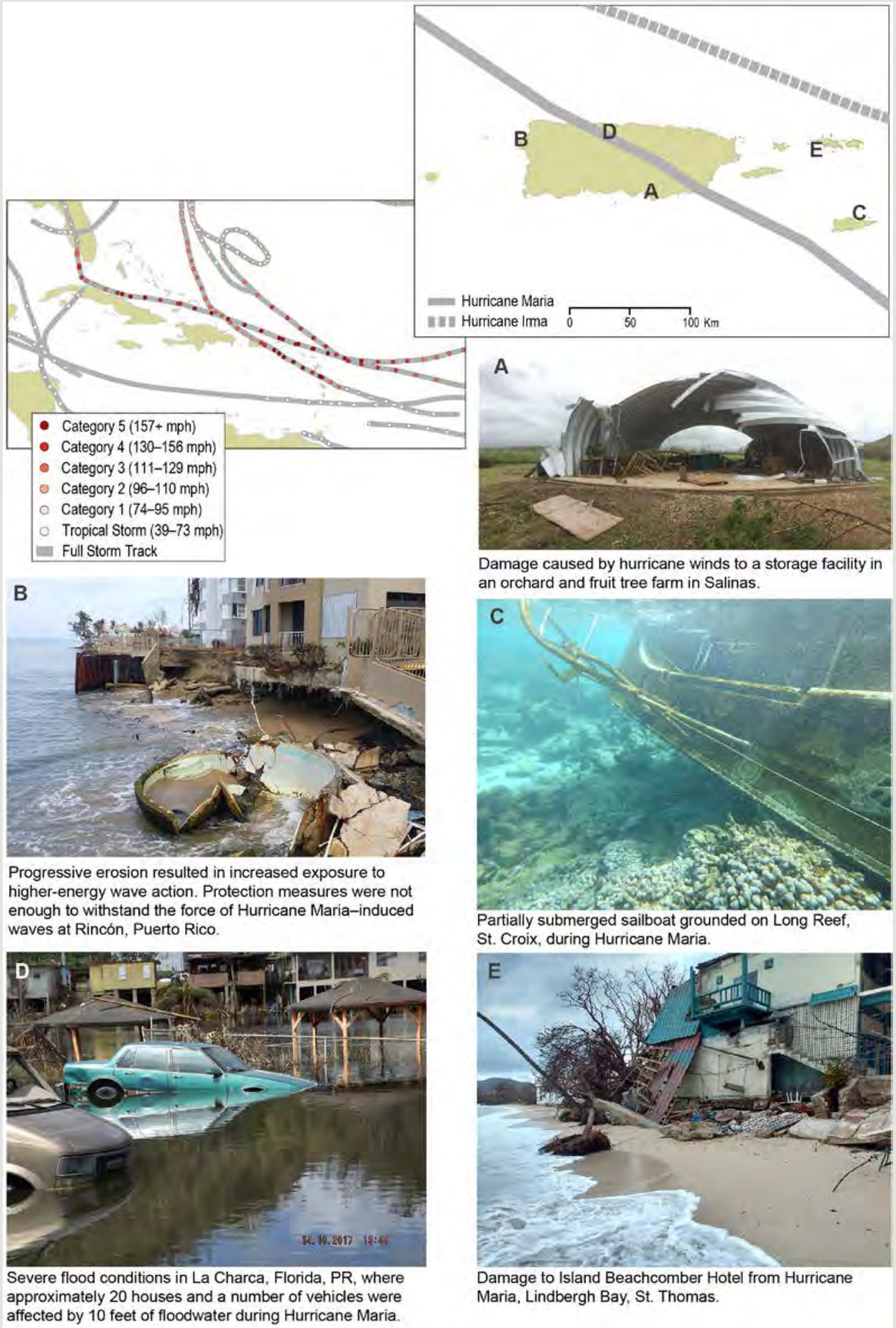
NOAA and its local and federal partners have been working on rapid assessments around the islands to determine the extent of damage to marine habitats in order to focus on habitat restoration and recovery efforts. Surveys in Puerto Rico from October to December 2017 looked at 30 high-value reef sites, of which 20 were identified as having moderate to major impacts needing emergency restoration. Damages included large coral heads being overturned or tossed into sand areas where they cannot grow successfully, extensive burial and breakage of corals from waves and storm surge, and physical impacts from grounded vessels and debris. Surveys in waters off Christiansted, St. Croix, found physical impacts to seagrass beds associated with barge and other vessel groundings due to Hurricane Maria. Whether marine habitats impacted by the hurricanes are left to recover naturally or experience some level of restoration, there are potential short-term impacts to ecosystem services such as fisheries and coastal protection while these habitats return to their pre-hurricane state.

The Caribbean lies in a region where the natural climate system acts in a way that compounds the effect that warm ocean temperatures have on hurricanes.[123] In particular, when ocean temperatures are unusually warm, other environmental factors that affect hurricanes tend to be optimized. This is not the case for regions along the U.S. mainland coast, where warmer waters tend to cause other factors to inhibit hurricanes.[124] There are also disparities between the United States' resources to respond to local hurricane impacts and those of the Caribbean SIDS. Furthermore, any impacts that may be exacerbated by global and regional climate change tend to disproportionately affect regions that are geographically small and relatively short on resources.[125]

The challenges of effective disaster response in the U.S. Caribbean region are daunting and formidable.[116] The 2017 Atlantic hurricane season provided a window into the vulnerabilities of the region and the difficulties in responding to hurricane impacts. As the response to the 2017 hurricane season continues in the region, sustained dialog among the range of stakeholders whose interests and areas of expertise are involved can improve strategies regarding response actions and coordination of response based on lessons learned in 2017 and 2018.

Box 20.1: 2017 Atlantic Hurricane Season Impacts, *continued*

Hurricane Impacts in 2017



A: Damage caused by hurricane winds to a storage facility in an orchard and fruit tree farm in Salinas.

B: Progressive erosion resulted in increased exposure to higher-energy wave action. Protection measures were not enough to withstand the force of Hurricane Maria–induced waves at Rincón, Puerto Rico.

C: Partially submerged sailboat grounded on Long Reef, St. Croix, during Hurricane Maria.

D: Severe flood conditions in La Charca, Florida, PR, where approximately 20 houses and a number of vehicles were affected by 10 feet of floodwater during Hurricane Maria.

E: Damage to Island Beachcomber Hotel from Hurricane Maria, Lindbergh Bay, St. Thomas.

Figure 20.15: In September 2017, the U.S. Caribbean region was impacted by two major hurricanes: Irma (Category 5) and Maria (Categories 4 and 5). This figure shows the hurricanes' tracks across both the Caribbean and (inset) the U.S. Caribbean region, as well as (A–E) some of the impacts felt throughout the region. Sources: (tropical cyclone tracks) NOAA NCEI and ERT, Inc. Photo credits: (A) Ricardo Burgos; (B) Ernesto Díaz, Puerto Rico DNER; (C) Michael Doig, NOAA; (D) Joel Figuero; (E) Greg Guannel, The University of the Virgin Islands.

Damages from Hurricanes Irma and Maria in Puerto Rico caused the longest-lasting power outage in U.S. history to date (Figure 20.16).[126] Communications for Puerto Rico and the USVI were largely disabled following the hurricanes, with a respective 88% and 69% of cellular communication infrastructure out of service.[119] For Puerto Rico, preliminary estimates suggest that economic losses to businesses due to wind damage for Hurricane Maria totaled $4.9 billion (in 2017 dollars, $4.8 billion in 2015 dollars).[127] Alongside economic loss and infrastructure damage, hurricane impacts also caused severe disturbances to terrestrial and marine ecosystems, including sensitive coral reef colonies in the region (see Box 20.1).

Historical events much less severe than those in 2017 have resulted in significant damages as well. In 1995, Hurricane Marilyn resulted in losses equivalent to 122% of the USVI's gross domestic product. From 2010 to 2016, hurricanes produced a loss of about $39 million (in 2015 dollars) to Puerto Rico's agricultural sector alone.

Over the past 20 years, floods in urban areas caused by extreme precipitation have frequently disrupted human and economic activities.[128] On July 18, 2013, a record 9 inches of rain fell in San Juan, Puerto Rico, in less than 24 hours,[129] affecting multiple residential and commercial areas. The resulting floods caused the temporary closure of the LMM International Airport, disrupting the movement of people and goods. In November 2016, heavy rains and associated flooding resulted in agricultural losses of approximately $13 million (in 2015 dollars) in Puerto Rico.[130]

Droughts are one of the most frequent climate hazards in the Caribbean. Since the 1950s, at least seven major droughts have occurred in the U.S. Caribbean.[131,132] Since 2000, there have been five moderate droughts in Puerto Rico that lasted, on average, 8.6 weeks (Figure 20.17). The most recent major regional drought of 2014–2016, classified as extreme, affected Puerto Rico and the USVI, as well as other islands in the region. At its peak, this drought covered more than 60% of Puerto Rico's land area.[133] Conditions resulted in water rationing for 1.2 million people and over $14 million in agricultural losses for 2015, primarily in livestock, grazing lands, bananas, and plantains.[40] While the onset and end of a drought are hard to determine, records of the U.S. Drought Monitor suggest that it takes only weeks of abnormally dry conditions before the declaration of a meteorological drought in Puerto Rico.[134]

Hurricane Maria Damage

Figure 20.16: Residential and vessel damages caused by Hurricane Maria in 2017, at (left) Palmas del Mar and (right) Punta Santiago, Humacao, Puerto Rico. Photo credits: (left) Ernesto Díaz, Puerto Rico DNER; (right) Vanessa Marrero, Puerto Rico DNER.

Maximum Extent of Drought

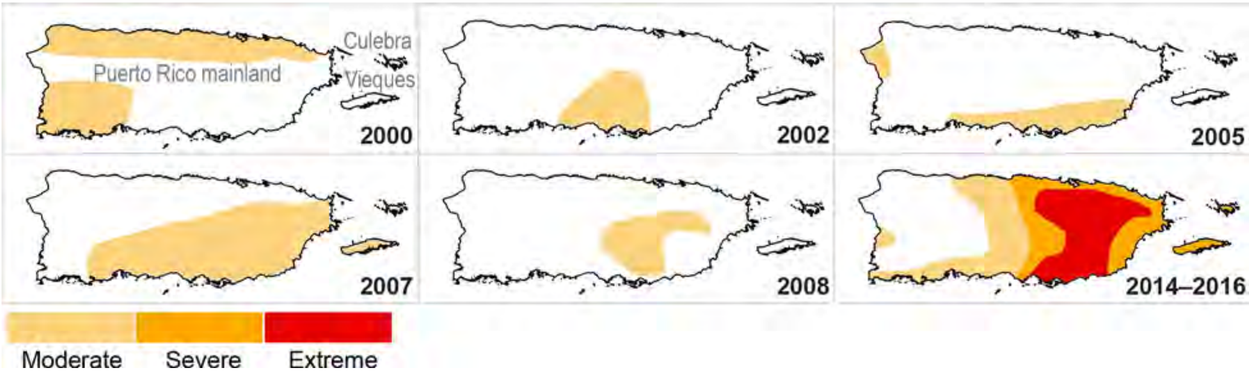


Figure 20.17: These maps show the maximum extent of each registered drought between 2000 and 2016 by the U.S. Drought Monitor. While six drought events were registered, the most severe of these occurred between 2014 and 2016, with extreme conditions covering the eastern half of the main island of Puerto Rico. The five events prior to 2014 were registered as moderate drought and were short-lived in comparison. Source: USDA Forest Service.

Future Climate Change Relevant to Regional Risks

While there is still much uncertainty in global climate model predictions of tropical cyclone formation,[135] climate models project an increase in the frequency of strong hurricanes (Categories 4 and 5) in the Atlantic Basin, including the Caribbean.[33] Drought projections for Puerto Rico suggest an increase in both drought intensity and frequency due to increases in both average and extreme temperatures and decreases in precipitation.[7]

Challenges, Opportunities, and Success Stories for Reducing Risk

The challenges for the U.S. Caribbean region in formulating disaster risk responses to extreme events lie in its geographical, social, and economic vulnerabilities. Puerto Rico and the USVI face common challenges, such as distance from continental resources, scarcity of land resources, increasing pressures on coastal and marine resources, high volume of food and fuel imports, and limited human resources.[1,25] Distance from the continental United States increases the region's vulnerability due to limited access to resources in times of need. Current fiscal and economic challenges of the region, coupled with an increasing elderly population, create additional challenges for the islands' governments to prepare for, respond to, and recover from climate-related disasters.

Improvements in data collection of extreme events and cost analyses of disasters have enhanced the resilience capacity of the U.S. Caribbean by supporting decision-making processes, particularly for drought events (see Box 20.4). Policymakers and disaster risk managers, as well as the general public, benefit from accurate data to support planning for disaster risk reduction. At present, current and historical data on the effects associated with extreme events are limited and not readily accessible for government officials and disaster risk managers.

Collaborative action has proven to be a successful strategy to manage and address the impacts from climate-related disasters.[136] Puerto Rico has actively provided humanitarian and technical support to other Caribbean nations and U.S. states during climate-related disasters and emergencies for at least 20 years. In Puerto Rico, collaborative actions among state and federal agencies, academics, and climate experts enabled improved preparation for and management of the 2014–2016 drought. Efficient coordination and collaboration among agencies prompted a largely effective governmental response to the disaster risk reduction challenges, while also promoting greater public education and awareness about extreme events (see Box 20.4).

Key Message 6

Increasing Adaptive Capacity Through Regional Collaboration

Shared knowledge, collaborative research and monitoring, and sustainable institutional adaptive capacity can help support and speed up disaster recovery, reduce loss of life, enhance food security, and improve economic opportunity in the U.S. Caribbean. Increased regional cooperation and stronger partnerships in the Caribbean can expand the region's collective ability to achieve effective actions that build climate change resilience, reduce vulnerability to extreme events, and assist in recovery efforts.

Shared Risks and Opportunities

Caribbean countries and territories share broad similarities in characteristics related to climate vulnerability, including low availability of resources, high debt rates, coastal populations, remoteness, and dependence on imports and global markets.[137] The recent impacts of Hurricanes Irma and Maria in 2017 brought to light the high vulnerability of Caribbean islands to natural disasters and the potential benefits of adopting long-term resilience measures. Increased regional cooperation and strengthening partnerships between Puerto Rico, the USVI, and the wider Caribbean countries can be achieved through collaborative climate research; by performing regional assessments of vulnerabilities, risks, and mitigation potential via joint efforts in adaptation planning and education; and by designing early warning systems to support strategic decision-making. These efforts are likely to increase resilience and the adaptive capacity of Caribbean countries by leveraging capabilities and resources and may help to speed up disaster recovery, reduce the loss of life, enhance food security, and improve economic opportunity in the region. The period following climate-related disasters can provide the opportunity to reduce future risks, when political attention is heightened and key decisions are being made on response, recovery, and planning. Being proactive and building back better is a simple idea, but its implementation has diverse challenges.[138] Recovery is not a neat linear progression with a clear end point but is rather a part of an ongoing process of development and change with attendant uncertainties and hurdles, including financing, personnel, and incentives for collaboration across Caribbean islands.[16,138,139]

New and sustained cooperation mechanisms between U.S. territories and Caribbean countries would likely increase the participation of Puerto Rico and the USVI in regional initiatives addressing climate adaptation and disaster risk reduction.

Effectiveness of Cross-Regional Collaboration for Building Resilience

There is a history of regional efforts on climate change assessment and governance in the Caribbean (Figure 20.18). Joint regional efforts to address climate challenges include the implementation of adaptation measures to reduce natural, social, and economic vulnerabilities, as well as actions to reduce greenhouse gas emissions. The Caribbean Small Island Developing States (SIDS) have articulated national climate change adaptation policies and implementation plans using processes similar to the UN Framework Convention on Climate Change guidance for preparation of national adaptation programs of action.

Climate Research and Risk Management Organizations

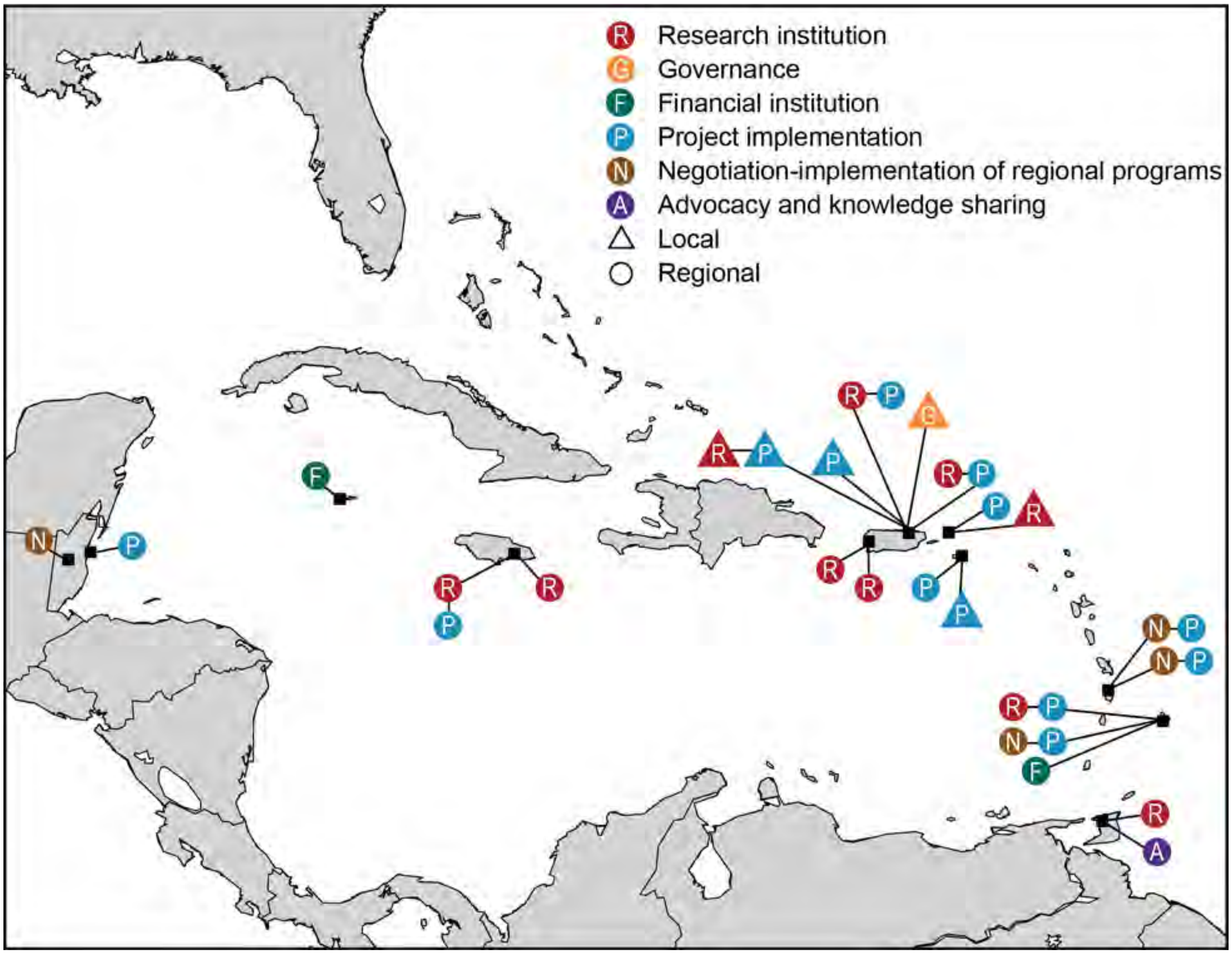


Figure 20.18: Some of the organizations working on climate risk assessment and management in the Caribbean are shown. Joint regional efforts to address climate challenges include the implementation of adaptation measures to reduce natural, social, and economic vulnerabilities, as well as actions to reduce greenhouse gas emissions. See the online version of this figure at http://nca2018.globalchange.gov/chapter/20#fig-20-18 for more details. Sources: NOAA and the USDA Caribbean Climate Hub.

Two regional entities specifically focused on developing and improving information, services, and planning to support climate risk management are the Caribbean Community Climate Change Centre (5Cs) and the Caribbean Institute for Meteorology and Hydrology (CIMH; see Boxes 20.2 and 20.3). The 5Cs is headquartered in Belize and is the main organization improving the framework and activities for addressing climate change in the Caribbean region.

The 5Cs projects include development and training in the use of analytical tools (for example, CCORAL; see Box 20.4), translating the outputs from global climate models for application at the scale of small islands, deployment of climate and coral reef monitoring equipment, provision of policy guidance for mainstreaming climate change considerations into regional development activities, preparation of a Regional Framework for Achieving Development Resilient to Climate Change[140] and its accompanying Implementation Plan, and the construction of desalination facilities powered by solar photovoltaic systems as solutions to water scarcity. The CIMH is an institution of the Caribbean Community (CARICOM) and is the technical arm of the Caribbean Meteorological Organization, a member of the UN World Meteorological Organization. The role of the CIMH is to assist in improving and developing climate services and to provide awareness of the benefits of meteorology and hydrology for economic and environmental well-being. Both the 5Cs and CIMH have engaged with U.S. territories in anticipating and reducing risks and supporting adaptation actions.

Common to most Caribbean countries and territories are the needs to 1) assess risks; 2) enable people and actions at regional, national, and local scales; and 3) assess changes in ecosystems and species to inform decision-making on habitat protection under a changing climate (Ch. 28: Adaptation, Figure 28.1).[16,17] The CARICOM regional strategy and the framework for transformation are clear steps in that direction and encompass goals that are shared by Puerto Rico and the USVI.

Box 20.2: United States Virgin Islands and 5Cs Partnership on Vulnerability Assessment

The 5Cs, in conjunction with the National Oceanic and Atmospheric Administration (NOAA), developed a Vulnerability and Capacity Assessment Methodology inventory (Ch. 16: International, KM 4), which was used and modified under the European Union–Global Climate Alliance Programme (2011–2015) in several Caribbean countries. The 5Cs–NOAA method was combined with the approach derived from a local planning guidebook on preparing for climate change developed under the NOAA Regional Integrated Sciences and Assessments program.[141] This combined approach led to a Caribbean-specific methodology that has been successfully applied in Antigua and Barbuda, Saint Lucia, Saint Kitts and Nevis, and Grenada.[142,143] Common challenges across the region include relatively small islands with diverse microclimates, locations, and levels of exposure to climate-related risks; the expanse of human settlement and critical facilities located along vulnerable coastlines; inadequate forward planning; and a heavy dependence on imports of commodities, equipment, and energy, which leads to extreme vulnerability to external economic shocks (Ch. 16: International, KM 1). These best-case examples provide a template for the vulnerability assessment that is currently being executed in the USVI under the Climate Change Adaptation Planning Assessment and Implementation project.

Box 20.3: CIMH, NOAA, and the 5Cs Partnership to Deliver Climate Services

In 2010, CIMH, in partnership with NOAA and the 5Cs, reestablished the Caribbean Regional Climate Outlook Forum to serve as the convening mechanism for regional engagement, early warning information, climate impacts, and responses.[16] Products resulting from this include the Caribbean Regional Drought Monitor and Climate Impacts Report.[144,145] Based on successes in the Caribbean Regional Outlook Forum, CIMH is leading the multisectoral Consortium of Sectoral Early Warning Information Systems Across Climate Timescales (EWISACTs). The EWISACTs agreement makes the Caribbean the first region to formally create and implement a joint commitment between climate-sensitive sectors and a public climate services provider to support climate-resilient risk management and development.

Box 20.4: Collaboration and Tools for Cross-Country Capacity Building and Decision-Making

The Caribbean Climate Online Risk and Adaptation tooL (CCORAL) is a planning tool that can help countries make climate-resilient decisions and take actions in response to a changing climate. (http://www.caribbeanclimate.bz/caribbean-climate-chage-tools/tools/)

The **Caribbean Catastrophe Risk Insurance Facility** is the world's first index-based parametric insurance mechanism. It is a partnership of 17 Caribbean countries and the World Bank. (https://www.ccrif.org/)

The **Caribbean Challenge Initiative** was launched in 2008, with support of The Nature Conservancy. Puerto Rico and the USVI later joined participating governments committed to conserving at least 20% of their nearshore marine and coastal environments by 2020 and to ensuring that these areas are managed through a long-term finance structure. (http://caribbeanchallengeinitiative.org/)

Reducing Risks and Supporting Adaptation: Gaps, Opportunities, and Benefits

The U.S. Caribbean region has potential to improve adaptation and mitigation actions by fostering stronger collaborations with Caribbean initiatives on climate change and disaster risk reduction. The U.S. Caribbean islands are not members of CARICOM. However, the Government of Puerto Rico established a memorandum of understanding with the 5Cs to work collaboratively in climate adaptation and mitigation initiatives. Such agreements provide mechanisms to foster cooperation and build capacity in the region beyond the capabilities of any single island, leveraging greater support to address common challenges. U.S.-based centers and activities can benefit from and contribute to regional resilience. Key among these are the U.S. Department of Agriculture's Caribbean Climate Hub, the U.S. Department of the Interior's Climate Adaptation Science Centers, and NOAA's Caribbean initiative, which is supported by NOAA's Climate Program Office and NOAA's Office for Coastal Management.

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Traceable Accounts

Process Description

The majority of our Key Messages were developed over the course of two separate author meetings. The first occurred March 9–10, 2017, and the second on May 3, 2017. Both meetings were held in San Juan, Puerto Rico; however, people were also able to join remotely from Washington, DC, Raleigh, North Carolina, and the U.S. Virgin Islands (USVI). In addition, the author team held weekly conference calls and organized separate Key Message calls and meetings to review and draft information that was integral to our chapter. To develop the Key Messages, the team also deliberated with outside experts who are acknowledged as our technical contributors.

Key Message 1

Freshwater

Freshwater is critical to life throughout the Caribbean. Increasing global carbon emissions are projected to reduce average rainfall in this region by the end of the century (*likely*, *high confidence*), constraining freshwater availability, while extreme rainfall events, which can increase freshwater flooding impacts, are expected to increase in intensity (*likely*, *medium confidence*). Saltwater intrusion associated with sea level rise will reduce the quantity and quality of freshwater in coastal aquifers (*very likely*, *high confidence*). Increasing variability in rainfall events and increasing temperatures will likely alter the distribution of ecological life zones and exacerbate existing problems in water management, planning, and infrastructure capacity (*likely*, *medium confidence*).

Description of evidence base

The average global atmospheric carbon dioxide (CO_2) concentration has increased from 378 parts per million (ppm) in 2005 to over 406 ppm during April of 2017. The rate of increase over this period appears to be constant, and there is no indication that the rate will decrease in the future.[146] Several climate change studies have concluded that owing to increased atmospheric CO_2 and the consequent global climate change, rainfall will likely decrease in the region between now and the end of the century (e.g., Meehl et al. 2007, Biasutti et al. 2012, Campbell et al. 2011, Cashman et al. 2010[2,3,4,5]). Neelin et al. (2006)[147] and Scatena (1998)[148] have predicted increasingly severe droughts in the region in the future. Several downscaling studies, which specifically considered Puerto Rico, predict a reduction in rainfall by the end of the century[6,7,34] and constraints on freshwater availability. Furthermore, Taylor et al. (2018)[149] used the most recent generation of global climate models and demonstrated that when global warming increases from 1.5°C to 2°C above the preindustrial values (1861–1900), the Caribbean experiences a shift to predominantly drier conditions. Small watersheds that feed reservoirs are typical of the Caribbean region, and they are less able to serve as a buffer for rainfall variability. Small watersheds exhibit variable drainage patterns, which in turn affect evapotranspiration, groundwater infiltration, and surface water runoff. Drainage patterns in watersheds are also affected by the specific geometry, configuration, and orientation in relation to the average direction of wind over the region, as well as the morphology of rivers. With a projected reduction in rainfall up to 30% on average for the island by the end of the century,[7] certain watersheds will likely be less able to buffer rainfall variability and will likely see water deficits in the near future. Increasing variability in rainfall events and increasing temperatures will likely exacerbate existing problems in water management, planning, and infrastructure capacity.

Streamflow is estimated using hydrologic models that are calibrated to networks of stream gauges and precipitation measurements. Reservoirs are considered in a permanent supply deficit if the annual streamflow leaving these reservoirs falls below zero after estimating withdrawals for human consumption, evapotranspiration, and rainfall. Projections of when deficit conditions could occur (circa 2025) are estimated using climate models.[46]

Saltwater intrusion associated with sea level rise will reduce the quantity and quality of freshwater in coastal aquifers. In Puerto Rico, groundwater quality can change when the water table is below sea level in coastal areas or when the intensity of pumping induces local upconing of deeper, poor-quality water.[43] Upconing is the process by which saline water underlying freshwater in an aquifer rises upward into the freshwater zone due to pumping.[150] When the water table is below sea level, the natural discharge of groundwater along the coast is reversed and can result in the inland movement of seawater or the upconing of low-quality water.[151,152] Diminished aquifer recharge and, to a lesser extent, increased groundwater withdrawals during 2012–2015 resulted in a reduction in the freshwater saturated thickness of the South Coast Aquifer. With sea level rise, groundwater quality will likely deteriorate even further in coastal aquifers in Puerto Rico.

Major uncertainties

As global changes continue to alter the hydrological cycle across the region, water resources are expected to be affected in both quantity and quality. There is still uncertainty as to the extent and severity of these global changes on small island nations such as Puerto Rico and the USVI, despite notable advancements in downscaled modeling exercises. Current climatological observations have presented an overall increase in mean annual precipitation across Puerto Rico.[153] However, climate model projections point toward an overall decrease in annual mean precipitation toward 2050 and an increase in rainfall intensity for extreme rainfall,[6,7,28,30,34,154] including rainfall associated with hurricanes. There is more uncertainty regarding the frequency and duration to changes in extreme rainfall within the region.[7,28,34]

Selected CMIP3 (Coupled Model Intercomparison Project, phase 3) and CMIP5 global climate models (GCMs) capture the general large-scale atmospheric circulation that controls seasonal rainfall patterns within the Caribbean[155] and provide justification that these GCM projections can be further downscaled to capture important rainfall characteristics associated with the islands.[156] Systemic dry biases exist, however, in the GCMs.[155] And many GCMs fail to capture the bimodal precipitation pattern in the region.[28] The CMIP3 generation of GCMs that do capture the bimodal rainfall pattern predict extreme drying at the middle and end of this century.[7,28] The CMIP5 generation of GCMs also projects drying by the middle and end of the century, but the magnitude of drying is not as large. Local and island-scale processes could affect these projected changes, since the land surface interacts with and affects both precipitation and evaporation rates.[157]

Description of confidence and likelihood

There is *high confidence* that freshwater availability will *likely* be constrained by the end of the century and *medium confidence* that extreme rainfall events will *likely* increase in intensity. There is *high confidence* that sea level rise will *very likely* cause saltwater intrusion impacts on coastal freshwater aquifers. There is *medium confidence* about *likely* changes to ecological life zones but *low confidence* about the distributional effects on the existing terrestrial ecosystems in the region.

Key Message 2

Marine Resources

Marine ecological systems provide key ecosystem services such as commercial and recreational fisheries and coastal protection. These systems are threatened by changes in ocean surface temperature, ocean acidification, sea level rise, and changes in the frequency and intensity of storm events. Degradation of coral and other marine habitats can result in changes in the distribution of species that use these habitats and the loss of live coral cover, sponges, and other key species (*very likely*, *high confidence*). These changes will likely disrupt valuable ecosystem services, producing subsequent effects on Caribbean island economies (*likely*, *medium confidence*).

Description of evidence base

In 2006, the National Marine Fisheries Service (NMFS) listed elkhorn and staghorn corals as threatened species under the Endangered Species Act, with persistent elevated sea surface temperatures and sea level rise being two of the key factors influencing the listing decision.[158] The Acropora Biological Review Team (2005) found that the number of hurricanes affecting reef ecosystems in the Caribbean has increased over the past two decades (2 hurricanes in the 1970s, 6 in the 1980s, and 12 in the 1990s). Sea surface temperature is expected to continue rising, and this implies an increasing threat to elkhorn and staghorn corals from bleaching-induced mortality and possibly an exacerbation of disease effects. In 2014, NMFS listed an additional 5 species of Atlantic/Caribbean corals (lobed, mountainous star, boulder star, pillar, and rough cactus) as threatened and reevaluated the listing of elkhorn and staghorn corals, confirming them as threatened species; it also listed 15 Indo-Pacific coral species as threatened,[159] with two of the key factors being ocean warming and ocean acidification. Brainard et al.[159] found that ocean warming and related effects of climate change have already created a clear and present threat to many corals that will likely continue into the future and can be assessed with certainty out to 2100. Increases in human population densities and activity levels in the coastal zone are expected to continue, meaning the vulnerability of these populations and infrastructure will likely continue increasing with climate change.[160] Direct measurements at the Bermuda Atlantic Time-series Study station shows that surface ocean acidity has increased by about 12% and aragonite saturation (Ω_{arg}) has decreased by about 8% over the past three decades.[161] These values agreed with those reported across the Caribbean[162] and Atlantic regions[18,161] using regional and global numerical marine carbonate system models.

Many coastal regions already experience low surface seawater pH and Ω_{arg} conditions (localized or coastal ocean acidification) due to processes other than CO_2 uptake. As a result, the effect of ocean acidification on coastal zones can be several times higher and faster than typically expected for oceanic waters.[163]

Caribbean coral reefs in the Bahamas, Belize, Bonaire, and Grand Cayman are already experiencing significant reductions in carbonate production rates, with 37% of surveyed sites showing net erosion.[164] Friedrich et al. (2012).[66] concluded that calcification rates may have already dropped by about 15% within the Caribbean with respect to their preindustrial values.

Major uncertainties

The link between climate stressors such as increasing sea surface temperatures and bleaching response and increasing prevalence of disease in corals is postulated. There is some scientific evidence indicating a link, but it is hard to make definitive conclusions. Effects of climate change on fisheries in the Caribbean have not been as well studied as the effects on marine habitats, particularly coral reefs.[74,165] Similarly, the social consequences of climate change and associated declines in marine fisheries and the effects on coastal communities reliant on coral reef fishery species have not been as well studied.[166]

Uncertainty with respect to ocean acidification is dominated by uncertainty about how ecosystems and organisms will respond, particularly due to multiple interactions with other stressors.

The value of the loss of ecosystem services to ocean acidification is unknown. Such losses are attributable to the degradation of ecosystems that support important economic marine species such as coral, conch, oysters, fish larvae, urchins, and pelagic fish in the Caribbean. There is strong evidence for decreasing carbonate production, calcification rates, coral cover, and biomass of major reef-building species throughout the Caribbean region. However, there is still not enough evidence to conclude that all these decreased ecosystem processes are due to ocean acidification.

There are only a few studies on ecosystem and organism responses to climate stressors (such as ocean warming) that consider ocean acidification in the Caribbean. For instance, low pH values could affect nursery areas of commercially important species such as tuna, presenting a source of vulnerability for the economy, but studies are scarce. Ocean acidification could also affect the food web dynamics at lower trophic levels and have physiological effects at larval stages that would likely cascade upward, affecting coral and fish recruitment.

The effects of ocean acidification on coral reefs, shellfish, fish, and marine mammals will likely cause an economic effect on fisheries, coastal protection, and tourism in the Caribbean. Ocean acidification can exacerbate the current global warming effects on coral reefs, and it will likely continue deteriorating reef conditions and cause ecological regime shifts from coral to algal reefs.[77,167] The primary effect on reef communities will probably be a reduction in their capacity to recover from acute events such as thermal bleaching.

Sea level rise is currently the most immediate and well-understood climate-related threat to mangroves.[70] It is not clear how mangroves will respond to elevated CO_2, and some studies suggest increases may actually be beneficial to mangroves.[70] Similarly, in the Caribbean where temperatures are already high, increasing temperatures, as well as declines in rainfall and corresponding increases in soil salinity during periods of drought, will likely increase plant water stress and reduce productivity. There have been limited studies on the effects of climate change on seagrass beds; therefore, these effects remain uncertain.[69] Sea level rise that results in reduced sunlight due to increased water depths can lead to the loss of seagrass beds from deeper waters. As discussed previously, the loss or degradation of these habitats, which are part of the coral reef ecosystem and serve as nursery habitat for important nursery species, will likely contribute to declines in fishery productivity due to climate change.

Description of confidence and likelihood

There is *high confidence* that increasing ocean temperatures, changes in ocean acidity, and changes in the frequency and intensity of storms are *extremely likely* to affect coastal and marine resources. Large storm events within the past decade have resulted in significant effects on marine resources, particularly coral habitats and organisms that rely on them. There is *medium confidence* in predictions that coral habitats will *likely* continue to decline throughout the Caribbean, with associated effects on resources dependent on these habitats; although, scientific studies are still needed in terms of climate change effects on fisheries resources, particularly for species that are found in offshore waters or are pelagic. Changes in coral habitats are already occurring as evidenced by massive coral bleaching events (including a three-year global-level bleaching event from 2015–2017) and the increase in these events. Such changes in bleaching events are due to rising sea surface temperatures. There is *high confidence* that there have been changes in ocean pH and *medium confidence* on the ecological effects. Due to the lack of studies on the social consequences of climate change and associated losses of resources such as fisheries, there is *medium confidence* that effects on coastal and marine resources resulting from climate change will affect island economies. These effects can be a result of changes in availability and condition of fishery resources, loss of reefs and other coral communities that serve as coastal barriers, and effects on tourism due to loss of the resources that are primary attractions for visitors.

There is *medium confidence* in the ecological effects that will result due to changes in ocean pH. The CO_2 system of seawater is well understood and established. As such, the understanding of the basic equilibria governing the process of ocean acidification dates back to at least 1960[168] and represents a foundational understanding of modern chemical oceanography. The ecological consequences of human-induced changes to the system (that is, ocean acidification) is, however, a considerably new field. Both themes were assessed considering recent findings and based on adequate observed local data (for example, atmospheric pCO_2 [carbon dioxide partial pressure] values are based on measurements of weekly air samples from St. Croix, the USVI, the United States, and Ragged Point, Barbados), complemented with empirical models. Projected changes in climate for the Caribbean islands were based on the future projections of fossil fuel emissions driven by reasonable models from the Intergovernmental Panel on Climate Change (IPCC).[169] Additional empirical species response data would be useful for increasing the understanding of expected effects of ocean acidification on species and habitats in the Caribbean.

Key Message 3

Coastal Systems

Coasts are a central feature of Caribbean island communities. Coastal zones dominate island economies and are home to critical infrastructure, public and private property, cultural heritage, and natural ecological systems. Sea level rise, combined with stronger wave action and higher storm surges, will worsen coastal flooding and increase coastal erosion (*very likely*, *very high confidence*), likely leading to diminished beach area (*likely*, *high confidence*), loss of storm surge barriers (*likely*, *high confidence*), decreased tourism (*likely*, *medium confidence*), and negative effects on livelihoods and well-being (*likely*, *medium confidence*). Adaptive planning and nature-based strategies, combined with active community participation and traditional knowledge, are beginning to be deployed to reduce the risks of a changing climate.

Description of evidence base

The Key Message and subsequent narrative text are based on the best available information for the U.S. Caribbean. There are not many studies on or projections for sea level rise for the U.S. Caribbean. Therefore, evidence of sea level rise used for this report comes from the U.S. Army Corps of Engineers' (USACE) Sea Level Change Curve Calculator.[95] To calculate the Intermediate and High scenarios, the USACE uses modified National Research Council (NRC) curves, the most recent IPCC projections, and modified NRC projections with local rate of vertical land movement.[95] The four NOAA estimates integrate data ranging from tide gauge records for the lowest scenario to projected ocean warming from the IPCC's global sea level rise projections combined with the maximum projection for glacier and ice sheet loss for 2100 for the highest scenario. The sea level rise analysis mainly focuses on data from two tide gauges chosen to be representative of the region, one in San Juan, Puerto Rico, and the other in Charlotte Amalie, USVI. There are two others in the region that provide sea level trend data located in Magueyes, Puerto Rico, and Lime Tree Bay, USVI.

Additional evidence that sea level is rising is well documented in Chapter 9: Oceans and in the *Climate Science Special Report*. There are also numerous empirical examples of sea level rise and its effects in Puerto Rico and the USVI, where beaches have been reduced by erosion, roads have been lost, and access to schools has been affected.

Major uncertainties

Sea level rise is already occurring. However, the uncertainty lies in how much of an increase will take place in the future and how coastal social and ecological systems will respond. There are various models and projections to estimate this number, but it is influenced by many unknown factors, such as the amount of future greenhouse gas emissions and how quickly glaciers and ice sheets melt. Another major uncertainty lies in humans' abilities to combat or adapt to these changes. The scale at which people and cities will be affected depends on the actions taken to reduce risk. Lastly, the experience of sea level rise on each coast and community is different, depending on land subsidence or accretion, land use, and erosion; thus, the severity of effects might differ based on these factors.

Due to the levels of uncertainty surrounding the projections, we focused much attention on the highest scenarios, as fewer consequences exist for planning in terms of the higher scenario (RCP8.5).

Description of confidence and likelihood

Sea levels have already risen and will likely continue to rise in the future. Based on current levels of greenhouse gas emissions, glacial melt, and ice sheet loss, there is *high confidence and likelihood* in these sea level rise projections.

Key Message 4

Rising Temperatures

Natural and social systems adapt to the temperatures under which they evolve and operate. Changes to average and extreme temperatures have direct and indirect effects on organisms and strong interactions with hydrological cycles, resulting in a variety of impacts. Continued increases in average temperatures will likely lead to decreases in agricultural productivity, changes in habitats and wildlife distributions, and risks to human health, especially in vulnerable populations. As maximum and minimum temperatures increase, there are likely to be fewer cool nights and more frequent hot days, which will likely affect the quality of life in the U.S. Caribbean. (*High Confidence*)

Description of evidence base

In warm tropical areas like Puerto Rico and the USVI, higher summertime temperatures mean more energy is needed to cool buildings and homes, increasing the demand for energy. Heat episodes are becoming more common worldwide, including in tropical regions like the U.S. Caribbean. Higher frequency, duration, and intensity of heat episodes are triggering serious public health issues in San Juan. Heat poses a greater threat to health and well-being in high-density urban areas. Land use and land cover have affected local climate directly and indirectly, facilitating the urban heat island (UHI) effect, with potential effects on heat-related morbidity and mortality among urban populations.

Major uncertainties

Warming is evident. A remaining scientific question is how ecological and social systems that have established themselves in a particular location can adapt to higher average temperatures.[170] Islands such as Puerto Rico are particularly vulnerable because of heat events associated with changes in both terrestrial and marine conditions. Although there is evidence suggesting that mortality relative to risk increases in San Juan due to extreme heat,[12] this association is not completely understood on tropical islands like Puerto Rico and the USVI. Addressing such hazards can benefit from new strategies that seek to determine linkages between human health, rapid and synoptic environmental monitoring, and the research that helps improve the forecast of hazardous conditions for particular human population segments or for other organisms.

Description of confidence and likelihood

There is *high confidence* that increasing temperatures threaten the health and well-being of people living in the U.S. Caribbean, especially in high-density urban areas where the UHI effect places further stress on city populations.

Key Message 5

Disaster Risk Response to Extreme Events

Extreme events pose significant risks to life, property, and economy in the Caribbean, and some extreme events, such as flooding and droughts, are projected to increase in frequency and intensity (*flooding as likely as not*, *medium confidence; droughts very likely*, *medium confidence*). Increasing hurricane intensity and associated rainfall rates (*likely*, *medium confidence*) will likely affect human health and well-being, economic development, conservation, and agricultural productivity. Increased resilience will depend on collaboration and integrated planning, preparation, and responses across the region (*high confidence*).

Description of evidence base

On both Puerto Rico and the USVI, disaster events have caused billions of dollars in property and crop damages.[171] Over the years, disaster-induced casualties have declined in both territories. Tropical cyclones, particularly hurricanes, continue to generate the most severe economic damage across the U.S. Caribbean. Floods and droughts are challenging to manage for both territories, and these challenges may be exacerbated by climate change induced shifts in precipitation regimes.

Climate modeling for tropical cyclone activity in the Atlantic Basin, including the Caribbean region, points toward an increase in the frequency of more intense hurricanes.[135] An increase in days with more than 3 inches of rain per 24-hour period is projected for Puerto Rico, based on statistically downscaled CMIP3 climate models.[28] Changes in precipitation patterns are expected for Puerto Rico in the periods 2030–2050 and 2100, pointing toward an overall decrease in mean precipitation for different climate change scenarios.[7,28,30,34]

While continental droughts typically affect vast regions, droughts affecting Puerto Rico and the USVI tend to vary significantly in extent and severity over smaller distances.[132] Statistically downscaled climate projections for Puerto Rico suggest an increase of drought intensity (measured as the total annual dry days) and extremes (measured as the annual maximum number of consecutive dry days) due to an increase in mean and extreme temperatures and a decrease in precipitation.[7]

An increase in mean atmospheric temperature has been observed across the U.S. Caribbean islands, particularly on Puerto Rico. An analysis of the observed temperatures across several NOAA weather stations in Puerto Rico showed rising temperature trends between 1970 and 2016.[172] Following the principles established by the international Expert Team on Climate Change Detection and Indices,[173] temperature extremes and trends were identified, indicating significant increases in rising annual temperatures and an increase in extreme heat episodes.

Major uncertainties

There are still uncertainties as to how these projected changes in tropical Atlantic cyclone activity will affect the frequency distribution of extreme precipitation events. While an increase in days with more than 3 inches of rain per 24-hour period has been projected based on statistically downscaled CMIP3 models,[28] more recent generations of GCMs do not show this increase in extreme rainfall events, and this adds uncertainty. Results from two dynamically downscaled climate models using the most recent generation of GCMs for the region do not show increases in the frequency of extreme events.[34]

At present, data pertaining to the costs and effects that are associated with extreme events and disasters are very limited and not readily accessible for government officials, disaster risk managers, or the general public. In the future, more accessible data could facilitate opportunities for more thorough analyses on the economic costs of extreme events for the U.S. Caribbean.

Description of confidence and likelihood

There is *high confidence* that increasing frequency of extreme events threatens life, property, and economy in the region, given that the U.S. Caribbean's vulnerable populations and fragile economies are continually exposed to climate extremes. There is *medium confidence* that the frequency and intensity of the most extreme hurricanes and droughts will likely increase. There is *high confidence* that extreme events will *likely* continue to affect human health and well-being, economic development and tourism, conservation, agriculture, and danger from flooding. There is *high confidence* that future recovery and cultural continuity will depend on significant and integrated resilience planning across the region, focusing on collaborative actions among stakeholders.

Key Message 6

Increasing Adaptive Capacity Through Regional Collaboration

Shared knowledge, collaborative research and monitoring, and sustainable institutional adaptive capacity can help support and speed up disaster recovery, reduce loss of life, enhance food security, and improve economic opportunity in the U.S. Caribbean. Increased regional cooperation and stronger partnerships in the Caribbean can expand the region's collective ability to achieve effective actions that build climate change resilience, reduce vulnerability to extreme events, and assist in recovery efforts (*very likely*, *high confidence*).

Description of evidence base

Cross-regional and international cooperation is a mechanism that will likely reduce climate vulnerability and risks in the U.S. Caribbean, because it builds capacity and leverages resources in a region that has low adaptive capacity, due in part to the high costs of mitigation and adaptation relative to gross domestic product.[1,17,145] There are several efforts among the islands focused on coordination, information exchange, and approaches for risk assessment and management in the Caribbean region.[142,143,144,145] There are emerging opportunities for improving these partnerships and capacity across the region.

Major uncertainties

There is high certainty that Caribbean island states are being affected by climate change, but the rate and degree of effects vary across countries due to the differences in environmental and socioeconomic conditions. Examples of regional cooperation efforts to share knowledge, conduct collaborative research, and develop joint projects have increased the adaptive capacity in the region; however, sustaining such efforts across the region remains a challenge. As efforts for regional coordination, cooperation, and information exchange evolve, evidence of the benefits of collaboration can be better assessed.

Description of confidence and likelihood

There is *high confidenc*e that climate change will *likely* result in serious water supply shortages and in increased risks for agriculture production, human health, wildlife, and the socioeconomic development of Puerto Rico, the USVI, and the wider Caribbean region. The effects of climate change in the Caribbean region are *likely* to increase threats to life and infrastructure from sea level rise and extreme events; reduce the availability of fresh water, particularly during the dry season; negatively affect coral reef ecosystems; and cause health problems due to high temperatures and an increase in diseases.

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21 Midwest

Carson, Wisconsin

Key Message 1

Agriculture

The Midwest is a major producer of a wide range of food and animal feed for national consumption and international trade. Increases in warm-season absolute humidity and precipitation have eroded soils, created favorable conditions for pests and pathogens, and degraded the quality of stored grain. Projected changes in precipitation, coupled with rising extreme temperatures before mid-century, will reduce Midwest agricultural productivity to levels of the 1980s without major technological advances.

Key Message 2

Forestry

Midwest forests provide numerous economic and ecological benefits, yet threats from a changing climate are interacting with existing stressors such as invasive species and pests to increase tree mortality and reduce forest productivity. Without adaptive actions, these interactions will result in the loss of economically and culturally important tree species such as paper birch and black ash and are expected to lead to the conversion of some forests to other forest types or even to non-forested ecosystems by the end of the century. Land managers are beginning to manage risk in forests by increasing diversity and selecting for tree species adapted to a range of projected conditions.

Key Message 3

Biodiversity and Ecosystems

The ecosystems of the Midwest support a diverse array of native species and provide people with essential services such as water purification, flood control, resource provision, crop pollination, and recreational opportunities. Species and ecosystems, including the important freshwater resources of the Great Lakes, are typically most at risk when climate stressors, like temperature increases, interact with land-use change, habitat loss, pollution, nutrient inputs, and nonnative invasive species. Restoration of natural systems, increases in the use of green infrastructure, and targeted conservation efforts, especially of wetland systems, can help protect people and nature from climate change impacts.

Key Message 4

Human Health

Climate change is expected to worsen existing health conditions and introduce new health threats by increasing the frequency and intensity of poor air quality days, extreme high temperature events, and heavy rainfalls; extending pollen seasons; and modifying the distribution of disease-carrying pests and insects. By mid-century, the region is projected to experience substantial, yet avoidable, loss of life, worsened health conditions, and economic impacts estimated in the billions of dollars as a result of these changes. Improved basic health services and increased public health measures—including surveillance and monitoring—can prevent or reduce these impacts.

Key Message 5

Transportation and Infrastructure

Storm water management systems, transportation networks, and other critical infrastructure are already experiencing impacts from changing precipitation patterns and elevated flood risks. Green infrastructure is reducing some of the negative impacts by using plants and open space to absorb storm water. The annual cost of adapting urban storm water systems to more frequent and severe storms is projected to exceed $500 million for the Midwest by the end of the century.

Key Message 6

Community Vulnerability and Adaptation

At-risk communities in the Midwest are becoming more vulnerable to climate change impacts such as flooding, drought, and increases in urban heat islands. Tribal nations are especially vulnerable because of their reliance on threatened natural resources for their cultural, subsistence, and economic needs. Integrating climate adaptation into planning processes offers an opportunity to better manage climate risks now. Developing knowledge for decision-making in cooperation with vulnerable communities and tribal nations will help to build adaptive capacity and increase resilience.

Executive Summary

The Midwest is home to over 60 million people, and its active economy represents 18% of the U.S. gross domestic product.[1] The region is probably best known for agricultural production. Increases in growing-season temperature in the Midwest are projected to be the largest contributing factor to declines in the productivity of U.S. agriculture.[2] Increases in humidity in spring through mid-century[3,4] are expected to increase rainfall, which will increase the potential for soil erosion[5,6] and further reduce planting-season workdays due to waterlogged soil.[7]

Forests are a defining characteristic of many landscapes within the Midwest, covering more than 91 million acres. However, a changing climate, including an increased frequency of late-growing-season drought conditions, is worsening the effects of invasive species, insect pests, and plant disease as trees experience periodic moisture stress. Impacts from human activities, such as logging, fire suppression, and agricultural expansion, have lowered the diversity of the Midwest's forests from the pre-Euro-American settlement period. Natural resource managers are taking steps to address these issues by increasing the diversity of trees and introducing species suitable for a changing climate.[8]

The Great Lakes play a central role in the Midwest and provide an abundant freshwater resource for water supplies, industry, shipping, fishing, and recreation, as well as a rich and diverse ecosystem. These important ecosystems are under stress from pollution, nutrient and sediment inputs from agricultural systems, and invasive species.[9,10] Lake surface temperatures are increasing,[11,12] lake ice cover is declining,[12,13,14] the seasonal stratification of temperatures in the lakes is occurring earlier in the year,[15] and summer evaporation rates are increasing.[13,16] Increasing storm impacts and declines in coastal water quality can put coastal communities at risk. While several coastal communities have expressed willingness to integrate climate action into planning efforts, access to useful climate information and limited human and financial resources constrain municipal action.

Land conversion, and a wide range of other stressors, has already greatly reduced biodiversity in many of the region's prairies, wetlands, forests, and freshwater systems. Species are already responding to changes that have occurred over the last several decades,[17,18,19] and rapid climate change over the next century is expected to cause or further amplify stress in many species and ecological systems in the Midwest.[20,21,22] The loss of species and the degradation of ecosystems have the potential to reduce or eliminate essential ecological services such as flood control, water purification, and crop pollination, thus reducing the potential for society to successfully adapt to ongoing changes. However, understanding these relationships also highlights important climate adaptation strategies. For example, restoring systems like wetlands and forested floodplains and implementing agricultural best management strategies that increase vegetative cover (cover crops and riparian buffers) can help reduce flooding risks and protect water quality.[23,24,25]

Midwestern populations are already experiencing adverse health impacts from climate change, and these impacts are expected to worsen in the future.[26,27] In the absence of mitigation, ground-level ozone concentrations are projected to increase across most of the Midwest, resulting in an additional 200–550 premature deaths in the region per year by 2050.[28] Exposure to high temperatures impacts workers' health, safety, and productivity.[29] Currently, days over 100°F in Chicago are rare. However, they could become increasingly more common by late century in both the lower and higher scenarios (RCP4.5 and RCP8.5).

The Midwest also has vibrant manufacturing, retail, recreation/tourism, and service sectors. The region's highways, railroads, airports, and navigable rivers are major modes for commerce activity. Increasing precipitation, especially heavy rain events, has increased the overall flood risk, causing disruption to transportation and damage to property and infrastructure. Increasing use of green infrastructure (including nature-based approaches, such as wetland restoration, and innovations like permeable pavements) and better engineering practices are beginning to address these issues.

Conservation Practices Reduce Impact of Heavy Rains

Integrating strips of native prairie vegetation into row crops has been shown to reduce sediment and nutrient loss from fields, as well as improve biodiversity and the delivery of ecosystem services.[33] Iowa State University's STRIPS program is actively conducting research into this agricultural conservation practice.[34] The inset shows a close-up example of a prairie vegetation strip. *From Figure 21.2 (Photo credits: [main photo] Lynn Betts, [inset] Farnaz Kordbacheh)*.

Citizens and stakeholders value their health and the well-being of their communities—all of which are at risk from increased flooding, increased heat, and lower air and water quality under a changing climate.[30,31] To better prevent and respond to these impacts, scholars and practitioners highlight the need to engage in risk-driven approaches that not only focus on assessing vulnerabilities but also include effective planning and implementation of adaptation options.[32]

The photo shows Menominee Tribal Enterprises staff creating opportunity from adversity by replanting a forest opening caused by oak wilt disease with a diverse array of tree and understory plant species that are expected to fare better under future climate conditions. *From Figure 21.4 (Photo credit: Kristen Schmitt)*.

Background

The Midwest is home to more than 60 million people, and its active economy represents 18% of the U.S. gross domestic product.[1] In this report, the Midwest covers Illinois, Indiana, Iowa, Michigan, Minnesota, Missouri, Ohio, and Wisconsin. The region is probably best known for agricultural production. Trends toward warmer, wetter, and more humid conditions provide challenges for field work, increase disease and pest pressure, and reduce yields to an extent that these challenges can be only partially overcome by technology.[35] The Midwest contains large tracts of federal, state, and private forests and preserves that provide significant economic and ecological benefits to the region. However, as a changing climate results in shifting precipitation patterns, altered disturbance regimes, and increased frequency of late-growing-season moisture stress, the effects of existing stressors such as invasive species, insect pests, and plant disease are amplified.[36] Natural resource managers are taking steps to address these issues by increasing the diversity of trees and introducing species suitable for a changing climate.[8]

The Midwest also has vibrant manufacturing, retail, recreation/tourism, and service sectors. The region's highways, railroads, airports, and navigable rivers are major modes for commercial activity. Increasing precipitation, especially heavy rain events, has increased the overall flood risk, causing disruption to transportation and damage to property and infrastructure (e.g., Winters et al. 2015[37]). Increasing use of green infrastructure (including nature-based approaches, such as wetland restoration, and innovations like permeable pavements) and better engineering practices are beginning to address these issues (e.g., City of Chicago 2015[38]).

Tourism and outdoor recreation are major economic activities that may be affected by climate change, particularly in coastal towns that are at risk from algal bloom impacts and in areas that host winter sports that are especially vulnerable to warming winters. For example, ice fishing was limited due to mild temperatures in the winters of 2015–2016 and 2016–2017, and the American Birkebeiner cross-country ski race in Wisconsin was cancelled due to a lack of snow in February 2017. Portions of Michigan, Wisconsin, and Minnesota contain ceded territory of many tribes, and these are used for hunting, fishing, and gathering native plants, all of which play vital roles in maintaining cultural heritage. Projected changes in climate and ecosystems will have strong impacts on these activities.[39]

The Great Lakes play a central role in the Midwest and provide an abundant freshwater resource for water supplies, industry, shipping, fishing, and recreation, as well as a rich and diverse ecosystem. The same can be said for the upper Mississippi, lower Missouri, Illinois, and Ohio River systems. Episodes of widespread heavy rains in recent years have led to flooding, soil erosion, and water quality issues from nutrient runoff into those systems.[10] Land managers are beginning to change some of their practices (such as increasing the use of cover crops) to better manage excess surface water.[40]

Citizens and stakeholders in the Midwest value their health and the well-being of their communities—all of which are at risk from increased flooding, increased heat, and lower air and water quality under a changing climate.[30,31]

Energy in the Midwest

The Midwest is a major consumer of coal. In 2015, coal provided 56% of the electricity consumed in the region, and the eight states in the region accounted for 32% of the Nation's coal consumption (in BTUs). Coal's share of electricity production is declining in the Midwest, following the national trend (Ch. 4: Energy, Figure 4.3). In 2008, coal accounted for more than 70% of electricity consumption in the Midwest. Wind power is a small but growing source of electricity for the region. Iowa leads the Nation in per capita consumption of wind power, with wind providing over 30% of the state's electrical needs in 2015.[41]

Renewable energy is expanding in the Midwest. As part of a campus-wide initiative to transition to renewable energy sources, in 2017, Michigan State University established five solar carports that have an estimated annual production of 15,000 megawatt hours, representing about 5% of electricity use on campus (Figure 21.1). In addition to reducing carbon emissions, this investment is expected to save the university $10 million over 25 years.[42]

Solar Charging Stations

Figure 21.1: Solar carports were recently installed on the Michigan State University campus. Photo credit: David Rothstein.

What Is New in NCA4

Two new Key Messages are introduced (Key Messages 3 and 6). Key Message 3 recognizes the important role that ecosystems of the Midwest play in supporting a diverse array of species and providing important benefits such as flood control, crop pollination, and outdoor recreation. Key Message 6 addresses how at-risk communities in the Midwest are becoming more vulnerable to climate change impacts and how they are working to build adaptive capacity. Tribal nations are especially vulnerable because of their reliance on threatened natural resources for their cultural, subsistence, and economic needs. The four remaining Key Messages address improvements in the understanding of risks and responses to climate change since NCA3. Key Message 1 on agriculture provides more specificity about the risk to agriculture by stating that agricultural productivity (the ratio of outputs to inputs) is projected to decline by 2050 to levels of the 1980s (that is, yields may increase but at the cost of substantial increases in inputs). Key Message 2 on forestry illustrates the progress foresters and land managers have made in climate adaptation through their efforts to incorporate climate change risks into management decision-making. Key Message 5 on transportation and infrastructure highlights a growing interest in green infrastructure—the use of plants and open space in storm water management—as an option for adapting to more frequent episodes of extreme precipitation. Finally, Key Message 4 on human health identifies specific health impacts by naming expected changes in magnitude and occurrence of extreme events, exposures, and economic impacts. The message explicitly states public health actions that can be implemented to avoid or reduce the health impacts.

Key Message 1

Agriculture

The Midwest is a major producer of a wide range of food and animal feed for national consumption and international trade. Increases in warm-season absolute humidity and precipitation have eroded soils, created favorable conditions for pests and pathogens, and degraded the quality of stored grain. Projected changes in precipitation, coupled with rising extreme temperatures before mid-century, will reduce Midwest agricultural productivity to levels of the 1980s without major technological advances.

Recent Agriculturally Important Trends

The two main commodity crops in the Midwest are corn and soybeans, which are grown on 75% of the arable land. Wheat and oats are important crops grown on fewer acres. An increasing number of niche but higher-value crops (such as apples, grapes, cherries, cranberries, blueberries, and pumpkins) also are grown in the region.[43]

Over the past 30 years, increased rainfall from April to June has been the most impactful climate trend for agriculture in the Midwest,[3] providing a favorable supply of soil moisture while also reducing flexibility for timing of spring planting and increasing soil erosion.[44] In addition, wet conditions at the end of the growing season can create elevated levels of mold, fungus, and toxins.[45] The last spring frost has occurred earlier, causing the frost-free season to increase by an average of nine days since 1901.[46] However, daily maximum temperatures in summer in the Midwest have not followed the upward global trend, in part due to higher early summer rainfall on deep, water-holding soils,[47] thereby avoiding plant stress detrimental to crops. The avoidance of heat stress and longer growing seasons have favored production in some parts of and some years in the Midwest.

Daily minimum temperatures have increased in all seasons due to increasing humidity.[48,49] Elevated growing-season minimum daily temperatures are considered a factor in reducing grain weight in corn due to increased nighttime plant respiration.[50] Warming winters have increased the survival and reproduction of existing insect pests[51] and already are enabling a northward range expansion of new insect pests and crop pathogens into the Midwest.[52]

A contributing factor underpinning Midwest growing-season trends in both temperature and precipitation is the increase in water vapor (absolute humidity):[49,53] higher humidity decreases the day–night temperature range and increases warm-season precipitation. Rising humidity also leads to longer dew periods and high moisture conditions that favor many agricultural pests and pathogens for both growing plants and stored grain.

Projected Trends and Agricultural Impacts

Warm-season temperatures are projected to increase more in the Midwest than any other region of the United States.[54] The frost-free season is projected to increase 10 days by early this century (2016–2045), 20 days by mid-century (2036–2065), and possibly a month by late century (2070–2099) compared to the period 1976–2005 according to the higher scenario (RCP8.5).[46]

By the middle of this century (2036–2065), 1 year out of 10 is projected to have a 5-day period that is an average of 13°F warmer than a comparable period at the end of last century (1976–2005).[54] Current average annual 5-day maximum temperature values range from about 88°F in Northern Minnesota to 97°F in Southern Missouri. Tables 21.1 and 21.2 show that by mid-century under the higher scenario (RCP8.5), 5-day maximum temperatures are projected to have moved further above optimum conditions for many crops and closer to the reproductive failure temperature, especially for corn in the southern half of the Midwest. Higher growing-season temperatures also shorten phenological stages in crops (for example, the grain fill period for corn).[35,50] Under these temperatures, overall yield trends will be reduced because of periodic pollination failures and reduced grain fill during other years.

Increases in humidity in spring through mid-century[3,4] are expected to increase rainfall, which will increase the potential for soil erosion[5,6] and further reduce planting-season workdays due to waterlogged soil.[7] As an example, for the Cedar River Basin in Iowa, the 100-year flood (1% chance of occurring in a given year) of the 20th century is projected to be a 25-year flood (4% chance per year) in the 21st century,[55] with associated increased frequency of flooding of agricultural land.

Increased spring precipitation and higher temperatures and humidity are expected to increase the number and intensity of fungus and disease outbreaks[56,57] and the prevalence of bacterial plant diseases,[58] such as bacterial spot in pumpkin and squash.[59] Increased precipitation and soil moisture in a warmer climate also lead to increased loss of soil carbon[60] and degraded surface water quality due to loss of soil particles and nutrients.[61,62] Transitions from extremes of drought to floods, in particular, increase nitrogen levels in rivers[63] and lead to harmful algal blooms.

Current understanding of drought in the Midwest is that human activity has not been a major component in historical droughts, and it remains uncertain how droughts will behave in the future. However, future projections show that Midwest surface soil moisture likely will transition from excessive levels in spring due to increased precipitation to insufficient levels in summer driven by higher temperatures, causing more moisture to be lost through evaporation.[64]

Average Annual 5-Day Maximum Temperature

Geographic Area	Modeled Historical (1976–2005)	Mid-21st Century (2036–2065) for Lower Scenario (RCP4.5)	Mid-21st Century (2036–2065) for Higher Scenario (RCP8.5)
Northern Minnesota	88°F	93°F	95°F
Southern Missouri	97°F	102°F	103°F

Table 21.1: These modeled historical and projected average annual 5-day maximum temperatures illustrate the temperature increases projected for the middle of this century across the Midwest. Sources: NOAA NCEI and CICS-NC.

Optimum and Failure Temperatures for Vegetative Growth and Reproduction

Crop	Optimum Growth	Failure for Growth	Optimum Reproduction	Failure for Reproduction
Corn	80°F	105°F	67°F	95°F
Soybean	86°F	101°F	72°F	102°F

Table 21.2: This table shows the temperatures at which corn and soybeans reach optimum growth and reproduction as well as the temperatures at which growth and reproduction fail.[50]

Projections of mid-century yields of commodity crops[65,66] show declines of 5% to over 25% below extrapolated trends broadly across the region for corn (also known as maize) and more than 25% for soybeans in the southern half of the region, with possible increases in yield in the northern half of the region. Increases in growing-season temperature in the Midwest are projected to be the largest contributing factor to declines in the productivity of U.S. agriculture.[2] In particular, heat stress in maize during the reproductive period is projected by crop models to reduce yields in the second half of the 21st century.[67] These losses may be mitigated by enhanced photosynthesis and reduced crop water use, although the magnitude is uncertain.[68,69] Elevated atmospheric CO_2 is expected to partially, but not completely, offset yield declines caused by climate extremes, with effects on soybeans less than on maize.[70]

Non-commodity crops produced in the Midwest include tree fruits, sweet corn, and vegetables for farmers markets and canning. While the general impacts of climate change on specialty crops are similar to commodity crops, the more intense heat waves, excessive rain interspersed with drought, and higher humidity of a future climate likely will degrade market quality as well as yield by mid-century.[71] Although data on climate-related losses are sparse, excess moisture is emerging as a major cause of crop loss.[72] Wild rice is an annual plant harvested by tribes and others in shallow wetlands of northern Minnesota, Wisconsin, and Michigan. Stable production depends on a stable climate that maintains ecosystem diversity. Declines in production are expected, related to increases in climate extremes and climate-related disease and pest outbreaks as well as northward shifts of favorable growing regions.[73]

Longer growing seasons and the introduction of hoop buildings (low, translucent, fabric-covered structures that protect plants from extreme weather) have allowed local growers of annual vegetable crops to extend the fresh produce season. However, unsheltered perennial crops such as tree fruits may be subjected increasingly to untimely budbreak followed by cold pulses due to earlier and longer occurrences of warm conditions in late winter.

Most animal agriculture in the region is in confinement, rather than range-based without shelter, and therefore offers an opportunity for mitigating some of the effects of climate change. Without adaptive actions, breeding success and production of milk and eggs will be reduced due to projected temperature extremes by mid-century.[74,75,76]

Adaptation

Soil-erosion suppression methods in row-crop agriculture subjected to more intense rains include use of cover crops, grassed waterways, water management systems, contour farming, and prairie strips.[6,40] More diversity in planting dates, pollination periods, chemical use, and crop and cultivar selection reduces vulnerability of overall production to specific climate extremes or the changes in pests and pathogens that they cause.

An example of a highly successful program is the Iowa State Science-based Trials of Row-crops Integrated with Prairie Strips (STRIPS) program that demonstrates that replacing 10 percent of cropland with prairie grasses reduced sediment loss 20-fold while total nitrogen concentrations were 3.3 times lower (Figure 21.2).[33] An example of a private–public response is the National Corn Growers Association's Soil Health Partnership (SHP),[77] a network of working farms across the Midwest

Conservation Practices Reduce Impact of Heavy Rains

Figure 21.2: Integrating strips of native prairie vegetation into row crops has been shown to reduce sediment and nutrient loss from fields, as well as improve biodiversity and the delivery of ecosystem services.[33] Iowa State University's STRIPS program is actively conducting research into this agricultural conservation practice.[34] The inset shows a close-up example of a prairie vegetation strip. Photo credits: (main photo) Lynn Betts, (inset) Farnaz Kordbacheh.

engaged in refining techniques for growing cover crops, implementing conservation tillage, and using science-based nutrient management to reduce erosion and nutrient loss while increasing organic matter.

Acreage under irrigation has expanded modestly since 2002,[78] mostly in the northern part of the Midwest where coarse soils of lower water-holding capacity are more vulnerable to drying under increased temperature. No strategies currently are available for maintaining historical trends in commodity agriculture production to cope with increases in spring rainfall and summer heat waves projected for mid-century.[2,65]

Key Message 2

Forestry

Midwest forests provide numerous economic and ecological benefits, yet threats from a changing climate are interacting with existing stressors such as invasive species and pests to increase tree mortality and reduce forest productivity. Without adaptive actions, these interactions will result in the loss of economically and culturally important tree species such as paper birch and black ash and are expected to lead to the conversion of some forests to other forest types or even to non-forested ecosystems by the end of the century. Land managers are beginning to manage risk in forests by increasing diversity and selecting for tree species adapted to a range of projected conditions.

Forests are a defining characteristic of many landscapes within the Midwest, covering more than 91 million acres. From the oak–hickory forests of the Missouri Ozarks to the northern hardwood forests of the Upper Midwest, forest ecosystems sustain the people and communities within the region by providing numerous ecological, economic, and cultural benefits. The economic output of the Midwest forestry sector totals around $122 billion per year.[79,80,81,82,83,84,85,86] Forest-related recreation such as hunting, fishing, hiking, skiing, camping, wildlife watching, off-highway vehicles, and many other pursuits add to the region's economy. For example, forest-based recreationists spend approximately $2.5 billion (in 1996 dollars) within Wisconsin communities.[87] Forests are fundamental to cultural and spiritual practices within tribal communities, supporting plants and animals of central cultural importance and providing food and resources for making items such as baskets, canoes, and shelters.[88]

Climate change is anticipated to have a pervasive influence on forests within this region over the coming decades.[36,89,90,91,92,93,94] Tree growth rates and forest productivity have benefited from longer growing seasons and higher atmospheric carbon dioxide concentrations, but continued benefits are expected only if adequate moisture and nutrients are available to support enhanced growth rates.[95] As growing-season temperatures rise, reduced tree growth[96,97] or widespread tree mortality[98] is expected as the frequency of drought stress increases from drier air (as a result of increases in vapor pressure deficit [VPD]; Figure 21.3) and changing patterns of precipitation. Greater tree mortality from increased VPD likely will be particularly evident where competition for water is high in dense stands of trees[99,100] or where forests naturally transition to grasslands due to limited soil moisture.[101] Late-growing-season heat- and drought-related vegetation stress is projected to shift the composition and structure of forests in the region[102] by increasing mortality of younger trees, which are sensitive to drought.[19] Warming winters will reduce snowpack that acts to insulate soil from freezing temperatures, increasing frost damage to shallow tree roots[103] and reducing tree regeneration.[104] Additionally, increases in existing biological stressors of forests are expected as temperatures rise. Effects of insect pests and tree pathogens are anticipated to intensify as winters warm, increasing winter survival of pests and allowing expansion into new regions.[105,106] Changing climate conditions and atmospheric carbon dioxide concentrations will likely favor invasive plant species over native species, potentially decreasing tree regeneration.[107,108] Overall, the increasing stress on trees from rising temperatures, drought, and frost damage raises the susceptibility of individual trees to the negative impacts from invasive plants, insect pests, and disease agents (Ch. 6: Forests, Figure 6.1).[109,110,111]

Impacts from human activities such as logging, fire suppression, and agricultural expansion have lowered the diversity of the Midwest's forests from the pre-Euro-American settlement period. The forest types that occur within the region have been altered significantly relative to presettlement forests, with greater homogeneity in tree species composition across existing forest types.[112] Changes in modern forest types also include reduced structural complexity and less diverse mixes of tree species and tree ages.[113] Forests with reduced diversity are at an increased risk of negative effects from climate change, because the potential for tree species or age classes that are resistant to impacts from biological stressors and climate change is reduced.[93] Forests composed of trees of similar size and age or with lower tree diversity are at increased risk of widespread mortality[114,115] or declines in productivity.[116] In many midwestern forests, fire suppression has decreased the prevalence of

Drying Effect of Warmer Air on Plants and Soils

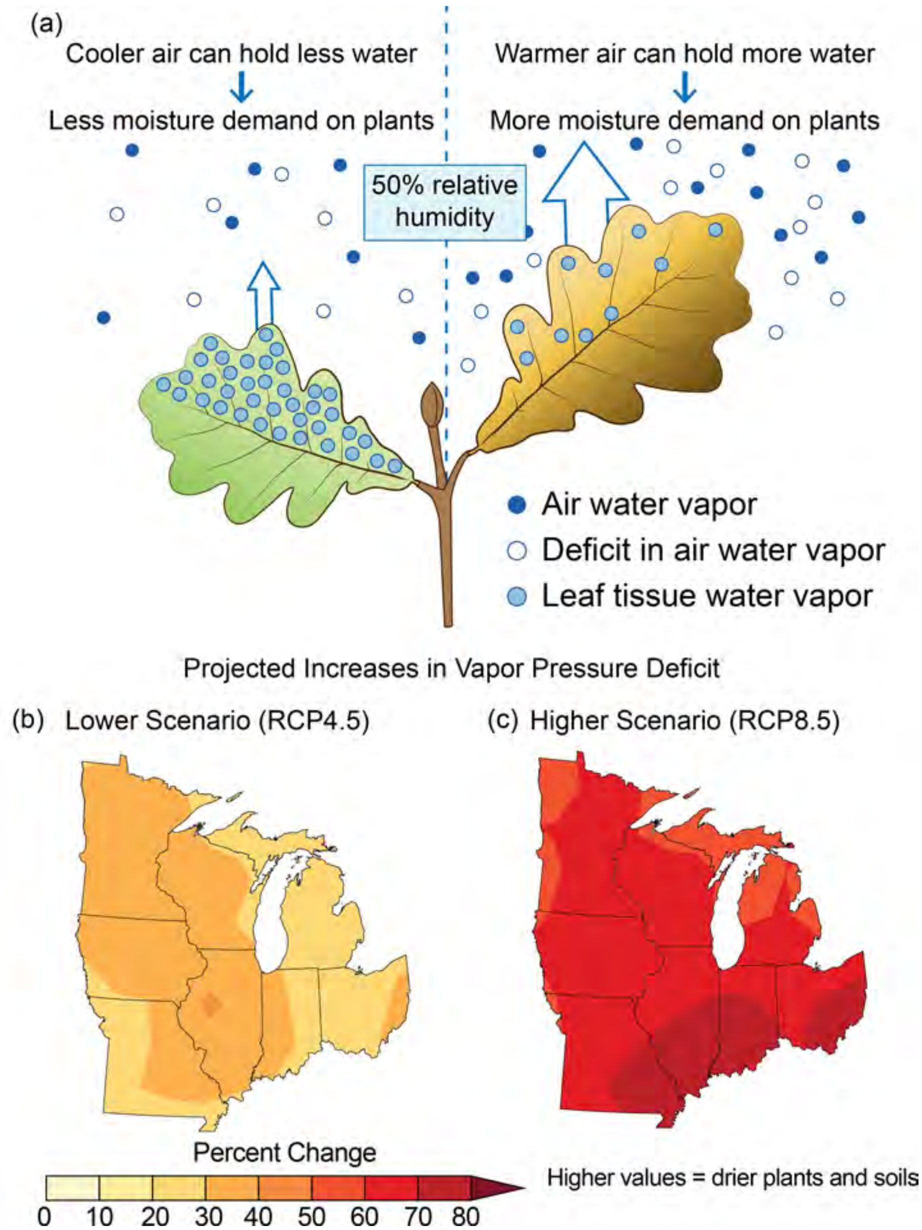

Figure 21.3: As air temperature increases in a warming climate, vapor pressure deficit (VPD) is projected to increase. VPD is the difference between how much moisture is in the air and the amount of moisture in the air at saturation (at 100% relative humidity). Increased VPD has a drying effect on plants and soils, as moisture transpires (from plants) and evaporates (from soil) into the air. (a) Cooler air can maintain less water as vapor, putting less demand for moisture on plants, while warmer air can maintain more water as vapor, putting more demand for moisture on plants. (b, c) The maps show the percent change in the moisture deficit of the air based on the projected maximum 5-day VPD by the late 21st century (2070–2099) compared to 1976–2005 for (b) lower and (c) higher scenarios (RCP4.5 and RCP8.5). Sources: U.S. Forest Service, NOAA NCEI, and CICS-NC.

the drought-tolerant tree species, such as oak, hickory, and pine, while increasing the abundance of species with higher moisture requirements, such as maples.[89,117] This results in greater risk of declines in forest health and productivity as the frequency of drought conditions increases.[118,119]

Changes in climate and other stressors are projected to result in changes in major forest types and changes in forest composition as tree species at the northern limits of their ranges decline and southern species experience increasingly suitable habitat.[120] However, the fragmentation of midwestern forests and the flatness of the terrain raise the possibility that the ranges of particular tree species will not be able to shift to future suitable habitats within the Midwest.[121] For example, to reach areas 1.8°F (1°C) cooler, species in flat terrain must move up to 90 miles (150 km) north to reach cooler habitat, whereas species in mountainous terrain can shift higher in altitude over less latitudinal (north–south) distance.[122] These changes raise the possibility of future losses of economic and cultural benefits of forests due to conversion to different forest types or the change to non-forest ecosystems.[119,123,124] Projected shifts in forest composition in the central hardwood region (southern Missouri, Illinois, Indiana, and Ohio) by the end of the century under a higher scenario (RCP8.5) would result in substantial declines in wildlife habitat and reduce economic value of timber in the region by up to $788 billion (in 2015 dollars).[125]

Changing climate conditions increasingly cause both cultural and economic impacts within the Midwest, and it is very likely these impacts will worsen in the future. For example, many tree species on which tribes depend for their culture and livelihoods—such as paper birch, northern white cedar, and quaking aspen—are highly vulnerable due to temperature increases.[90,91,92,126] Populations of the emerald ash borer, a destructive invasive insect pest that attacks native ash trees, will increase due to warming winters in the region. Mortality of black ash trees, which are important for traditional basket-making for many tribes, is highly likely as winter temperatures continue to rise.[127]

Warming winters already have economic impacts on the forest industry, as well. Forest operations (for example, site access, tree harvesting, and product transport) in many northern regions are conducted on snowpack or frozen ground to protect the site from negative impacts such as soil disturbance and compaction,[128] but the timing of suitable conditions has become shorter and more variable. In the Upper Midwest, the duration of frozen ground conditions suitable for winter harvest has been shortened by 2 to 3 weeks in the past 70 years.[129] The contraction of winter snow cover and frozen ground conditions has increased seasonal restrictions on forest operations in these areas,[130] with resulting economic impacts to both forestry industry and woodland landowners through reduced timber values.[131]

Forestry professionals in the Midwest increasingly are considering the risks to forests from climate change[132] and are responding by incorporating climate adaptation into land management.[8] There are a growing number of examples of climate adaptation in forest management developed by more than 150 organizations that have participated in the Climate Change Response Framework, an approach to climate change adaptation led by the U.S. Forest Service.[133,134,135] Management actions intended to maintain healthy and productive forests in a changing climate include a diverse suite of actions[135] but largely focus on activities that enhance species and structural diversity of existing forest communities and on management approaches that aim to increase the prevalence of species that are better suited to future climatic conditions.[8] Forest management on tribal lands and ceded territory within the region increasingly integrates Scientific Ecological Knowledge of natural resource management with Traditional Ecological Knowledge, a highly localized, place-based system of knowledge learned and observed over many generations.[136] This integration can inform the co-creation of approaches to climate adaptation important for maintaining healthy, functioning forests that continue to provide cultural and spiritual benefits (see Case Study "Adaptation in Forestry").

Case Study: Adaptation in Forestry

The Menominee Forest is well known as an exemplary forest; for generations, the Menominee Tribe has pioneered practices that have preserved nearly 220,000 acres with numerous species and varied habitats while maximizing the sustainable production of forest products. However, climate change—along with invasive species and insect pests and diseases—is creating new challenges for maintaining these diverse habitats and the sustainable supply of timber.

In response to tree mortality caused by oak wilt disease, an introduced exotic disease first identified in 1944 in Wisconsin, foresters at Menominee Tribal Enterprises (MTE) have integrated climate change adaptation into reforestation activities on severely disturbed areas created by the disease.[134] Using science guided by Traditional Ecological Knowledge of forest communities, forest openings created by oak wilt disease were replanted with a diverse array of tree and understory plant species that are expected to fare better under future climate conditions. Many of these species tolerate late-growing-season heat- and drought-related stress, while also providing important cultural benefits to the tribe such as food and medicine. The selection of locally collected plants and seeds used for restoring the oak wilt-affected openings combined scientific information on the future habitat of tree species with Indigenous knowledge of the forest communities necessary for guiding the development of diverse and healthy forests.

Figure 21.4: The photo shows Menominee Tribal Enterprises staff creating opportunity from adversity by replanting a forest opening caused by oak wilt disease with a diverse array of tree and understory plant species that are expected to fare better under future climate conditions. Photo credit: Kristen Schmitt.

> The grass, plant, and shrub species are put together to strengthen the immune system of the deep-rooted trees. We tried to emphasize the underground biotic community within these openings. A healthy underground community ensures a healthy aboveground community. The shrubs hold the key to a healthy change of species within the local plant communities.
>
> —MTE forester and tribal member

Key Message 3

Biodiversity and Ecosystems

The ecosystems of the Midwest support a diverse array of native species and provide people with essential services such as water purification, flood control, resource provision, crop pollination, and recreational opportunities. Species and ecosystems, including the important freshwater resources of the Great Lakes, are typically most at risk when climate stressors, like temperature increases, interact with land-use change, habitat loss, pollution, nutrient inputs, and nonnative invasive species. Restoration of natural systems, increases in the use of green infrastructure, and targeted conservation efforts, especially of wetland systems, can help protect people and nature from climate change impacts.

Species already are responding to environmental changes that have occurred over the last several decades,[17,18,19] and rapid climate change over the next century is expected to cause or further amplify stress in many species and ecological systems in the Midwest.[20,21,22] Land conversion and a wide range of other stressors have already greatly reduced biodiversity in many of the region's prairies, wetlands, forests, and freshwater systems. High rates of change in climate factors like air and water temperature and increasing drought risk likely will accelerate the rate of species declines and extinctions.[18,137] The Midwest region supports the world's largest freshwater ecosystem, the Great Lakes, which are at risk from rising temperatures, changes in seasonal stratification of lake temperatures, and increased summer evaporation rates, combined with stresses from pollution, nutrient inputs that promote harmful algal blooms, and invasive species (Box 21.1).

The loss of species and degradation of ecosystems have the potential to reduce or eliminate essential ecological services such as flood control, water purification, and crop pollination, thus reducing the potential for society to successfully adapt to ongoing changes.

Observations, ecological theory, experimental studies, and predictive models provide insights into how shifts in several climate factors (temperature, precipitation patterns, humidity, and moisture stress) may interact over the next several decades.[120,138,139] Vulnerability assessments for species and ecosystems quickly become complex, as species in the same ecosystem may have different climate sensitivities, and interactions with land-use change and other factors can strongly influence the level of impact (Ch. 5: Land Changes, KM 2; Ch. 17: Complex Systems, KM 1). Local expertise, input from multiple stakeholders, and tools like scenario planning can help improve assessment of vulnerability so that risks can be connected to management actions.[132,140] Changes observed in the Midwest include species range shifts (avoiding exposure to new climatic conditions by shifting location), changes in population size (indicating a change in viability in a given place), shifts in body size and growth rates, and changes in the timing of seasonal events (phenology). Since the Third National Climate Assessment,[27] the number of studies documenting these types of changes has continued to grow. For example, climate change appears to have contributed to the apparent local extinction of populations of the Federally Endangered Karner blue butterfly at sites in the southern end of its range in northern Indiana, despite active management and extensive habitat restoration efforts. While climate change cannot be singled out as the only cause, the populations disappeared following multiple years of warming conditions and a very early onset of spring in 2012.[139] New evidence of shifting ranges comes from

Wisconsin forests, where a set of 78 understory plant species sampled in the 1950s and again in the 2000s have demonstrated shifts in their abundance centroids (a measure of the distribution and local abundance of populations) of about 30 miles (49 km ± 29 km) over this 50-year period (Figure 21.5).[141] The dominant direction of this shift was to the northwest, which matches the direction of change in important climatic conditions associated with the distributions of these species. While this shift suggests the potential for successful adaptation to changing conditions, the rate of change for most species was much less than the amount of change in the climate metrics over the same time period, raising the concern that the climate is changing too fast for these species to keep up.[141] Similarly, a study of shifts in the timing of spring green-up, an indicator of when plant-feeding insects emerge, and the timing of migratory bird arrivals found that while both are shifting earlier in the Midwest, the arrival of birds is not advancing as quickly as the plants.[142] Risks to birds from this mismatch in phenology include the potential for birds to arrive after food availability has peaked or for later arrivals to be less able to compete for territories or mates. Land protection and management strategies that help maintain or increase phenological variation of plants within key migratory and breeding habitats like the Great Lakes coastlines may help increase the odds that birds can find the resources they need.[143]

The drivers of changes in species ranges or abundance can be complex and difficult to detect until key thresholds are crossed. For example, in the Midwest region, cool- and coldwater fishes in inland lakes are particularly susceptible to changes in climate because habitat with appropriate temperatures and oxygen concentrations is often limited during summer months. In lakes at the southern (warmer) end of their ranges, these fish experience a squeezing of available habitat during summer months as the water near the lake surface becomes too warm and the dissolved oxygen levels in deeper waters drop (Figure 21.6).[144,145,146] This "invisible" loss of habitat is driven by increases in water temperatures, longer duration of the stratified period (which delays the mixing of oxygen-rich water into the deeper waters), and declines in ice cover.[147,148,149,150] Recent research has identified fish kill events tied to temperature and oxygen stress from increased air temperatures, and modeling results forecast increased numbers of these events, likely leading to local extinction of cool- and coldwater fish species in some lakes and reduced geographic distribution across the Midwest.[151,152,153,154]

Climate Change Outpaces Plants' Ability to Shift Habitat Range

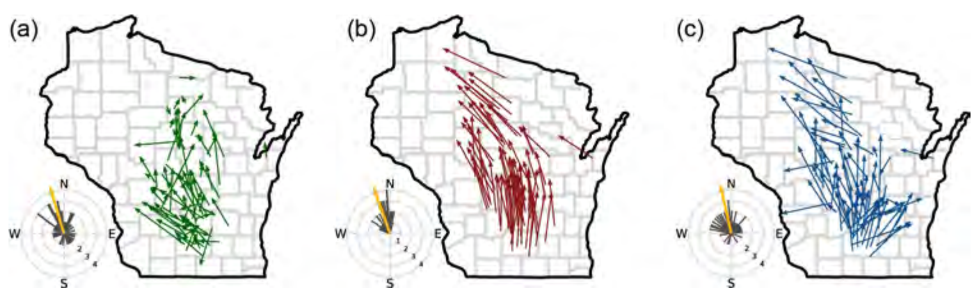

Figure 21.5: While midwestern species, such as understory plants in Wisconsin, are showing changes in range, they may not be shifting quickly enough to keep up with changes in climate. The panels here represent 78 plant species, showing (a) observed changes in the center of plant species abundances (centroids) from the 1950s to 2000s, (b) the direction and magnitude of changes in climate factors associated with those species, and (c) the lag, or difference, between where the species centroid is now located and where the change in climate factors suggests it should be located in order to keep pace with a changing climate. Source: adapted from Ash et al. 2017.[141] ©John Wiley & Sons, Ltd.

Coldwater Fish at Risk

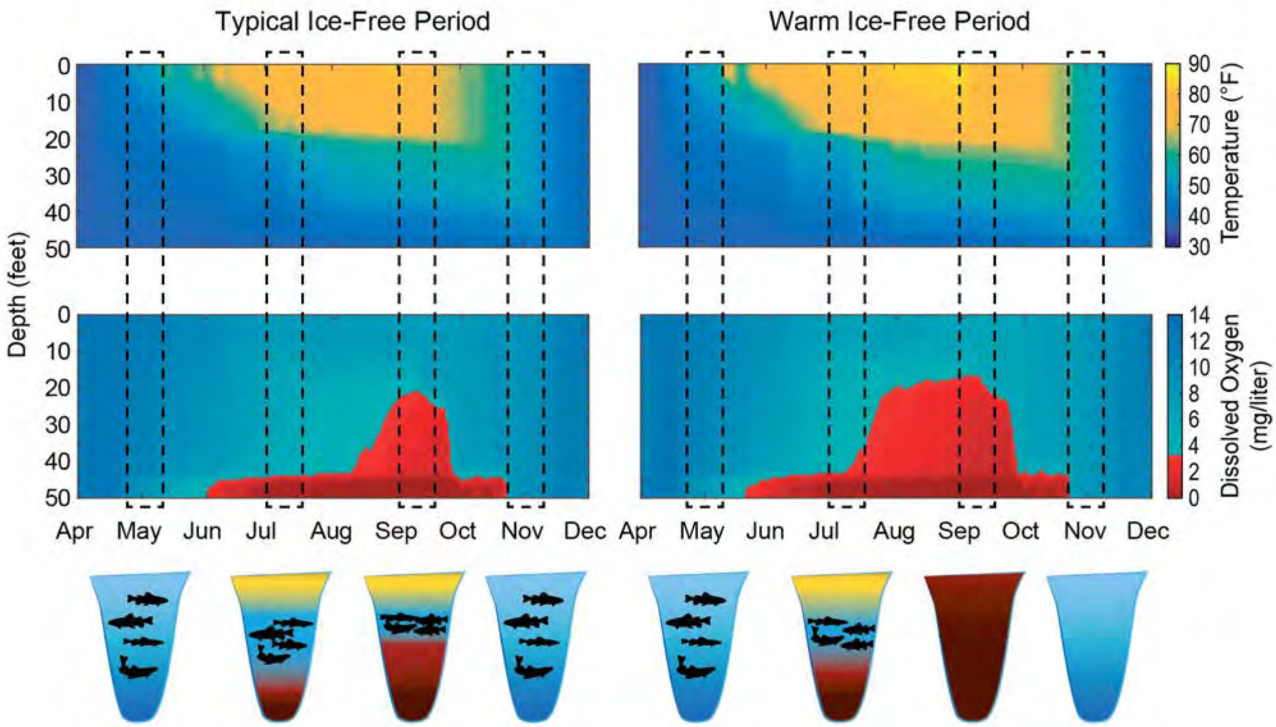

Figure 21.6: The graphic shows the oxythermal (oxygen and temperature) habitat of coldwater fish in midwestern inland lakes, illustrated by water depth under (left) a typical ice-free period and (right) a warm ice-free period (right). The top plots show water temperatures during the ice-free period, and the bottom plots show the dissolved oxygen concentrations. The schematics at the bottom illustrate the area of the lake that is ideal habitat for coldwater fish (in blue) and areas that represent water outside of the temperature or dissolved oxygen limit (in yellow and red, respectively). The left plots show how available habitat "squeezes" during a typical year, while the right plots illustrate a complete loss of suitable habitat during very warm years. Source: Madeline Magee, University of Wisconsin.

Taken individually, responses like range shifts, changes in local abundance, or changes in phenology may indicate that a species is successfully adapting to new conditions, or conversely may indicate a species is under stress. The extent to which responses indicate risk and the challenge of attributing changes to climate drivers when systems are exposed to many additional stressors are important sources of uncertainty that likely slow progress on climate change adaptation within the resource management sector.[155,156] Further, while evidence of species- and ecosystem-level responses to direct climate change impacts is increasing, many of the most immediate risks are even more challenging to track, because they relate to climate-driven enhancement of existing stressors, such as habitat loss and degradation, pollution, the spread of invasive species, and drainage and irrigation practices in agricultural landscapes.[138,157] As species are lost from midwestern ecosystems, there likely will be a net loss of biodiversity, as numerous additional stressors, especially widespread land conversion across the southern Midwest, limit opportunities for these gaps to be filled by species moving in from other regions (Ch. 7: Ecosystems, KM 1 and 2).[158,159]

While movement of species from the south-central United States could help sustain species-diverse ecosystems as some of the Midwest's current species move north, these range expansions can further stress current species. Many species and ecosystems in the Midwest, especially the Upper Midwest, are best suited to survive and compete for resources when winter conditions are harsh and growing seasons are short. As winter warms and the growing season extends, species from the south-central United States, as well as species from outside the country that are more traditionally viewed as invasive species, are expected to be able to grow faster and take advantage of these changes, increasing the rate of loss of the region's native species.[160,161] For invasive insect pests, these impacts may be compounded as extended growing seasons allow time for additional generations to be produced in a single season;[162] the same mechanism can promote higher impacts from native insect pests, as well. Given that some native species will decline in the region, to maintain or increase species diversity, some managers are beginning to plan for and even promote some native plant species that are present in a region, but more common to the south, as conditions change. While these can be important strategies for maintaining diversity and ecosystem functions, especially in isolated habitats where inward migration is not likely, careful consideration of the source of plant stocks is important when seeking to avoid introducing new or more competitive genotypes.[163] Further, as some native species decline, managers will benefit from increased vigilance in keeping potential invasive species from outside of North America from gaining a foothold.

Declines in native pollinator species are another important concern in the Midwest, as both native and managed pollinator species (typically nonnative bee species) play vital roles in supporting food production and farmer livelihoods and are critical for supporting wild plant reproduction and the diversity of ecosystems.[164,165] Key threats to this diverse group of insects, mammals, and birds include habitat loss and degradation, pathogens, pesticide use, and invasive species.[164,165,166] Most native and agricultural crops that require a pollinator are pollinated by insects, and where information is available, declines in populations of pollinator insects in the Midwest have primarily been linked to the expansion of intensive agriculture.[167,168,169,170] In addition to habitat loss, climate change is likely to act as an added stressor for many species, through many different mechanisms.[164] Many insects may be limited by their ability to shift to new habitats as conditions change; for example, many bumble bee species are showing population declines at southern range edges but not expanding as quickly at northern range edges.[171] It is likely that pollinators that specialize on one or a few species for some aspect of their life history will be particularly vulnerable.[172] Within the Midwest, observed high rates of decline in the monarch butterfly,[167] which relies on milkweed species as a host plant, are the focus of a network of outreach and ambitious multi-partner conservation efforts that are helping raise awareness of pollinator declines and links between pollinators and habitat availability.[173] These efforts, boosted by research demonstrating that habitat restoration can help sustain pollinator populations,[174,175] provide examples of how to help support the adaptation of this critical group of species.

Perhaps more than in any other region of the United States, human land use has influenced the structure and function of natural systems of the Midwest. Widespread conversion of natural systems to agriculture has changed much of the region's water and energy balance (Ch. 5: Land Changes, KM 1). When vegetation has been removed or undergoes a major change, runoff and flooding both tend to increase.[24,176,177] As land has been cleared for agriculture and cities, it simultaneously has lost the capacity to store water due to the resulting conversion to pavement, compaction of soils, and widespread loss of wetlands. More than half of the region's wetlands have been drained (Ch. 22: N. Great Plains, Case Study "Wetlands and the Birds of the Prairie Pothole Region"); in states at the southern end of the region, fewer than

10%–15% of presettlement wetlands remained in the 1980s.[178] The growth of agriculture and loss of wetlands in the Midwest mean that changes to the timing, type (snow or rain), and amount of precipitation are acting on a system that is already highly altered in ways that tend to promote flooding.[24] Climate change modeling suggests that the southern half of the Midwest likely will see increases in saturated soils, which also indicates risks to agriculture and property from inundation and flooding;[179] recent work incorporating land-use change and population changes also suggests the number of people at risk from flooding will increase across much of the Midwest.[180] However, understanding these relationships also highlights important climate adaptation strategies. For example, restoring systems like wetlands and forested floodplains and implementing agricultural best management strategies that increase vegetative cover (such as cover crops and riparian buffers) can help reduce flooding risks and protect water quality (Figure 21.7).[23,24,25]

Wetland Restoration Projects Can Help Reduce Impacts

Figure 21.7: The Blausey Tract restoration project on the U.S. Fish and Wildlife Service's Ottawa National Wildlife Refuge (Ohio) restored 100 acres of former Lake Erie coastal wetlands that were previously in row crop production. In addition to providing habitat for wildlife and fish, these wetlands help reduce climate change impacts by storing water from high-water events and by filtering nutrients and sediments out of water pumped from an adjacent farm ditch. This work was carried out by two conservation groups, The Nature Conservancy and Ducks Unlimited, in partnership with the U.S. Fish and Wildlife Service, and was funded by The Great Lakes Restoration Initiative.[186,187] (top) Shown here is the Blausey Tract restoration site in early spring of 2011, prior to the restoration activities. (bottom) In the spring of 2013, just two years after the start of restoration, the site already was providing important habitat for wildlife and fish. Photo credits: (top) ©The Nature Conservancy, (bottom) Bill Stanley, ©The Nature Conservancy.

As the flooding risk example above illustrates, understanding both the history of change and how future climate patterns can drive additional changes is useful for identifying meaningful strategies for reducing risks to both people and biodiversity through strategically protecting and restoring ecosystems. Since the Third National Climate Assessment,[27] the recognition, promotion, and implementation of green or ecosystem-based climate change adaptation solutions have expanded. While the idea of using natural systems to reduce risks and provide benefits to society is not new, efforts to document and quantify benefits, costs, and costs savings (relative to hard, or "gray," infrastructure) of these types of approaches are increasing.[181] These approaches often help replace systems that have been lost, such as Great Lakes coastal wetlands, prairies, and vegetated floodplains along rivers and streams that slow waterflows and act as sponges that keep floodwaters from people, property, and infrastructure (Figure 21.7),[182,183] or tree cover that increases shade and improves urban air quality.[181,184] The important role of nature-based solutions like reforestation for mitigating climate change is also increasingly being recognized and quantified.[185] From the perspective of protecting the biodiversity of the Midwest, adaptation and mitigation strategies that incorporate protection or restoration of natural systems can be a great win-win approach, because they often add habitat and restore ecological and hydrological functions that were reduced as a result of land conversion.

Box 21.1: Focus on the Great Lakes

The Great Lakes contain 20% of the world's surface freshwater, provide drinking water and livelihood to more than 35 million people,[188] and allow for important economic and cultural services such as shipping and recreation. The Great Lakes influence regional weather and climate conditions and impact climate variability and change across the region. The lakes influence daily weather by 1) moderating maximum and minimum temperatures of the region in all seasons, 2) increasing cloud cover and precipitation over and just downwind of the lakes during winter, and 3) decreasing summertime convective clouds and rainfall over the lakes.[189,190] In recent decades, the Great Lakes have exhibited notable changes that are impacting and will continue to impact people and the environment within the region.[191] In particular, lake surface temperatures are increasing,[11,12] lake ice cover is declining,[12,13,14] the seasonal stratification of temperatures in the lakes is occurring earlier in the year,[15] and summer evaporation rates are increasing.[13,16]

Along the Great Lakes, lake-effect snowfall has increased overall since the early 20th century. However, studies have shown that the increase has not been steady, and it generally peaked in the 1970s and early 1980s before decreasing.[193] As the warming in the Midwest continues, reductions in lake ice may increase the frequency of lake-effect snows until winters become so warm that snowfall events shift to rain.[194,195]

Lake-surface temperatures increased during the period 1985–2009 in most lakes worldwide, including the Great Lakes.[196] The most rapid increases in lake-surface temperature occur during the summer and can greatly exceed temperature trends of air at locations surrounding the lakes.[197] From 1973 to 2010, ice cover on the Great Lakes declined an average of 71%;[14] although ice cover was again high in the winters of 2014 and 2015,[192] a continued decrease in ice cover is expected in the future.[198,199]

Water levels in the Great Lakes fluctuate naturally, though levels more likely than not will decline with the changing climate.[200] A period of low water levels persisted from 1998 to early 2013. A single warm winter in

Box 21.1: Focus on the Great Lakes, *continued*

The Changing Great Lakes

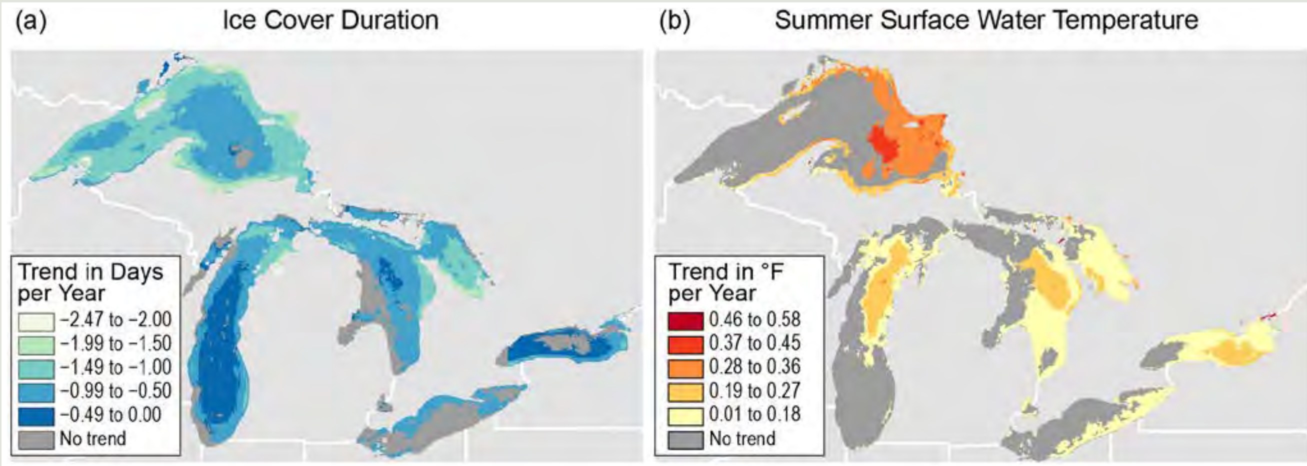

Figure 21.8: The duration of seasonal ice cover decreased in most areas of the Great Lakes between 1973 and 2013, while summer surface water temperature (SWT) increased in most areas between 1994 and 2013. (a) The map shows the rate of change in ice cover duration. The greatest rate of decrease in seasonal ice cover duration is seen near shorelines, with smaller rates occurring in the deeper central parts of Lakes Michigan and Ontario, which rarely have ice cover. (b) The map shows the rate of change in summer SWT. The greatest rates of increase in summer SWT occurred in deeper water, with smaller increases occurring near shorelines. Source: adapted from Mason et al. 2016.[192] Used with permission from Springer.

1997–1998 (corresponding to a major El Niño event) and ongoing increases in sunlight reaching the lake surface (due to reduced cloud cover) were likely strong contributors to these low water levels.[11] Following this period, water levels rose rapidly. Between January 2013 and December 2014, Lake Superior's water rose by about 2 feet (0.6 meters) and Lakes Michigan and Huron's by about 3.3 feet (1.0 meter).[201] Recent projections with updated methods of lake levels for the next several decades under 64 global model-based climate change simulations (from the Coupled Model Intercomparison Project Phase 5, or CMIP5 database, using the RCP4.5, RCP6.0, and RCP8.5 scenarios) on average show small drops in water levels over the 21st century (approximately 6 inches for Lakes Michigan and Huron and less for the other lakes), with a wide range of uncertainty.[200]

An important seasonal event for biological activity in the Great Lakes is the turnover of water, or destratification, which historically has occurred twice per year. Destratification occurs during the fall as the water temperature drops below a threshold of 39°F, the point at which freshwater attains its maximum density, and again during the spring when the water temperature rises above that threshold. The resultant mixing carries oxygen down from the lake surface and nutrients up from the lake bottom and into the water column. In a pattern that is similar to changes in duration of the growing season on land, the climate projections suggest that the overturn in spring that triggers the start of the aquatic "growing season" will happen earlier, and the fall overturn will happen later.[198,202] This trend toward a longer stratified season has been documented at locations in Lake Superior.[197,203] As the duration of the stratified period increases, the risk of impacts from low oxygen levels at depth and a lack of nutrient inputs at the surface increases, potentially leading to population declines of species in both zones. As warming trends continue, it is possible that a full overturning may not occur each year.[204] For example, lake surface temperatures failed to drop below the 39°F threshold during the winters of 2012 and 2017 in parts of southern Lake Michigan and Lake Ontario (see https://coastwatch.glerl.noaa.gov/glsea/glsea.html). When this lack of water mixing contributes to persistently low oxygen levels, the result may be reductions in the growth of phytoplankton (algae) and zooplankton (microscopic animals) that form the basis of aquatic food webs, potentially leading to cascading effects on the health and abundance of species across all levels of Great Lakes food webs.[202,205,206]

Box 21.1: Focus on the Great Lakes, *continued*

Ecological impacts of climate change in the Great Lakes occur in the context of multiple stressors, as these important ecosystems are under stress from pollution, nutrient and sediment inputs from agricultural systems, and invasive species (Ch. 17: Complex Systems, KM 1).[9,10] Human influence on habitats is another stressor. Examples include coastal wetland damage[207] and disturbance by human structures that change habitat conditions and water flow patterns.[208] Fish harvest and other management activities also have influences on populations.[209] Especially in Lake Erie, runoff from agricultural watersheds can carry large volumes of nutrients and sediments that can reduce water quality, potentially leading to hypoxia (inadequate oxygen supply),[210,211] an occurrence that is predicted to be more likely as the climate continues to change.[10] Increased water temperatures and nutrient inputs also contribute to algal blooms, including harmful cyanobacterial algae that are toxic to people, pets, and many native species.[212,213]

As with the inland lake fish described above (see Figure 21.6), climate change is expected to impact the species and fisheries of the Great Lakes.[214] However, the vast size and low temperatures in these lakes suggest that mortality events from temperature are a much lower risk. One key aspect of the influence of warming lakes on fish growth is the availability of suitable thermal habitat, as ectotherms, or cold-blooded species, can grow faster in warmer water due to temperature impacts on metabolic rates. Fish can behaviorally thermoregulate, meaning they can migrate to the portion of the water column that contains water of the particular species' preferred temperature.[215] Bottom-water temperatures in the deep parts of the lakes are expected to remain close to 39°F, while temperatures above the seasonal thermocline (the distinct temperature transition zone separating warmer surface waters from colder waters below) are expected to warm considerably.[202] This means that fish will be able to find habitats that favor higher growth rates for a longer period of time during the year. This same growth rate increase may occur for some species in smaller lakes, but the potential for exceeding critical thresholds is likely higher (Figure 21.6). If sufficient food is available, this will enhance the growth rates for economically important species like yellow perch and lake whitefish even though they are classed as cool-water and coldwater fishes, respectively.[216] It remains unclear, however, if a sufficient food supply will be available to sustain this increase in growth rates.

While some native fish may show enhanced growth, these same changes can influence the survival and growth of invasive species. Nonnative species such as alewife[217] and zebra and quagga mussels[218] have had dramatic impacts on the Great Lakes. Warmer conditions may lead to increases in invasion success and may increase the impact of invasive species that are already present. For example, sea lamprey are parasitic fish that are native to the Atlantic Ocean, and in the Great Lakes, they are the focus of several forms of control efforts.[219] Climate change has potential to reduce the effectiveness of these efforts. In the Lake Superior watershed, in years with longer growing seasons (defined as the number of days with water temperatures above 50°F), lamprey reach larger weights before spawning.[161] Larger body sizes suggest a greater impact on other fish species, because larger lamprey produce more eggs and require more food to survive.[161]

Coastal communities and several economic sectors, including shipping, transportation, and tourism, are vulnerable to the aforementioned climate impacts (Ch. 8: Coastal, KM 1). While the most recent research[200] underscores the great uncertainty in future lake levels, earlier research showed that scenarios of decreasing lake levels will increase shipping costs even if the shipping season is longer,[220] or that lower ice cover could increase the damage to coastal infrastructure caused by winter storms.[221,222] While several coastal communities have expressed willingness to integrate climate action into planning efforts, access to useful climate information and limited human and financial resources constrain municipal action. Producers and users of climate

Box 21.1: Focus on the Great Lakes, *continued*

information are working together to create customized climate information and resources, which increases trust and legitimacy, addressing this challenge (see Case Study "Great Lakes Climate Adaptation Network"). This has been demonstrated in projects, for instance, with marinas and harbors in Michigan, with ravine management in Illinois and Wisconsin, and with the Chicago Climate Action Plan in Illinois.[223,224,225,226] Although many communities in the region are taking steps to incorporate climate change and related impacts into policy and planning decisions, many more may benefit from using their existing stakeholder networks to engage with producers of climate information and build upon lessons learned from leaders in the region.[227]

Key Message 4

Human Health

Climate change is expected to worsen existing health conditions and introduce new health threats by increasing the frequency and intensity of poor air quality days, extreme high temperature events, and heavy rainfalls; extending pollen seasons; and modifying the distribution of disease-carrying pests and insects. By mid-century, the region is projected to experience substantial, yet avoidable, loss of life, worsened health conditions, and economic impacts estimated in the billions of dollars as a result of these changes. Improved basic health services and increased public health measures—including surveillance and monitoring—can prevent or reduce these impacts.

Climate change directly and indirectly impacts human health (Ch. 14: Human Health, KM 1). Midwestern populations are already experiencing adverse health impacts from climate change, and these impacts are expected to worsen in the future.[26,27] The risks are especially high for people who are less able to cope because characteristics like age, income, or social connectivity make them more vulnerable.[228]

Air Quality

Degraded air quality impacts people living in the Midwest. Increases in ground-level ozone and particulate matter are associated with the prevalence of various lung and cardiovascular diseases, which can lead to missed school days, hospitalization, and premature death (Ch. 13: Air Quality, KM 1).[26,28] Despite successful efforts to reduce particulate matter and ozone pollution, climate change could increase the frequency of meteorological conditions that lead to poor air quality.[26,229] In the absence of mitigation, ground-level ozone concentrations are projected to increase across most of the Midwest, resulting in an additional 200 to 550 premature deaths in the region per year by 2050.[28] These account for almost half of the total projected deaths due to the climate-related increase in ground-level ozone nationwide and may cost an estimated $4.7 billion (in 2015 dollars).[28]

Pollen production has been on the rise in the Midwest in recent years, with pollen seasons starting earlier and lasting longer (Ch. 13: Air Quality, KM 3).[28,230] People, particularly children, with asthma and other respiratory diseases are especially vulnerable to aeroallergens.[231] Aeroallergens can cause allergic rhinitis and exacerbate asthma and sinusitis.[231] Oak pollen may be responsible for an increase of 88 to 350 asthma-related emergency room visits by 2050 under the higher scenario (RCP8.5), with an estimated average annual cost ranging between $43,000 and $170,000 (in 2015 dollars).[28]

Projected Changes in Ozone-Related Premature Deaths

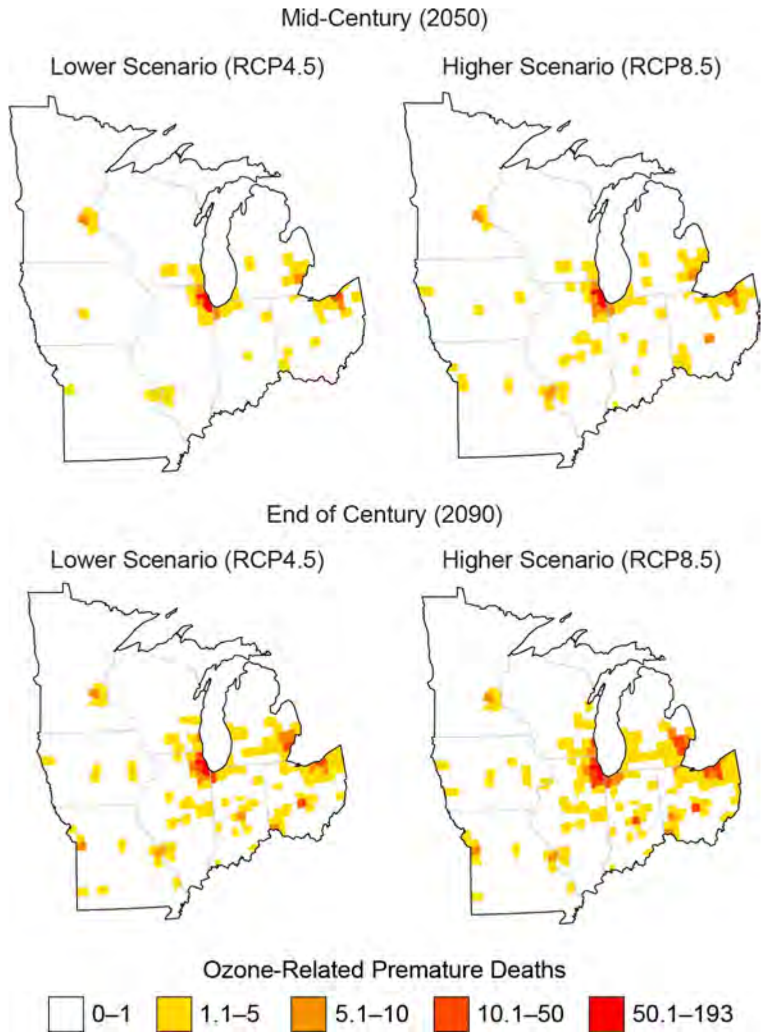

Figure 21.9: Maps show county-level estimates for the change in average annual ozone-related premature deaths over the summer months in 2050 (2045–2055) and 2090 (2085–2095) compared to 2000 (1995–2005) under the lower and higher scenarios (RCP4.5 and RCP8.5) in the Midwest. The results represent the average of five global climate models. Source: adapted from EPA 2017.[28]

Temperature

Increased daytime and nighttime temperatures are associated with heat-related diseases (for example, dehydration and heatstroke) and death in the Midwest.[26,232] Extreme heat in urban centers like Chicago, St. Louis, Cincinnati, Minneapolis/St. Paul, Milwaukee, and Detroit can cause dangerous living conditions.[26,232,233,234,235,236] High rates of heat-related illness also have been observed in rural populations,[235] where occupational exposure to heat and access to care is a concern. Exposure to high temperatures impacts workers' health, safety, and productivity.[29]

Future risk of heat-related disease could be significantly higher. As an example, Figure 21.10 shows the projected number of days over 100°F in Chicago over the 21st century using 32 models and two scenarios. Currently, days over 100°F in Chicago are rare. However, they could become increasingly more common in both the lower and higher scenarios (RCP4.5 and RCP8.5). The higher scenario (RCP8.5) yields a wider range and a higher number of days over 100°F than the lower scenario (RCP4.5), especially by 2070–2090. Near the upper end of the model results (95th percentile) at late-century, with the potential for almost 60 days per year over 100°F, conditions could be more typical of present-day Las Vegas than Chicago. While the degree of uncertainty becomes larger further into the future, all model results show an increase in heat in the last two periods of the 21st century—changes that would pose a significant challenge to Chicago and other midwestern cities.

Compared to other regions where worsening heat is also expected to occur, the Midwest is projected to have the largest increase in extreme temperature-related premature deaths under the higher scenario (RCP8.5): by 2090, 2,000 additional premature deaths per year, compared to the base period of 1989–2000, are projected due to heat alone without adaptation efforts.[28] Northern midwestern communities and vulnerable populations (see Key Message 6) that historically have not experienced high temperatures may be at risk for heat-related disease and death. Risk of death from extremely cold temperatures will decrease under most climate projection scenarios.[28]

Unabated climate change will translate into costs among the workforce and in utility bills, potentially exacerbating existing health disparities among those most at risk. By 2050, increased temperatures under the higher scenario (RCP8.5) are estimated to cost around $10 billion (in 2015 dollars) due to premature deaths and lost work hours.[28] Increased electricity demand is estimated to amount to $1.2 billion by 2090 (in 2015 dollars).[28] For those who are chronically ill or reliant on electronic medical devices, the increased cost of electricity, which contributes to energy insecurity,[28] may introduce financial and health burdens.

Days Above 100°F for Chicago

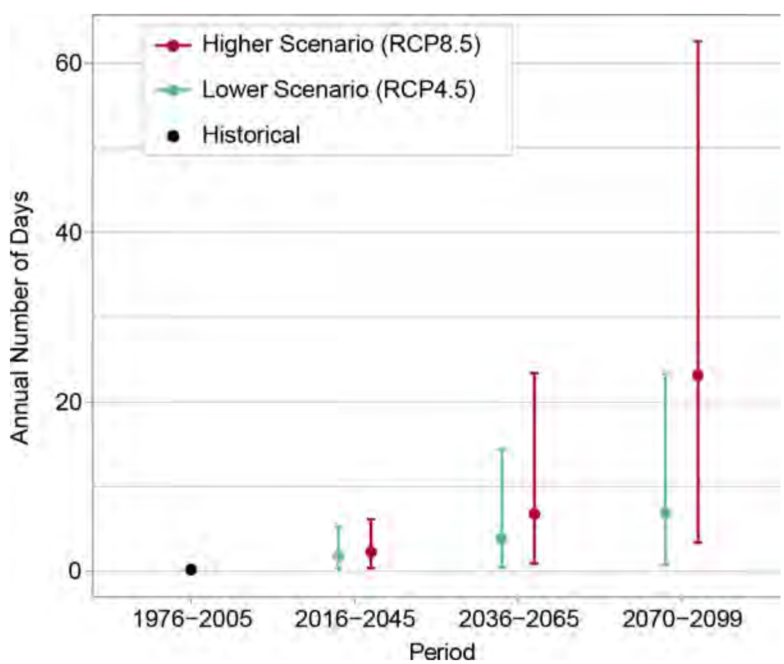

Figure 21.10: This graph shows the annual number of days above 100°F in Chicago for the historical period of 1976–2005 (black dot) and projected throughout the 21st century under lower (RCP4.5, teal) and higher (RCP8.5, red) scenarios. Increases at the higher end of these ranges would pose major heat-related health problems for people in Chicago. As shown by the black dot, the average number of days per year above 100°F for 1976–2005 was essentially zero. By the end of the century (2070–2099), the projected number of these very hot days ranges from 1 to 23 per year under the lower scenario and 3 to 63 per year under the higher scenario. For the three future periods, the teal and red dots represent the model-weighted average for each scenario, while the vertical lines represent the range of values (5th to 95th percentile). Both scenarios show an increasing number of days over 100°F with time but increasing at a faster rate under the higher scenario. Sources: NOAA NCEI and CICS-NC.

Precipitation

An increase in localized extreme precipitation and storm events can lead to an increase in flooding.[27] River flooding in large rivers like the Mississippi, Ohio, and Missouri Rivers and their tributaries can flood surface streets and low-lying areas, resulting in drinking water contamination, evacuations, damage to buildings, injury, and death.[26] Flooded buildings can experience mold growth that can trigger asthma attacks and allergies during cleanup efforts.[237] Mental stress following flooding events can cause substantial health impacts, including sleeplessness, anxiety, depression, and post-traumatic stress disorder.[238] Similarly, drought has been identified as a slow-moving stressor that contributes to acute and chronic mental health impacts such as anxiety and depression.[239]

Precipitation events can transport pathogens that cause gastrointestinal illnesses, putting populations who rely on untreated groundwater (such as wells) at an increased risk of disease,[240] particularly following large rainfall events.[241] Many midwestern communities use wells as their drinking water sources. Adaptive measures, such as water treatment installations, may substantially reduce the risk of gastrointestinal illness, in spite of climate change.[240]

Habitat Conditions

Climate-related changes in habitats (see Key Message 3) for disease-carrying insects like the mosquito found in the Midwest (*Culex pipiens* and *Culex tarsalis*) that transmits West Nile virus (WNV) and the blacklegged, or deer, tick (*Ixodes scapularis*) that transmits Lyme disease have been associated with higher rates of infection.[242,243] Northern expansion of the *Culex* species in the Midwest is expected to result in upwards of 450 additional WNV cases above the 1995 baseline by 2090 absent greenhouse gas mitigation.[28]

Harmful algal blooms (Box 21.1), such as one that occurred in August 2014 in Lake Erie, can introduce cyanobacteria into drinking and recreational water sources, resulting in restrictions on access and use.[28] Contact with and consumption of water contaminated with cyanobacteria have been associated with skin and eye irritation, respiratory illness, gastrointestinal illness, and liver and kidney damage.[26] The occurrence of conditions that encourage cyanobacteria growth, such as higher water temperatures, increased runoff, and nutrient-rich habitats, are projected to increase in the Midwest.[28]

Challenges and Opportunities

Climate-sensitive health impacts are complex and dynamic. Coordination across public health, emergency preparedness, planning, and communication agencies can maximize outreach to the most at-risk populations while directing activities to reduce health disparities and impacts.[244] Public health agencies in the Midwest have developed interdisciplinary communities of practice around climate and health adaptation efforts, effectively enhancing the resilience of the region's public health systems.[244,245,246,247,248] Activities around increased surveillance of climate-sensitive exposures and disease are gaining momentum and interest among practitioners and researchers.[249,250]

Actions tied to reducing contributions to global climate change can result in direct co-benefits related to health and other outcomes (such as economic development).[251] Reducing emissions related to energy production and transportation may involve changes to fuel sources, vehicle technology, land use, and infrastructure.[251] Active transportation, such as biking and walking, has been found to significantly decrease disease burden.[252,253,254] A study of the 11 largest midwestern metropolitan areas estimated a health benefit of nearly 700 fewer deaths per year by swapping half of short trips from car to bike.[255] As Midwest Rust Belt metropolitan areas revitalize and reinvest, there are opportunities to prioritize active living to maximally reduce climate change drivers and improve health.

Key Message 5

Transportation and Infrastructure

Storm water management systems, transportation networks, and other critical infrastructure are already experiencing impacts from changing precipitation patterns and elevated flood risks. Green infrastructure is reducing some of the negative impacts by using plants and open space to absorb storm water. The annual cost of adapting urban storm water systems to more frequent and severe storms is projected to exceed $500 million for the Midwest by the end of the century.

Climate change poses several challenges to transportation and storm water systems in the Midwest. Annual precipitation in the Midwest has increased by 5% to 15% from the first half of the last century (1901–1960) compared to present day (1986–2015).[193] Winter and spring precipitation are important to flood risk in the Midwest and are projected to increase by up to 30% by the end of this century. Heavy precipitation events in the Midwest have increased in frequency and intensity since 1901 and are projected to increase through this century.[193]

There has been an increase in extreme precipitation events that overwhelm storm water sewage systems, disrupt transportation networks, and cause damage to infrastructure and property. Runoff from extreme precipitation events can exceed the capacity of storm water systems, resulting in property damage, including basement backups (Ch. 11: Urban, KM 2).[37,256] In addition, in metropolitan areas with older sewer systems that combine sanitary sewage with storm water, extreme rain can result in the release of raw sewage into rivers and streams, posing both health and ecological risks.[257] These releases, known as combined sewer overflows (CSO), pose challenges to major sources of drinking water including the Mississippi River[258] and the Great Lakes.[259,260] On the Great Lakes, increases in CSO frequency and volume are projected under mid-high and higher scenarios (RCP6.0 and RCP8.5).[261] The U.S. Environmental Protection Agency (EPA) estimates that the cost of adapting urban storm water systems to handle more intense and frequent storms in the Midwest could exceed $480 million per year (in 2015 dollars) by the end of the century under either the lower or higher scenario (RCP4.5 or RCP8.5).[28] Extreme precipitation events also affect transportation systems (Ch. 12: Transportation, KM 1). Heavy rainstorms can result in the temporary closure of roadways. In addition, faster streamflow caused by extreme precipitation can erode the bases of bridges, a condition known as scour. A study of six Iowa bridges deemed to be critical infrastructure found that under all emissions scenarios (in the Coupled Model Intercomparison Project Phase 3), each location was projected to have increased vulnerability from more frequent episodes of overtopping and potential scour.[55] The EPA estimates that the annual cost of maintaining current levels of service on midwestern bridges in the face of increased scour damage from climate change could reach approximately $400 million in the year 2050 under either the lower or higher scenario (RCP4.5 or RCP8.5).[28]

In addition to its impacts on infrastructure, heavy precipitation also affects the operation of roadways by reducing safety and capacity while increasing travel times (Ch. 12: Transportation, KM 1). Projected increases in the number of extreme precipitation events have been linked to an increased risk of traffic crashes.[262] Intelligent Transportation Systems (ITS) use sensors and cameras to monitor road conditions. This allows for rapid deployment of emergency response vehicles and use of electronic signage to reroute traffic. Such systems allow transportation agencies to minimize the adverse impacts associated with extreme weather.[263]

Flooding on major rivers also poses a challenge to Midwest communities. Major river floods differ from flash floods on smaller streams in that they affect a larger area and require longer periods of heavy precipitation to create flood conditions. The Nation's two largest rivers, the Mississippi and the Missouri, flow through the Midwest. River floods can cause loss of life, as well as significant property damage. River floods have caused the closure of interstate highways in the Midwest and temporary inundation of secondary roads. During floods in May 2017, more than 400 state roads in Missouri were closed due to flooding, including several stretches of Interstate 44 (Figure 21.11).[264] High water also disrupts barge traffic on the Mississippi River.[265,266,267,268,269,270] Billion-dollar floods in the Midwest have occurred three times in the last quarter-century.[271] Climate projections suggest an increased risk of inland flooding under either the lower or higher scenario (RCP4.5 or RCP8.5). Average annual damages from heightened flooding risk in the Midwest are projected to be in excess of $500 million (in 2015 dollars) by 2050.[28]

Changes in temperature also can pose challenges to infrastructure. Extreme heat creates material stress on road pavements, bridge expansion joints, and railroad tracks. Milder winter temperatures, however, may be expected to partially offset these damages by reducing the amount of rutting caused by the freeze–thaw cycle. Even taking into account the benefits of milder winters for paved surfaces, the EPA estimates that higher temperatures associated with unmitigated climate change would result in approximately $6 billion annually in added road maintenance costs and over $1 billion in impacts to rail transportation by 2090 (in 2015 dollars).[28]

River Flooding in the Midwest

Figure 21.11: This composite image shows portions of Interstate 44 near St. Louis that were closed by Meramec River flooding in both 2015 and 2017. The flooding shown here occurred in May 2017. Image credit: Surdex Corporation.

Green infrastructure—the use of plants and open space to manage storm water—is helping communities in the Midwest become more resilient to challenges associated with heavy precipitation. At the site or neighborhood level, rain gardens and other planted landscape elements collect and filter rainwater in the soil, slowing runoff into sewer systems. Permeable pavements on parking lots allow water to be stored in the soil. Trees planted next to streets also provide important storm water management benefits. Larger-scale projects include preservation of wetlands. In addition to their storm water management benefits, some types of green infrastructure, such as urban trees and green roofs, contribute to climate change mitigation by acting as carbon sinks.[272,273,274]

There are many examples of green infrastructure projects in the Midwest, though not all explicitly identify climate change as a rationale. The examples below enhance resilience to the heavy rains that are projected to become more frequent.

- The Cermak/Blue Island Sustainable Streetscape Project in the Pilsen neighborhood of Chicago uses bioswales, rain gardens, and permeable pavements to reduce up to 80% of storm water runoff. It also uses street trees and other vegetation to reduce the urban heat island effect while also providing an attractive public space.[275]

- The Metropolitan Sewer District in St. Louis has embarked upon a $100 million rainscaping project designed to divert storm water runoff in the northern portion of the City of St. Louis and adjacent north St. Louis County.[276]

- The City of Minneapolis uses street trees to reduce storm water runoff through enhanced evaporation and infiltration of water into the soil.[277] The City of Cleveland also prioritizes tree planting as an adaptation strategy, with an emphasis on increasing the tree canopy in low-income neighborhoods. In addition to its storm water management benefits, urban forestry also reduces the urban heat island effect and acts as a carbon sink.[278]

At the scale of a metropolitan region, preservation and restoration of streams, floodplains, and watersheds are enhancing biodiversity while also reducing storm water runoff.

- *Open Space Preservation*: Many communities in the Midwest are recognizing that preservation of open space, particularly in floodplains, is a cost-effective method for managing storm water. Ducks Unlimited, a non-profit organization, has purchased conservation easements that restrict future development on nearly 10,000 acres of floodplain around the confluence of the Mississippi and Missouri Rivers. In the Milwaukee area, the Ozaukee Washington Land Trust has preserved more than 6,000 acres of forests, wetlands, and open space through acquisitions and the purchase of conservation easements, preserving lands important for absorbing rainwater and filtering toxins from sediment.[279,280]

- *Stream Restoration*: Several midwestern communities are turning to dechannelization (the removal of concrete linings placed in waterways) and daylighting (bringing back to the surface streams that had been previously buried in pipes) as methods of storm water management. The Milwaukee Metropolitan Sewerage District is currently undertaking a dechannelization of the Kinnickinnic River. According to the District, the concrete lining of the waterway actually makes the waterway more dangerous during heavy rain. Flooding motivated the City of Kalamazoo to daylight a 1,500-foot section of Arcadia Creek in the downtown district.[281,282]

- *Ravine Restoration*: Lake Michigan's western shore in Wisconsin and northern Illinois holds more than 50 small watersheds, known locally as ravines. Storm water runoff subjects these ravines to serious erosion, which threatens property and infrastructure. The Great Lakes Alliance has produced guides to reduce erosion through best management practices, including stream buffers, use of native plants for stabilization, and reducing the steepness or gradient of the stream bank.[223]

Key Message 6

Community Vulnerability and Adaptation

At-risk communities in the Midwest are becoming more vulnerable to climate change impacts such as flooding, drought, and increases in urban heat islands. Tribal nations are especially vulnerable because of their reliance on threatened natural resources for their cultural, subsistence, and economic needs. Integrating climate adaptation into planning processes offers an opportunity to better manage climate risks now. Developing knowledge for decision-making in cooperation with vulnerable communities and tribal nations will help to build adaptive capacity and increase resilience.

Vulnerability and Adaptation

In the Midwest, negative impacts related to climate change are projected to affect human systems, including cities, rural and coastal communities, and tribes.[28,283,284] Higher temperatures, increasing variation in precipitation patterns, and changes in lake levels are likely to increase the vulnerability of these systems to extreme events (including flooding, drought, heat waves, and more intense urban heat island effects), compounding already existing stressors such as economic downturns, shrinking cities, and deteriorating infrastructure.[285] Extreme heat such as that experienced in July 2011 (with temperatures reaching over 100°F in the majority of the Midwest) is expected to intensify,[286] and urban heat islands may cause hardships to those most vulnerable, such as the old and infirm and those without resources to control their microclimate (for example, through the use of air conditioning).[287] Under the higher scenario (RCP8.5), extreme heat is projected to result in losses in labor and associated losses in economic revenue up to $9.8 billion per year in 2050 and rising to $33 billion per year in 2090 (in 2015 dollars).[28] Expanding the use of green infrastructure and locating it properly may mitigate the negative impact of heat islands in urban settings (see Key Messages 4 and 5) (see also Ch. 11: Urban, KM 4).

To mitigate or better respond to these impacts, scholars and practitioners highlight the need to engage in risk-based approaches that not only focus on assessing vulnerabilities but also include effective planning and implementation of adaptation options (Ch. 28: Adaptation, KM 3).[32] These place-based approaches actively rely on participatory methodologies to evaluate and manage risk and to monitor and evaluate adaptation actions.[32] However, documented implementation of climate change planning and action in Midwest cities and rural communities remains low. For example, in 2015, only four counties and cities in the region—Marquette and Grand Rapids in Michigan and Dane County and Milwaukee in Wisconsin—had created formal climate adaptation plans, none of which have been implemented.[288] Moreover, a recent study of 371 cities in the Great Lakes region found that only 36 of them could identify a climate entrepreneur, that is, a public official clearly associated with pushing for climate action.[285] Attempts to assess vulnerabilities, especially for poor urban communities, face persisting environmental and social justice barriers, such as lack of participation and historical disenfranchisement,[289] despite evidence that these communities are going to be disproportionately affected by climate impacts.[290] Additionally, in-depth interviews with local decision-makers on water management across scales have suggested that a lack of political and financial support at the state and federal levels is a barrier to adaptation action in cities and counties.[291] While initiatives are underway in the Midwest to mainstream adaptation action—that is, embed and integrate climate adaptation action in what cities already do (see Case Study "Great Lakes Climate Adaptation Network") (see also Ch. 28: Adaptation, KM 5)—there are few examples in the published literature that document failure or success (but see Kalafatis et al. 2015, Vogel et al. 2016[292,293]).

Case Study: Great Lakes Climate Adaptation Network

The Great Lakes Climate Adaptation Network (GLCAN) is a regional, member-driven peer network of local government staff who work together to identify and act on the unique climate adaptation challenges of the Great Lakes region. GLCAN formed in 2015 as a regional network of the Urban Sustainability Directors' Network (USDN) to unite Great Lakes cities with universities in the region. It has been cooperating actively with a regional climate organization, the Great Lakes Integrated Sciences and Assessments (GLISA), a NOAA-supported program housed at the University of Michigan and Michigan State University, to create climate information in support of decision-making in member cities. In this example of sustained engagement, GLCAN and GLISA work as a boundary chain that moves climate information from producers at the Universities to users in the cities, as well as across cities. This minimizes transaction costs, in terms of human and financial resources, while building trust and legitimacy.[292,294] In one example of this partnership, with funding from USDN, GLCAN and GLISA worked with the Huron River Watershed Council and five Great Lakes cities (Ann Arbor, Dearborn, Evanston, Indianapolis, and Cleveland) to develop a universal vulnerability assessment template that mainstreams the adaptation planning process and results in the integration of climate-smart and equity-focused information into all types of city planning.[295] The template is publicly available;[296] its purpose is to reduce municipal workloads and save limited resources by mainstreaming existing, disparate planning domains (such as natural hazards, infrastructure, and climate action), regardless of city size or location. Based on this work, USDN funded a follow-up project for GLISA to work with additional Great Lakes and Mid-Atlantic cities and a nonprofit research group (Headwaters Economics) to develop a socioeconomic mapping tool for climate risk planning.

Linked Boundary Chain Model

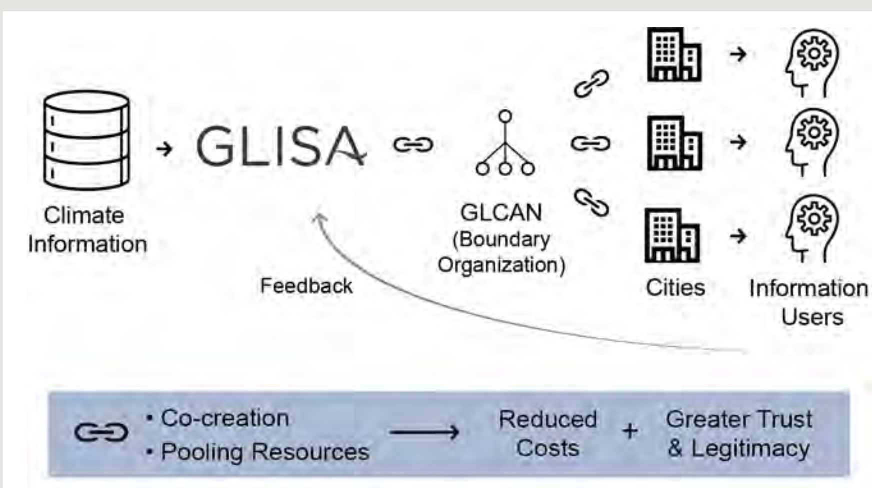

Figure 21.12: Shown here is a configuration of the boundary chain employed in the Great Lakes Climate Adaptation Network (GLCAN) Case Study. The information is tailored and moves through different boundary organizations (links in the chain) to connect science to users. By co-creating information and pooling resources throughout the chain, trust and legitimacy are built and cost is decreased. Source: adapted from Lemos et al. 2014.[294] ©American Meteorological Society.

In addition, work on estimating the cost of adaptation nationally and in the Midwest remains limited, though the EPA has estimated that the Midwest is among the regions with the largest expected damages to infrastructure, including the highest estimated damages to roads, rising from $3.3 billion per year in 2050 to $6 billion per year in 2090 (in 2015 dollars) under a higher scenario (RCP8.5), and highest number of vulnerable bridges (Key Message 5).[28] Additionally, economic models that value climate amenities—for example, offering residents the benefits of warmer winters or cooler summers—indicate that while the Midwest is among the regions with the largest predicted amenity loss, certain cities (such as Minneapolis and Minnesota) and subregions (such as upper Michigan) will be among the few places where the value of warmer winters outweighs the cost of hotter summers.[297,298] Limited evidence indicates that household consideration of climate amenities may contribute to reversing long-standing trends in out-migration from the Midwest[298] and that changes in national migration patterns will contribute to population growth in the region.[28] More research is needed to understand how cities in the Midwest might be affected by long-term migration to the region.[31]

Collaboratively Developing Knowledge and Building Adaptive Capacity

Interactions among producers of climate information (for example, universities and research institutes), end users (such as city planners, watershed managers, and natural resource managers), and intermediaries (for example, information brokers and organizations) play a critical role in increasing the integration and use of climate knowledge for adaptation.[299] In the Midwest, organizations such as the Great Lakes Integrated Sciences and Assessments (GLISA; glisa.umich.edu) and the Wisconsin Initiative on Climate Impacts (wicci.wisc.edu), and research projects such as Useful to Usable (U2U), have created mechanisms and tools, such as climate scenarios, decision support tools, and climate data, that promote the joint development of usable climate information across different types of stakeholders, including city officials, water managers, farmers, and tribal officials.[224,294,300] For example, working closely with corn farmers and climate information intermediaries, including extension agents and crop consultants, in Iowa, Nebraska, Michigan, and Indiana, an interdisciplinary team of climate scientists, agronomists, computer scientists, and social scientists have not only created a suite of decision support tools (see Key Message 1) but also significantly advanced understanding of corn farmers' perceptions of climate change,[301] willingness to adapt,[302] and opportunities for and limitations of the use of climate information in the agricultural sector.[294,303] Strategies being implemented as a result of these collaborations, including the use of green infrastructure and water conservation efforts, are proving effective at reducing sensitivity to the impacts of climate change in the Midwest.[304,305,306] In addition, binational partnerships between the United States and Canada, in support of the Great Lakes Water Quality Agreement, synthesized annual climate trends and impacts for a general audience in a pilot product for 2017 to provide a timely and succinct summary in an easy-to-understand format (Ch. 16: International, KM 4).[307] However, these organizations face challenges including the high costs in interacting with users, contextualizing and customizing climate information, and building trust.[308] The development of new forms of sustained engagement likely would increase the use of climate information in the region.

Tribal Adaptation

Tribes and Indigenous communities in the Midwest have been among the first to feel the effects of climate change as it impacts their culture, sovereignty, health, economies, and ways of life.[39] The Midwest contains ceded territory—large swaths of land in Minnesota, Wisconsin, and Michigan in which Ojibwe tribes reserved hunting, fishing, and gathering rights in treaties with the United States government.[88] Climate change presents challenges to the O jibwe tribes in co-managing these resources with other land managers; as the climate changes, various species utilized by tribes are declining and may shift entirely outside of treaty boundaries and reserved lands.[127,309,310] In certain tribal cultures, all beings (species) are important; climate adaptation efforts that favor certain beings at the detriment of others can be problematic. Adaptation to climate change might also mean giving up on something deeply embedded in tribal culture for whichno substitute exists.[31] A family sugarbush (a forest stand used for maple syrup), for example, cannot be replaced culturally, spiritually, or economically if the sugar maple range were to shift outside of treaty or reservation boundaries. As the effects of climate change become more pronounced, further research can shed light on how tribal nations are being affected.

Projected changes in climate, particularly increases in extreme precipitation events, will have pronounced impacts on tribal culture and tribal people in the Midwest.[283] Reservations often are located in isolated rural communities, meaning emergency response to flooding presents challenges in getting help to tribal citizens. Additionally, in areas of the Midwest, infestations of the invasive emerald ash borer already are devastating ash tree populations and corresponding Indigenous cultural and economic traditions.[127]

Across the United States, a number of tribal nations are developing adaptation plans, including in the Midwest (Ch. 15: Tribes, KM 3).[283] These plans bring together climate data and projections with Traditional Ecological Knowledge[311,312] of tribal members. Within Indigenous oral history lies a complex and rich documentation of local ecosystems—not found in books—that can be used to understand and document the changes that are occurring.[313] Climate change effects are not typically immediate or dramatic because they occur over a relatively long period of time, but tribal elders and harvesters have been noticing changes, such as declining numbers of waabooz (snowshoe hare), many of which Scientific Ecological Knowledge has been slower to document. The Traditional Ecological Knowledge of elders and harvesters who have lived and subsisted in a particular ecosystem can provide a valuable and nuanced understanding of ecological conditions on a smaller, more localized scale. Integrating this Traditional Ecological Knowledge with Scientific Ecological Knowledge in climate change initiatives provides a more complete understanding of climate change impacts.[136] Community input to tribal adaptation plans ensures that Traditional Ecological Knowledge can be used to produce adaptation strategies trusted by community members.[314]

Acknowledgments

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Traceable Accounts

Process Description

The chapter lead authors were identified in October 2016, and the author team was recruited in October and November 2016. Authors were selected for their interest and expertise in areas critical to the Midwest with an eye on diversity in expertise, level of experience, and gender. The writing team engaged in conference calls starting in December 2016, and calls continued on a regular basis to discuss technical and logistical issues related to the chapter. The Midwest chapter hosted an engagement workshop on March 1, 2017, with the hub in Chicago and satellite meetings in Iowa, Indiana, Michigan, and Wisconsin. The authors also considered other outreach with stakeholders, inputs provided in the public call for technical material, and incorporated the available recent scientific literature to write the chapter. Additional technical authors were added as needed to fill in the gaps in knowledge.

Discussion amongst the team members, along with reference to the Third National Climate Assessment and conversations with stakeholders, led to the development of six Key Messages based on key economic activities, ecology, human health, and the vulnerability of communities. In addition, care was taken to consider the concerns of tribal nations in the northern states of the Midwest. The Great Lakes were singled out as a special case study based on the feedback of the engagement workshop and the interests of other regional and sector chapters.

Note on regional modeling uncertainties

Interaction between the lakes and the atmosphere in the Great Lakes region (e.g., through ice cover, evaporation rates, moisture transport, and modified pressure gradients) is crucial to simulating the region's future climate (i.e., changes in lake levels or regional precipitation patterns).[315,316] Globally recognized modeling efforts (i.e., the Coupled Model Intercomparison Project, or CMIP) do not include a realistic representation of the Great Lakes, simulating the influence of the lakes poorly or not at all.[192,198,317,318,319] Ongoing work to provide evaluation, analysis, and guidance for the Great Lakes region includes comparing this regional model data to commonly used global climate model data (CMIP) that are the basis of many products practitioners currently use (i.e., NCA, IPCC, NOAA State Climate Summaries). To address these challenges, a community of regional modeling experts are working to configure and utilize more sophisticated climate models that more accurately represent the Great Lakes' lake–land–atmosphere system to enhance the understanding of uncertainty to inform better regional decision-making capacity (see http://glisa.umich.edu/projects/great-lakes-ensemble for more information).

Key Message 1

Agriculture

The Midwest is a major producer of a wide range of food and animal feed for national consumption and international trade. Increases in warm-season absolute humidity and precipitation have eroded soils, created favorable conditions for pests and pathogens, and degraded the quality of stored grain (*very likely*, *very high confidence*). Projected changes in precipitation, coupled with rising extreme temperatures before mid-century, will reduce Midwest agricultural productivity to levels of the 1980s without major technological advances (*likely*, *medium confidence*).

Description of evidence base

Humidity is increasing. Feng et al. (2016)[3] show plots of trends in surface and 850 hPa specific humidity of 0.4 and 0.2 g/kg/decade, respectively, from 1979–2014 for the April–May–June period across the Midwest. These represent increases of approximately 5% and 3% per decade, respectively. Automated Surface Observing Stations in Iowa[320] having dew point records of this length and season show dew point temperature increases of about 1°F per decade. Brown and DeGaetano (2013)[49] show increasing dew points in all seasons throughout the Midwest. Observed changes in annual average maximum temperature for the Midwest over the 20th century (Vose et al. 2017,[54] Table 6.1) have been less than 1°F. However, future projected changes in annual average temperature (Vose et al. 2017,[54] Table 6.4), as well as in both warmest day of the year and warmest 5-day 1-in-10 year events (Vose et al. 2017,[54] Table 6.5), are higher for the Midwest than in any other region of the United States.

Garbrecht et al. (2007)[321] state that precipitation changes are sufficient to require U.S. policy changes for agricultural lands. The Soil Erosion Site (http://soilerosion.net/water_erosion.html) describes the soil erosion process and provides links to soil erosion models.[322] Nearing et al. (2004)[44] report that global climate models project increases in erosivity (the ability or power of rain to cause soil loss) across the northern states of the United States over the 21st century.

Spoilage in stored grain is caused by mold growth and insect activity, which are related to the moisture content and temperature of the stored grain.[323] The ability of fungi to produce mycotoxins, including aflatoxin and fumonisins, is largely influenced by temperature, relative humidity, insect attack, and stress conditions of the plants.[57,324] Humidity has a determining influence on the growth rate of these degradation agents.[325]

Germination of wheat declined in storage facilities where moisture level increased with time.[326] Freshly harvested, high-moisture content grain must be dried to minimize (or prevent) excessive respiration and mold growth on grains.[327] The storage life of grain is shortened significantly when stored at warm temperatures. One day of holding warm, wet corn before drying can decrease storage life by 50%.[45]

Feng et al. (2016)[3] show humidity is rising in the Midwest in the warm season. Cook et al. (2008)[4] show that the factors leading to these humidity increases (warming Gulf of Mexico and strengthening of the Great Plains Low-Level Jet) will increase in a warming climate.

The ability of fungi to produce mycotoxins is largely influenced by temperature, relative humidity, insect attack, and stress conditions of the plants.[324] More extreme rainfall events would favor formation of Deoxynivalenol, also known as vomitoxin.[57]

Hatfield et al. (2011,[50] Table 1) give the relationships between temperature and vegetative function as well as reproductive capacity. This work was expanded and updated in Walthall et al. (2012).[328]

Mader et al. (2010)[74] report a comprehensive climate index for describing the effect of ambient temperature, relative humidity, radiation, and wind speed on environmental stress in animals. St-Pierre et al. (2003)[329] provide tables estimating economic losses in dairy due to reduced reproduction. The data show a strong gradient across the Midwest (with losses in Iowa, Illinois, and Indiana being three times the losses in Minnesota, Wisconsin, and Michigan under the current climate). Temperature and humidity increases projected for the Midwest will increase economic losses across the entire region. Lewis and Bunter (2010)[330] document heat stress effects of temperature on pig production and reproduction.

St-Pierre et al. (2003)[329] provide tables estimating economic losses in dairy, beef, swine, and poultry, resulting in declines from both meat/milk/egg production. The data show a strong gradient across the Midwest (with losses in Iowa, Illinois, and Indiana being twice the losses in Minnesota, Wisconsin, and Michigan under the current climate). Temperature and humidity increases projected for the Midwest will increase losses across the entire region. Babinszky et al. (2011)[75] identified temperature thresholds for meat/egg/milk production, beyond which performance declines. The adverse effects of heat stress include high mortality, decreased feed consumption, poor body weight gain and meat quality in broiler chickens, and poor laying rate, egg weight, and shell quality in laying hens.[76]

Takle et al. (2013)[65] found that by mid-century, yields of corn and soybean are projected to fall well below projections based on extrapolation of trends since 1970 even under an optimistic economic scenario, with larger interannual variability in yield and total production. Liang et al. (2017)[2] report that the ratio of measured agricultural output to measured inputs would drop by an average 3% to 4% per year under medium to high emissions scenarios and could fall to pre-1980 levels by 2050 even when accounting for present rates of innovation. Schauberger et al. (2017)[66] found that the impact of exposure to temperatures from 30°C to 36°C projected for the end of the century under RCP8.5 creates yield losses of 49% for maize and 40% for soybean.

According to Easterling et al. (2017),[193] evidence suggests that droughts have become less frequent in the Midwest as the region has become wetter. However, they note that "future higher temperatures will likely lead to greater frequencies and magnitudes of agricultural droughts throughout the continental United States as the resulting increases in evapotranspiration outpace projected precipitation increases."

Major uncertainties

Global and regional climate models do not simulate well the dynamical structure of mesoscale convective systems in the Midwest, which are the critical "end processes" that create intense precipitation from increasing amounts of moisture evaporated over the Gulf of Mexico and transported by low-level jets (LLJs) into the Midwest. Secondly, the strengthening of future LLJs depends on strengthening of both the Bermuda surface high pressure and the lee surface low over the eastern Rocky Mountains. Confirming simulations of this in future climates are needed. Global and regional climate models do simulate future scenarios having increasing temperatures for the region with high confidence (a necessary ingredient for increased humidity). There is uncertainty of the temperature thresholds for crops because, as pointed out by Schauberger et al. (2017),[66] some negative impacts of higher temperatures can be overcome through increased water availability. Agricultural yield models, productivity models, and integrated assessment models each provide different ways of looking at agricultural futures, and each of these three types of models has high levels of uncertainty. However, all point to agriculture futures that fail to maintain upward historical trends.

Description of confidence and likelihood

There is *very high confidence* that increases in warm-season absolute humidity and precipitation *very likely* have eroded soils, created favorable conditions for pests and pathogens, and degraded quality of stored grain. There is *medium confidence* that projected increases in moisture, coupled with rising mid-summer temperatures, *likely* will be detrimental to crop and livestock production and put future gains in commodity grain production at risk by mid-century. Projected changes in precipitation, coupled with rising extreme temperatures, provide *medium confidence* that by mid-century Midwest agricultural productivity *likely* will decline to levels of the 1980s without major technological advances.

Key Message 2

Forestry

Midwest forests provide numerous economic and ecological benefits, yet threats from a changing climate are interacting with existing stressors such as invasive species and pests to increase tree mortality and reduce forest productivity (*likely*, *high confidence*). Without adaptive actions, these interactions will result in the loss of economically and culturally important tree species such as paper birch and black ash (*very likely*, *very high confidence*) and are expected to lead to the conversion of some forests to other forest types (*likely*, *high confidence*) or even to non-forested ecosystems by the end of the century (*as likely as not*, *medium confidence*). Land managers are beginning to manage risk in forests by increasing diversity and selecting for tree species adapted to a range of projected conditions.

Description of evidence base

Multiple ecosystem vulnerability assessments that have been conducted for major forested ecoregions within the Midwest[89,90,91,92,93] suggest that climate change is expected to have significant direct impacts to forests through effects of warming and changes in the timing and amounts of precipitation.[96,98,103,104]

Significant indirect impacts to forests are expected as warming increases the negative effects of invasive plants, insect pests, and tree pathogens of forests.[105,106] Increasing stress on individual trees from climate changes (warming temperatures, drought, and frost damage) increases the susceptibility of trees to the impacts from invasive plants, insect pests, and disease agents.[109,111]

Direct and indirect impacts of climate change may lead to the decline of culturally[88,127] and economically important tree species,[125] as well as leading to shifts in major forest types and altered forest composition as tree species at the northern limits of their ranges decline and southern species experience increasing suitable habitat.[120] These shifts raise the possibility of future losses of economic and cultural benefits of forests due to conversion to different forest types or the change to non-forest ecosystems.[119,123,124]

Many examples of land managers implementing climate adaptation in forest management exist, suggesting significant willingness to address the impacts of a changing climate across diverse land ownerships in managed forests[134] and urban forests.[133] Forest management strategies to adapt to a changing climate highlight the importance of increasing forest diversity and managing for tree species adapted to a range of climate conditions.[8] The importance of Traditional Ecological Knowledge for informing approaches for climate adaptation on tribal lands and within ceded territory is recognized.[331]

Major uncertainties

There is significant uncertainty surrounding the ability of tree species migration rates to keep pace with changes in climate (based on temperature and precipitation) due to existing forest fragmentation and loss of habitat. Uncertainty in forest management responses, including active and widespread adaptation efforts that alter forest composition, add to the uncertainty of tree species movements. This leads to considerable uncertainty in the extent to which shifts in tree species ranges may lead to altered forest composition or loss of forest ecosystems in the future.

Due to the complex interactions among species, there is uncertainty in the extent that longer growing seasons, warming temperatures, and increased CO_2 concentrations will benefit tree species, due to both limitations in available water and nutrients, as well as limited benefits for trees relative to the positive influences of these changes on stressors (invasives, insect pests, pathogens).

Description of confidence and likelihood

There is *high confidence* that the interactions of warming temperatures, precipitation changes, and drought with insect pests, invasive plants, and tree pathogens will *likely* lead to increased tree mortality of some species, reducing productivity of some forests. There is *very high confidence* that these interactions will *very likely* result in the decline of some economically or culturally important tree species. Additionally, there is *high confidence* that suitable habitat conditions for tree species will change as temperatures increase and precipitation patterns change, making it *likely* that forest composition will be altered and forest ecosystems may shift to new forest types. Due to uncertainties on species migration rates and forest management responses to climate changes, there is *medium confidence* that by the end of the century, some forest ecosystems are *as likely as not* to convert to non-forest ecosystems.

Key Message 3

Biodiversity and Ecosystems

The ecosystems of the Midwest support a diverse array of native species and provide people with essential services such as water purification, flood control, resource provision, crop pollination, and recreational opportunities. Species and ecosystems, including the important freshwater resources of the Great Lakes, are typically most at risk when climate stressors, like temperature increases, interact with land-use change, habitat loss, pollution, nutrient inputs, and nonnative invasive species (*very likely*, *very high confidence*). Restoration of natural systems, increases in the use of green infrastructure, and targeted conservation efforts, especially of wetland systems, can help protect people and nature from climate change impacts (*likely*, *high confidence*).

Description of evidence base

Changes in climate will very likely stress many species and ecological systems in the Midwest. As a result of increases in climate stressors, which typically interact with multiple other stressors, especially in the southern half of the Midwest region, both the ecological systems and the ecological services (water purification, pollination of crops and wild species, recreational opportunities, etc.) they provide to people are at risk. We draw from a wide range of national and global scale assessments of risks to biodiversity (e.g., Maclean and Wilson 2011, Pearson et al. 2014, and the review by Staudinger et al. 2013 that covered literature included in the Third National Climate Assessment[20, 18,22]), which all agree that on the whole, we are highly likely to see increases in species declines and extinctions as a result of climate change. It is very challenging to say specifically what combination of factors will drive these responses, but the weight of evidence suggests very high confidence in the overall trends. The link to interactions with other stressors is also very strong and is described in Brook et al. (2008)[157] and Cahill et al. (2013),[17] among others. Terrestrial ecosystem connectivity, thought to be important for the adaptive capacity of many species, is very low in the southern half of the Midwest region.[158,159] This may limit the movement of species to more suitable habitats or for species from the southern United States to migrate into the Midwest. These connectivity/movement potential studies also support the idea that land-use change will constrain the potential for retaining function and overall diversity levels. The last section refers to the benefits of restoration as a mechanism for protecting people and nature from climate change impacts. While it is not possible to fully demonstrate that protection of people and nature is indeed occurring now from climate change impacts (we would need attribution of current floods, etc.), there is strong evidence that actions like restoring wetlands can reduce flooding impacts[182] and that protecting forests protects water quality and supply.

Major uncertainties

There is significant uncertainty surrounding the ability of species and ecosystems to persist and thrive under climate change, and we expect to see many different types of responses (population increases, declines, local and regional extinctions).[17] In some cases, climate change does have the potential to benefit species; for example, fish in the coldest regions of the Great Lakes (i.e., Lake Superior) are likely to show increases in productivity, at least in the short run.[332] However, as a whole, given the environmental context upon which climate change is operating, and the presence of many cold-adapted species that are close to the southern edge of their distributional range, we expect more declines than increases.

The last section of the Key Message focuses on land protection and restoration—conservation strategies intended to reduce the impacts of land-use change. Many modeling studies have called out loss of habitat in the Midwest as a key barrier to both local survival and species movement in response to climate change (Schloss et al. 2012 and Carroll et al. 2015 are two of the most recent[158,159]). Restoring habitat can restore connectivity and protect key ecological functions like pollination services and water purification. Restoring wetlands also can help protect ecosystems and people from flooding, which is the rationale for the last line in the Key Message.

Description of confidence and likelihood

In the Midwest, we already have seen very high levels of habitat loss and conversion, especially in grasslands, wetlands, and freshwater systems. This habitat degradation, in addition to the pervasive impacts of invasive species, pollution, water extraction, and lack of connectivity, all suggest that the adaptive capacity of species and systems is compromised relative to systems that are more intact and under less stress. Over time, this pervasive habitat loss and degradation has contributed to population declines, especially for wetland, prairie, and stream species. A reliance on cold surface-water systems, which often have compromised connectivity (due to dams, road-stream crossings with structures that impede stream flow, and other barriers) suggests that fresh-water species, especially less mobile species like mussels, which are already rare, are at particular risk of declines and extinction. Due to the variety of life histories and climate sensitivities of species within the region, it is very challenging to specify what mechanisms will be most important in terms of driving change. However, knowing that drivers like invasive species, habitat loss, pollution, and hydrologic modifications promote species declines, it is *very likely* that the effects of climate change will interact, and we have *very high confidence* that these interactions will tend to increase, rather than decrease, stresses on species that are associated with these threats. While there is strong evidence that investments in restoring habitat can benefit species, we currently do not have strong observational evidence of the use of these new habitats, or benefits of restored wetlands, in response to isolated climate drivers. Thus, the confidence level for this statement is lower than for the first half of the message.

Key Message 4

Human Health

Climate change is expected to worsen existing conditions and introduce new health threats by increasing the frequency and intensity of poor air quality days, extreme high temperature events, and heavy rainfalls; extending pollen seasons; and modifying the distribution of disease-carrying pests and insects (*very likely*, *very high confidence*). By mid-century, the region is projected to experience substantial, yet avoidable, loss of life, worsened health conditions, and economic impacts estimated in the billions of dollars as a result of these changes (*likely*, *high confidence*). Improved basic health services and increased public health measures—including surveillance and monitoring—can prevent or reduce these impacts (*likely*, *high confidence*).

Description of evidence base

There is strong evidence that increasing temperatures and precipitation in the Midwest will occur by the middle and end of the 21st century.[27] The impacts of these changes on human health are broadly captured in the 2016 U.S. Global Change Research Program's Climate and Health Assessment.[26] Air quality, including particulate matter and ground-level ozone, is positively associated with increased temperatures and has been well-documented to show deleterious impacts on morbidity and mortality.[231] Likewise, increased temperatures have been shown in communities in the Midwest, as well as across the United States, to have substantial impacts on health and well-being.[232,233,235,236,333,334] The frequency of extreme rainfall events in the Midwest has increased in recent decades, and this trend is projected to continue.[193] Studies have shown that extreme rainfall events lead to disease, injury, and death.[237] Increases in seasonal temperatures and shifting precipitation patterns have been well documented to be correlated with increased pollen production, allergenicity, and pollen season length.[230,231] Similarly, there is agreement that shifting temperature and precipitation patterns are making habitats more suitable for disease-carrying vectors to move northward toward the Midwest region.[242,243,250,335,336,337] The disease burden and economic projections primarily are based on EPA estimates.[28]

Access to basic preventive care measures quantifiably reduces disease burden for climate-sensitive exposures.[238,240] Gray literature indicates that public health practitioners are dedicated to increasing capacity for adapting to climate change through classic public health activities such as conducting vulnerability assessments, employing communication and outreach campaigns, and investing in surveillance efforts.[26,244,245,246,247,248]

Major uncertainties

While the modeling performed by the EPA was completed using the best available information, there is uncertainty around the extent to which biophysical adaptations will protect midwestern populations from heat-, air pollution-, aeroallergen-, and vector-related illness and death. Likewise, while there is a general consensus regarding habitat suitability for disease-carrying vectors in the eastern and western United States, the degree to which the disease burden may increase or decrease is largely uncertain.

Description of confidence and likelihood

Based on the evidence, there is *very high confidence* that climate change is *very likely* to impact midwesterners' health.

Key Message 5

Transportation and Infrastructure

Storm water management systems, transportation networks, and other critical infrastructure are already experiencing impacts from changing precipitation patterns and elevated flood risks (*medium confidence*). Green infrastructure is reducing some of the negative impacts by using plants and open space to absorb storm water (*medium confidence*). The annual cost of adapting urban storm water systems to more frequent and severe storms is projected to exceed $500 million for the Midwest by the end of the century (*medium confidence*).

Description of evidence base

The patterns of increased annual precipitation, and the size and frequency of heavy precipitation events in the Midwest, are shown in numerous studies and highlighted in Melillo et al. (2014)[27] and Easterling et al. (2017).[193] Increases in annual precipitation of 5% to 15% are reported across the Midwest region.[193] In addition, both the frequency and the intensity of heavy precipitation events in the Midwest have increased since 1901.[193]

For the early 21st century (2016–2045), both lower and higher scenarios (RCP4.5 and RCP8.5) indicate that average annual precipitation could increase by 1% to 5% across the Midwest, suggesting that the observed increases are likely to continue. By mid-century (2036–2065), both scenarios (RCP4.5 and RCP8.5) indicate precipitation increases of 1% to 5% in Missouri and Iowa and 5% to 10% increases in states to the north and east. By late century (2070–2089), precipitation is expected to increase by 5% to 15% over present day, with slightly larger increases in the higher scenario (RCP8.5). Model simulations suggest that most of these increases will occur in winter and spring over the 21st century. Similar to annual precipitation, the amounts from the annual maximum one-day precipitation events (a measure of heavy precipitation events) are projected to increase over time in the Midwest. The size of the events could increase by 5% to 15% by late century.[193]

Gray literature documents that heavy rains in the Midwest are overwhelming storm water management systems, leading to property damage. Kenward et al. (2016)[256] provide examples of rain-related sewage overflows in the Midwest. These include an overflow of 681 million gallons during heavy rains in April 2015 in Milwaukee and an overflow of over 100 million gallons from December 26–28, 2015, in St. Louis. Winters et al. (2015)[37] document that failure of storm water management systems in heavy rain leads to property damage, including basement backups.

The disruption of transportation networks by heavy precipitation in the Midwest has been documented by collecting contemporary news reports and by compiling state government reports. Posey (2016)[338] relates that four storms between April 2013 and April 2014 forced evacuations or damaged cars in St. Louis, Missouri. In the same period, there were 18 flood-related closures on Missouri roads, a figure that excludes closures on small local roads. Flooding in May 2017 led to the closure of more than 400 roads across Missouri, a figure that again excludes local roads. Closed roadways included multiple stretches of Interstate 44, as well as sections of I-55, affecting interstate traffic between St. Louis and Memphis.[339] News reports document that the same stretch of I-44 was shut down during the floods of December 2015–January 2016.[340]

Flood-related disruptions to Midwest barge and rail traffic in 2013 were documented by several articles in *Journal of Commerce*, a shipping trade magazine.[265,266] *WorkBoat*, a trade journal of the inland shipping industry, documents that Mississippi River navigation has been halted by flooding in 2013, 2015, 2016, and 2017. It also documents low river conditions affecting navigation in 2012 and 2015.[267,268,269,270,341] Disruptions to rail service caused by the floods of 2017 were documented in news media accounts.[342] Changon (2009)[343] documents that flooding in 2008 resulted in extensive damage to railroads in Illinois and adjacent states, with costs exceeding $150 million due to direct damage and lost revenue.

Although there is ample documentation of transportation systems in the Midwest being disrupted by floods in recent years, there is a lack of long-term time series data on disruptions with which to determine whether these incidents are becoming more frequent. Development of long-term data on transportation disruptions in the Midwest is a research need. It is clear that flood frequency and severity on major rivers in the Midwest have increased in recent decades, although additional research is needed on the relative contributions of climate change and land-use change to increases in flood risk.[344,345,346]

The EPA estimated economic costs related to infrastructure and transportation in the Midwest, including costs associated with bridge scour and pavement degradation.[28] The use of green infrastructure to reduce impacts associated with heavy precipitation is also documented in gray literature, including municipal planning documents. Using planted areas to absorb rainfall and reduce runoff has become a common approach to storm water management.[223,275,276,347,348,349,350] Dechannelization and restoration of streams as a technique for improving storm water management is described in Trice (2013)[282] and Milwaukee Metropolitan Sewer District (2017).[281] Preservation of open space is described in Ducks Unlimited (2017)[279] and the Ozaukee Washington

Land Trust (2016).[280] The use of urban forestry as an adaptation method is documented in the Minneapolis Marq2 Project (2017)[277] and the Cleveland Tree Plan (2015).[278] Projected costs to storm water systems are based on EPA projections.[28]

Major uncertainties

Although there is *very high confidence* that flood risk is increasing in the Midwest, there remains uncertainty about the relative contributions of climate change and land-use change. There is, however, sufficient evidence that changing precipitation patterns are leading to changes in hydrology in the Midwest,[351,352,353,354,355] and that heavier precipitation patterns are consistent with projections from climate models, to justify a rating of *medium confidence* to the assertion that climate change is contributing to changes in flooding risk. There is *high confidence* that local governments and nongovernmental organizations are turning to green infrastructure solutions as a response to increased flooding risk. Additional research is needed to quantify the aggregate benefits of these approaches.

While it is clear that flood frequency and severity on major rivers in the Midwest have increased in recent decades, it must be emphasized that the change in precipitation levels is not the only factor contributing to the increase in flood risk. Land-use change, particularly the destruction of floodplains by levee systems, has also been documented as a key contributor to increasing flood risk in the Midwest.[344,345,346] On smaller streams, tile drainage systems have been shown to exacerbate flood risk.[24] Determining the relative contribution of land-use change and climate change to increases in riverine flood risk is an important research need.

Description of confidence and likelihood

There is *medium confidence* that climate change is contributing to increased flood risk in the Midwest; there is *medium confidence* that green infrastructure is reducing flood risk. There is much uncertainty associated with specific numerical projections. This leads to *medium confidence* that costs will exceed $500 million. However, the EPA projections are sufficient to provide *high confidence* that increasing the capacity of existing storm water systems in order to maintain current levels of service would require significant expenditures on the part of urban sewer districts.

Key Message 6

Community Vulnerability and Adaptation

At-risk communities in the Midwest are becoming more vulnerable to climate change impacts such as flooding, drought, and increases in urban heat islands (*as likely as not*, *high confidence*). Tribal nations are especially vulnerable because of their reliance on threatened natural resources for their cultural, subsistence, and economic needs (*likely*, *medium confidence*). Integrating climate adaptation into planning processes offers an opportunity to better manage climate risks now (*medium confidence*). Developing knowledge for decision-making in cooperation with vulnerable communities and tribal nations will help to build adaptive capacity and increase resilience (*high confidence*).

Description of evidence base

Limited evidence in the scientific literature indicates that at-risk communities in the Midwest will be increasingly vulnerable to the impacts of climate change, including increased flooding resulting from increased variation in precipitation patterns and changing lake levels,[285] urban heat islands,[287] and an intensification of heat and drought (see also the impacts and associated references in the previous sections).[286]

Several recent survey reports[28,283,284] project negative climate impacts for tribal nations and Indigenous communities, especially as a result of an increased frequency of extreme precipitation events.[283] Tribal nations are especially vulnerable to climate impacts because of their reliance on natural resources,[127] the isolation of rural communities, and potential shifts of species out of sovereign land.[309,310] Climate change thus poses a threat to tribal culture, sovereignty, health, and way of life.[39]

Gray literature,[293] survey reports,[32] and scientific literature[292] point to a few initiatives to integrate adaptation into municipal planning processes and utilize participatory methodologies to evaluate and manage climate risk.

A growing body of research indicates that interaction between producers of climate information, intermediaries, and end users plays a critical role in increasing climate knowledge integration and use for adaptation in the Midwest.[224,294,300,308] Limited evidence links the implementation of adaptation actions identified as a result of these collaborations to reduced sensitivity.[304,305,306]

Major uncertainties

Limited research specific to the Midwest region contributes to uncertainty around the specific vulnerabilities of at-risk communities, including urban and rural communities and tribal nations. Though climate change planning and action in both Midwest cities and rural areas are underway, documentation remains low, few examples exist in the public literature of the failure or success of efforts to mainstream climate action into municipal governance, and attempts to assess vulnerabilities, especially in poor urban communities, frequently encounter climate justice barriers. Likewise, the number, scope, and nature of tribal adaptation plans remain undocumented, as does the degree of implementation of these plans and the manner in which Traditional Ecological Knowledge is incorporated.

Description of confidence and likelihood

There is *high confidence* that communities in the Midwest will *as likely as not* be increasingly vulnerable to climate change impacts such as flooding, urban heat islands, and drought. Similarly, there is *medium confidence* that tribal nations in the Midwest are *likely* to be especially vulnerable because of their reliance on threatened natural resources for their cultural, subsistence, and economic needs. Due to limited documentation in the literature, there is *medium confidence* that integrating adaptation into planning processes will offer an opportunity to manage climate risk better. Finally, there is *high confidence* that developing knowledge for decision-making in cooperation with vulnerable communities and tribal nations will help to decrease sensitivity and build adaptive capacity.

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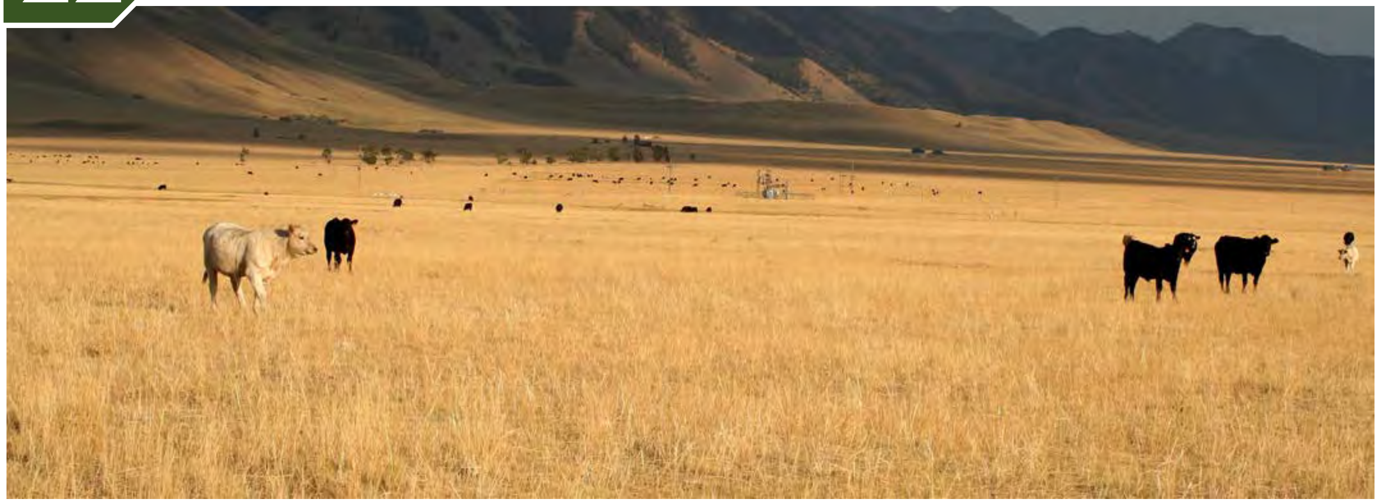
22 Northern Great Plains



Cameron, Montana

Key Message 1

Water

Water is the lifeblood of the Northern Great Plains, and effective water management is critical to the region's people, crops and livestock, ecosystems, and energy industry. Even small changes in annual precipitation can have large effects downstream; when coupled with the variability from extreme events, these changes make managing these resources a challenge. Future changes in precipitation patterns, warmer temperatures, and the potential for more extreme rainfall events are very likely to exacerbate these challenges.

Key Message 2

Agriculture

Agriculture is an integral component of the economy, the history, and the culture of the Northern Great Plains. Recently, agriculture has benefited from longer growing seasons and other recent climatic changes. Some additional production and conservation benefits are expected in the next two to three decades as land managers employ innovative adaptation strategies, but rising temperatures and changes in extreme weather events are very likely to have negative impacts on parts of the region. Adaptation to extremes and to longer-term, persistent climate changes will likely require transformative changes in agricultural management, including regional shifts of agricultural practices and enterprises.

Key Message 3

Recreation and Tourism

Ecosystems across the Northern Great Plains provide recreational opportunities and other valuable goods and services that are at risk in a changing climate. Rising temperatures have already resulted in shorter snow seasons, lower summer streamflows, and higher stream temperatures and have negatively affected high-elevation ecosystems and riparian areas, with important consequences for local economies that depend on winter or river-based recreational activities. Climate-induced land-use changes in agriculture can have cascading effects on closely entwined natural ecosystems, such as wetlands, and the diverse species and recreational amenities they support. Federal, tribal, state, and private organizations are undertaking preparedness and adaptation activities, such as scenario planning, transboundary collaboration, and development of market-based tools.

Key Message 4

Energy

Fossil fuel and renewable energy production and distribution infrastructure is expanding within the Northern Great Plains. Climate change and extreme weather events put this infrastructure at risk, as well as the supply of energy it contributes to support individuals, communities, and the U.S. economy as a whole. The energy sector is also a significant source of greenhouse gases and volatile organic compounds that contribute to climate change and ground-level ozone pollution.

Key Message 5

Indigenous Peoples

Indigenous peoples of the Northern Great Plains are at high risk from a variety of climate change impacts, especially those resulting from hydrological changes, including changes in snowpack, seasonality and timing of precipitation events, and extreme flooding and droughts as well as melting glaciers and reduction in streamflows. These changes are already resulting in harmful impacts to tribal economies, livelihoods, and sacred waters and plants used for ceremonies, medicine, and subsistence. At the same time, many tribes have been very proactive in adaptation and strategic climate change planning.

Executive Summary

In the Northern Great Plains, the timing and quantity of both precipitation and runoff have important consequences for water supplies, agricultural activities, and energy production. Overall, climate projections suggest that the number of heavy precipitation events (events with greater than 1 inch per day of rainfall) is projected to increase. Moving forward, the magnitude of year-to-year variability overshadows the small projected average decrease in streamflow. Chang- es in extreme events are likely to overwhelm average changes in both the eastern and western regions of the Northern Great Plains. Major flooding across the basin in 2011 was followed by severe drought in 2012, representing new and unprecedented variability that is likely to become more common in a warmer world.

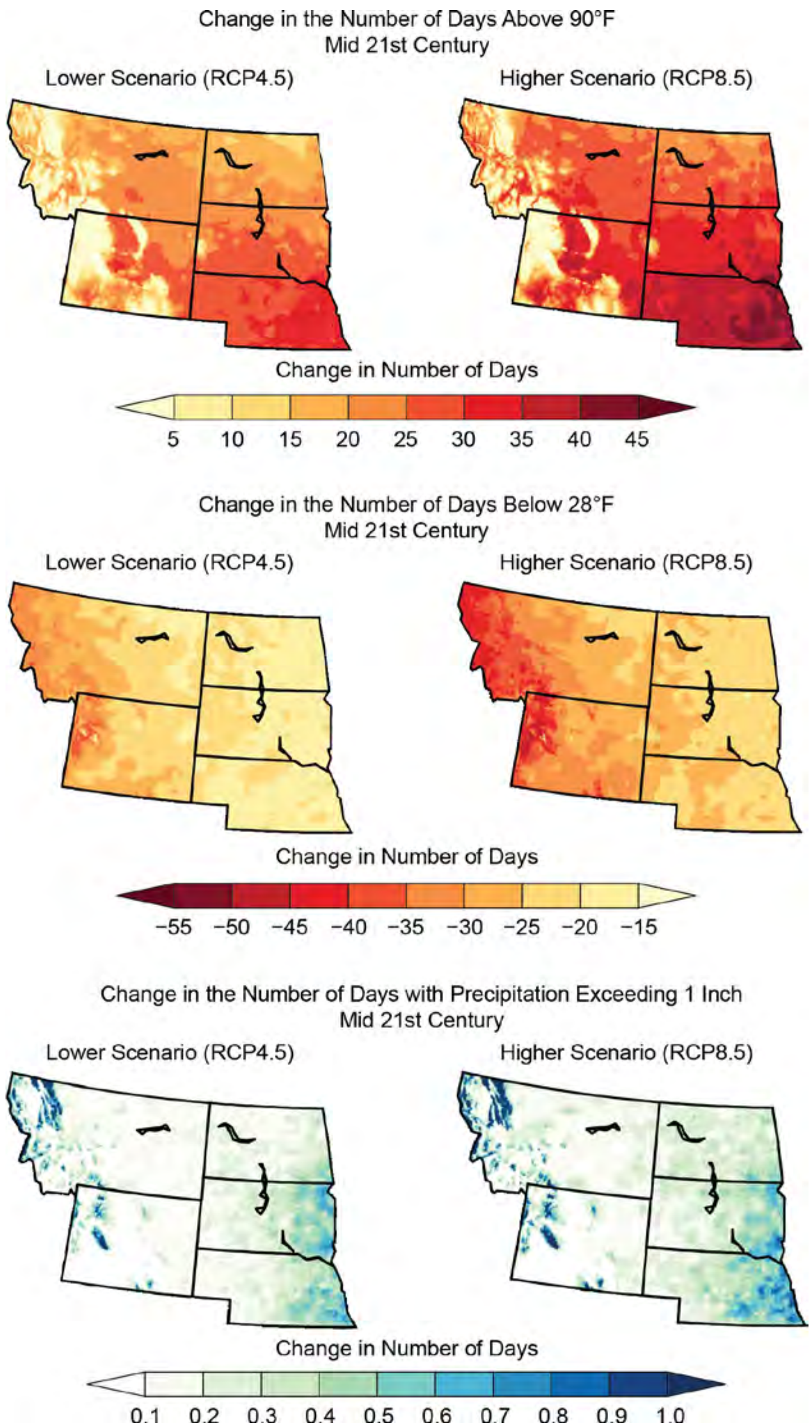
The Northern Great Plains region plays a critical role in national food security. Among other anticipated changes, projected warmer and generally wetter conditions with elevated atmospheric carbon dioxide concentrations are expected to increase the abundance and competitive ability of weeds and invasive species,[1,2] increase livestock production and efficiency of production,[3] and result in longer growing seasons at mid- and high latitudes.[4,5] Net primary productivity, including crop yields[6] and forage production,[7,8] is also likely to increase, although an increasing number of extreme temperature events during critical pollination and grain fill periods is likely to reduce crop yields.[9]

Ecosystems across the Northern Great Plains provide recreational opportunities and other valuable goods and services that are ingrained in the region's cultures. Higher temperatures, reduced snow cover, and more variable precipitation will make it increasingly challenging to manage the region's valuable wetlands, rivers, and snow-dependent ecosystems. In the mountains of western Wyoming and western Montana, the fraction of total water in precipitation that falls as snow is expected to decline by 25% to 40% by 2100 under a higher scenario (RCP8.5),[10] which would negatively affect the region's winter recreation industry.[11] At lower-elevation areas of the Northern Great Plains, climate-induced land-use changes in agriculture can have cascading effects on closely entwined natural ecosystems, such as wetlands,[12] and the diverse species and recreational opportunities they support.

Energy resources in the Northern Great Plains include abundant crude oil, natural gas, coal, wind, and stored water, and to a lesser extent, corn-based ethanol, solar energy, and uranium. The infrastructure associated with the extraction, distribution, and energy produced from these resources is vulnerable to the impacts of climate change. Railroads and pipelines are vulnerable to damage or disruption from increasing heavy precipitation events and associated flooding and erosion.[13] Declining water availability in the summer would likely increase costs for oil production operations, which require freshwater resources.[13] These cost increases will either lead to lower production or be passed on to consumers. Finally, higher maximum temperatures, longer and more severe heat waves, and higher overnight lows are expected to increase electricity demand for cooling in the summer, further stressing the power grid.[13]

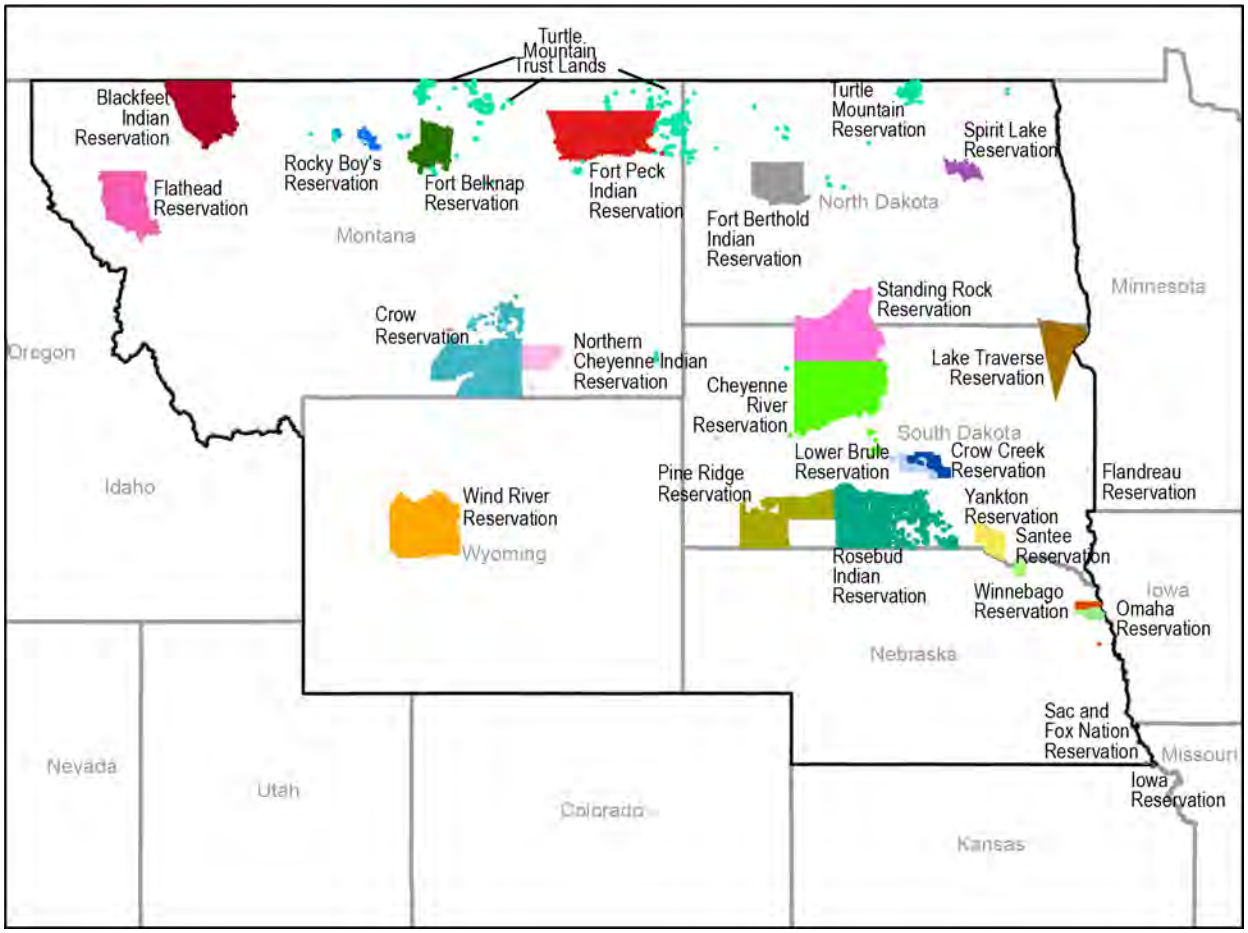
Indigenous peoples in the region are observing changes to climate, many of which are impacting livelihoods as well as traditional subsistence and wild foods, wildlife, plants and water for ceremonies, medicines, and health and well-being.[14,15,16,17,18,19,20,21,22,23,24,25,26] Because some tribes and Indigenous peoples are among those in the region with the highest rates of poverty and unemployment, and because many are still directly reliant on natural resources, they are among the most at risk to climate change (e.g., Gamble et al. 2016, Cozzetto et al. 2013, Espey et al. 2014, Wong et al. 2014, Kornfeld 2016, Paul and Caplins 2016, Maynard 2014, USGCRP 2017[18,24,25,27,28,29,30,31]).

Projected Changes in Very Hot Days, Cool Days, and Heavy Precipitation



Projected changes are shown for (top) the annual number of very hot days (days with maximum temperatures above 90°F, an indicator of crop stress and impacts on human health), (middle) the annual number of cool days (days with minimum temperatures below 28°F, an indicator of damaging frost), and (bottom) heavy precipitation events (the annual number of days with greater than 1 inch of rainfall; areas in white do not normally experience more than 1 inch of rainfall in a single day). Projections are shown as changes from the 1976–2005 average for the middle of the 21st century (2036–2065) for the lower and higher scenarios (RCP4.5 and RCP8.5). *From Figure 22.2 (Sources: NOAA NCEI and CICS-NC).*

Northern Great Plains Tribal Lands



The map outlines reservation and off-reservation tribal lands in the Northern Great Plains, which shows where the 27 federally recognized tribes have a significant portion of lands throughout the region. Information on Indigenous peoples' climate projects within the Northern Great Plains is described in Chapter 15: Tribes and Indigenous Peoples. *From Figure 22.7 (Sources: created by North Central Climate Science Center [2017] with data from the Bureau of Indian Affairs, Colorado State University, and USGS National Map)*.

Background

The Northern Great Plains has three distinct regional geographic features associated with a strong east-to-west gradient of decreasing precipitation and a stark rise in elevation at the montane western boundary. The eastern edge of the region includes a humid-continental climate and the Red River Valley, where the capacity to store water is often exceeded, leading to extensive flooding. A large swath of the central Northern Great Plains falls within the Upper Missouri River Basin. Much of this basin is arid to semiarid, and because temperatures and rates of evapotranspiration (the evaporation of water from the soil and transpiration from plants) are so high, only 9% of precipitation ultimately reaches the Missouri River as runoff. For comparison, other basins in the United States yield more than 40% runoff. In the mountainous far western part of the region, including central and western Wyoming and Montana, water dynamics are driven by large seasonal snowpack that accumulates in winter and early spring and provides critical resources for non-montane areas through runoff during the warm season.

These intraregional gradients in precipitation, temperature, and water availability drive east–west differences in land use and climate. The eastern portion of the region is characterized by rainfed row crop agriculture and is often subject to flooding. For example, Devils Lake in North Dakota is a closed basin, meaning that it has no natural outflows. The basin is often so full that it is prone to flooding the communities around it. Separately, the irrigated cropland and grazing lands in the central portion of the Northern Great Plains are critical for U.S. livestock production, yet the arid to semiarid climate is highly variable from year to year, which makes it difficult to manage agriculture, recreation, and cultural resources. The western portion of the region is devoted primarily to native ecosystems used for grazing and recreation, but dryland cropping is also important, and forestry is important in the far-western edge of the region. Coal, oil, and natural gas are produced throughout the Northern Great Plains.

The highly variable climate of the Northern Great Plains poses challenges for the sustainable use of water, land, and energy resources by competing urban, suburban, rural, and tribal populations. Climate change is expected to exacerbate those challenges, which include 1) effectively managing both overabundant and scarce water resources, 2) supporting adaptation of sustainable agricultural systems, 3) fostering conservation of ecosystems and cultural and recreational amenities, 4) minimizing risk to energy infrastructure that is vulnerable to climate change and extreme weather events, and 5) mitigating climate impacts to vulnerable populations.

Diverse land uses across the region are overlain with a quilt work of private, state, federal, tribal, and other land ownership. Many of these institutions foster adaptation to existing climatic variability (Figure 22.1). For example, the Missouri Headwaters Drought Resilience Demonstration Project was launched in July 2014 to demonstrate how federal, state, and local stakeholders can work together to build long-term drought resilience. The project leverages federal and state resources and engages communities in the development and implementation of local watershed drought resilience plans and activities. Led by the Montana Department of Natural Resources and Conservation, more than 10 federal agencies, 20 watershed groups, and 14 nongovernmental organizations are contributing to the project (see Missouri Headwaters Drought Resilience Demonstration Project 2015[32]). It is a replicable model that is producing concrete, on-the-ground results, including tools for drought monitoring, assessment, and forecasting. In another example,

Climate Change Impacts and Adaptation Across the Northern Great Plains

1

Impact: Flash droughts and high heat events illustrate challenges for sustainability of ranching operations, with emergent impacts on rural prosperity and mental health.

Response: Adaptive management frameworks, developed through management–science partnerships, proactively increase flexibility in operational decision-making to reduce economic and ecological risk.

2

Impact: Consecutive years of drought across the region force ranchers to consider selling off their herds.

Response: Montana's Matador Ranch establishes a "grassbank" that allows local ranchers to pay discounted fees for access to additional grass during droughts in exchange for wildlife-friendly practices on their own operations.

3

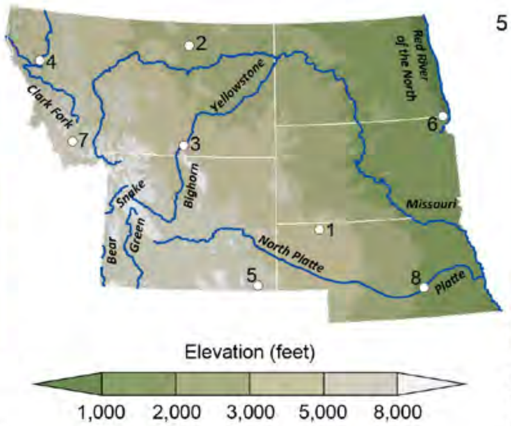
Impact: Rising temperatures hasten the spread of invasive species in riparian ecosystems, threatening culturally significant native species and food sources in the Crow Indian (Apsaalooké) Reservation.

Response: The USDA NRCS Crow Agency worked with Little Big Horn College students to remove invasive populations along the Little Big Horn River. They also revegetated plains cottonwood in sandbars and developed riparian buffer zones.

4

Impact: Anticipated climate change impacts on cultural resources raise concerns within the leadership of the Confederated Salish and Kootenai Tribes.

Response: Tribal leaders developed their climate change strategic plan to address climate impacts and vulnerabilities drawing heavily on Traditional Ecological Knowledge.



5

Impact: Greenhouse gas emissions from petroleum and natural gas production across the Northern Great Plains are among the highest in the Nation.

Response: Potential wind energy resources are among the largest in the Northern Great Plains.

6

Impact: The Prairie Pothole Region, considered the world's most productive habitat for waterfowl, is threatened by warming temperatures.

Response: The Prairie Pothole Joint Venture implements wetland and grassland protection, restoration, and enhancement projects to sustain populations of waterfowl, shorebirds, and prairie landbirds.

7

Impact: Changing runoff characteristics and increasing stream temperatures threaten water and ecological resources.

Response: The Beaverhead Drought Resiliency Plan was written to improve preparedness by reducing vulnerabilities to future drought events.

8

Impact: Increased growing season length and greater variability in temperature and precipitation stress critically important natural resources.

Response: The Platte Basin Timelapse project (PBT) uses time-lapse photography and multimedia storytelling to document life across the Platte River watershed.

Figure 22.1: The Northern Great Plains exhibits a high amount of geographical, ecological, and climatological variability, in part because of the dramatic elevation change across the region. The impacts of climate change throughout the Northern Great Plains include changes in flooding and drought, rising temperatures, and the spread of invasive species. Ranchers, tribal communities, universities, government institutions, and other stakeholders from across the region have taken action to confront these challenges. Photo credits: 1) Justin Derner, USDA Agricultural Research Service, 2) Kenton Rowe Photography, 3) Kurrie Jo Small, 4) Eugene Wilson (CC BY-NC 2.0), 5) Jacob Byk, 6) Benjamin Rashford, 7) Chris Carparelli, 8) Mariah Lundgren, University of Nebraska Platte Basin Timelapse Project.

Nebraska completed a statewide climate change assessment report in 2014.[33] Officials were then able to use this report to convene eight sector-based roundtable discussions in 2015, engaging more than 350 people, to identify a suite of key issues, strategies, and next steps to help develop a statewide climate change action plan.[34]

Key Message 1

Water

Water is the lifeblood of the Northern Great Plains, and effective water management is critical to the region's people, crops and livestock, ecosystems, and energy industry. Even small changes in annual precipitation can have large effects downstream; when coupled with the variability from extreme events, these changes make managing these resources a challenge. Future changes in precipitation patterns, warmer temperatures, and the potential for more extreme rainfall events are very likely to exacerbate these challenges.

Streamflow in the Northern Great Plains is driven by a number of factors. Because the Northern Great Plains is so far from the coasts and the modulating effect of the oceans, the regional climate system is prone to dramatic climate variability. The Upper Missouri River Basin (the region's primary surface water feature spanning all five states) is very sensitive to climatic fluctuations, resulting in extreme drought or flooding events roughly every decade over the past century.[35] The timing and quantity of both precipitation and runoff have important consequences for water supplies, agricultural activities, and energy production. Parts of the region are among the most arid in the Nation—for example, less than 10% of regional precipitation reaches streams and the Missouri River[36]—so relatively small changes in annual precipitation can produce large changes in runoff. High evaporation rates result in lower soil moisture and streamflow in the region relative to more humid parts of the country. Trends in annual runoff across the region over the past 50 years show a distinct east–west difference where the western portions show a decrease and eastern areas show an increase.[37] Soil moisture and snowpack have a major impact on streamflow, and as a result of these factors combined with variability in precipitation, the amount of annual streamflow can vary by as much as a factor of three from year to year.[35] In the western montane portion of the region, 39 glaciers contribute to streamflows through their seasonal melt process. These glaciers are experiencing sustained loss,[38] and, like global glacier losses over recent decades, local glacier losses are attributable to higher temperatures.[39,40] Glacier flows are critically important for local watersheds and ecosystems; however, their contribution to the entire Upper Missouri River Basin is very small. High variability in the proportion of precipitation that reaches streams in a given year, coupled with a relatively high frequency of extreme events (for example, heavy rainfall events and droughts), makes managing climate change impacts on water resources challenging. Major flooding across the basin in 2011 was followed by severe drought in 2012, representing new and unprecedented variability that is likely to become more common in a warmer world.

Given the losses in important snowpack water storage, reservoirs and groundwater represent critical buffers to climate impacts, since they have large storage capacity that can be filled during wet periods and withdrawn during dry periods. Evaporation rates exceed 100% of precipitation in some cases,[41] which results in a deficit of surface water and thus reliance upon groundwater. Groundwater and aquifer recharge rates[42] are relatively high in the region (including parts of Wyoming, South Dakota, Montana, and Nebraska) and seem sustainable given current rates of groundwater extraction.

Projected Changes in Very Hot Days, Cool Days, and Heavy Precipitation

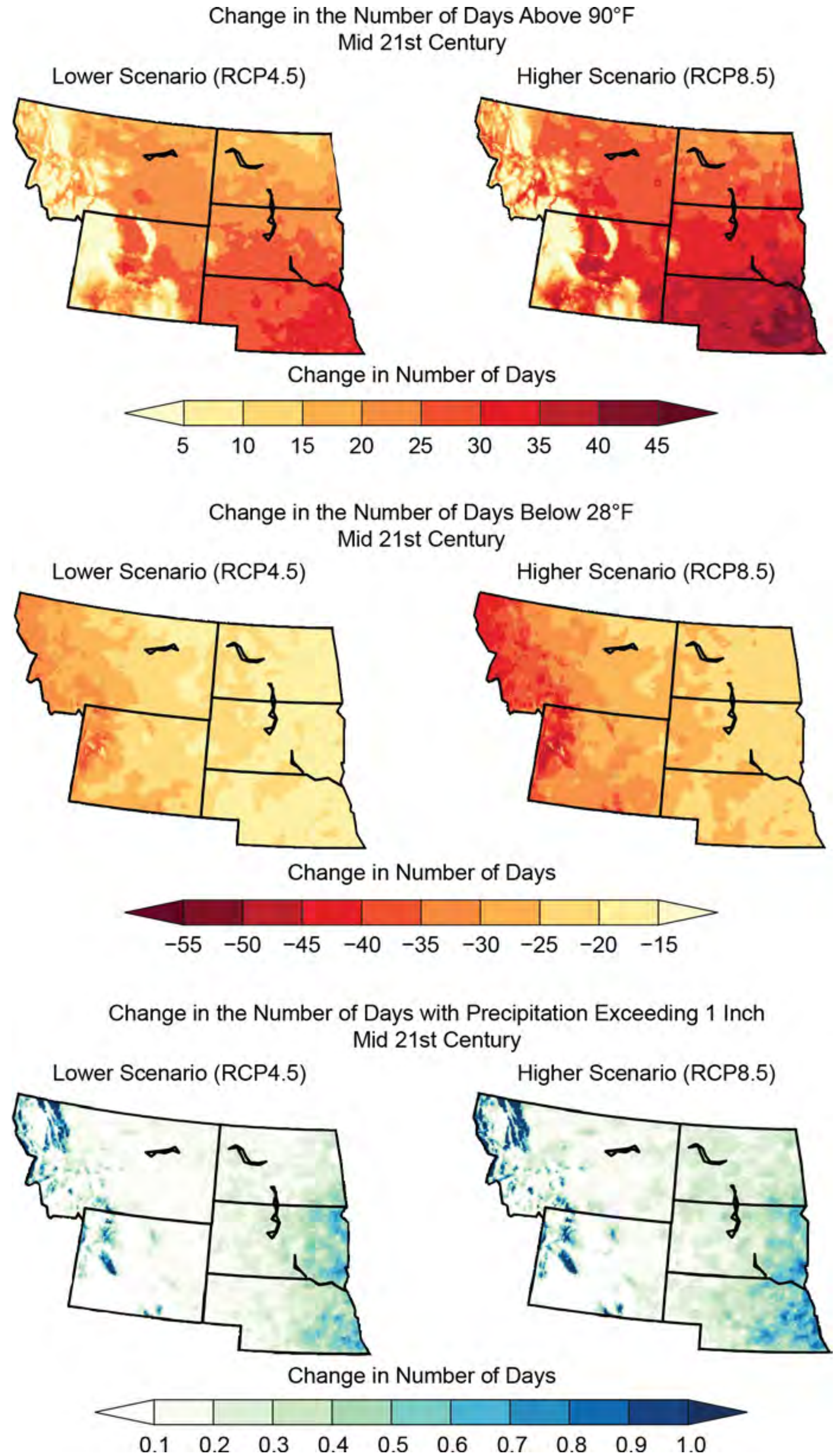


Figure 22.2: Projected changes are shown for (top) the annual number of very hot days (days with maximum temperatures above 90°F, an indicator of crop stress and impacts on human health), (middle) the annual number of cool days (days with minimum temperatures below 28°F, an indicator of damaging frost), and (bottom) heavy precipitation events (the annual number of days with greater than 1 inch of rainfall; areas in white do not normally experience more than 1 inch of rainfall in a single day). Projections are shown as changes from the 1976–2005 average for the middle of the 21st century (2036–2065) for the lower and higher scenarios (RCP4.5 and RCP8.5). Sources: NOAA NCEI and CICS-NC.

Hydrologic Changes Across the Northern Great Plains

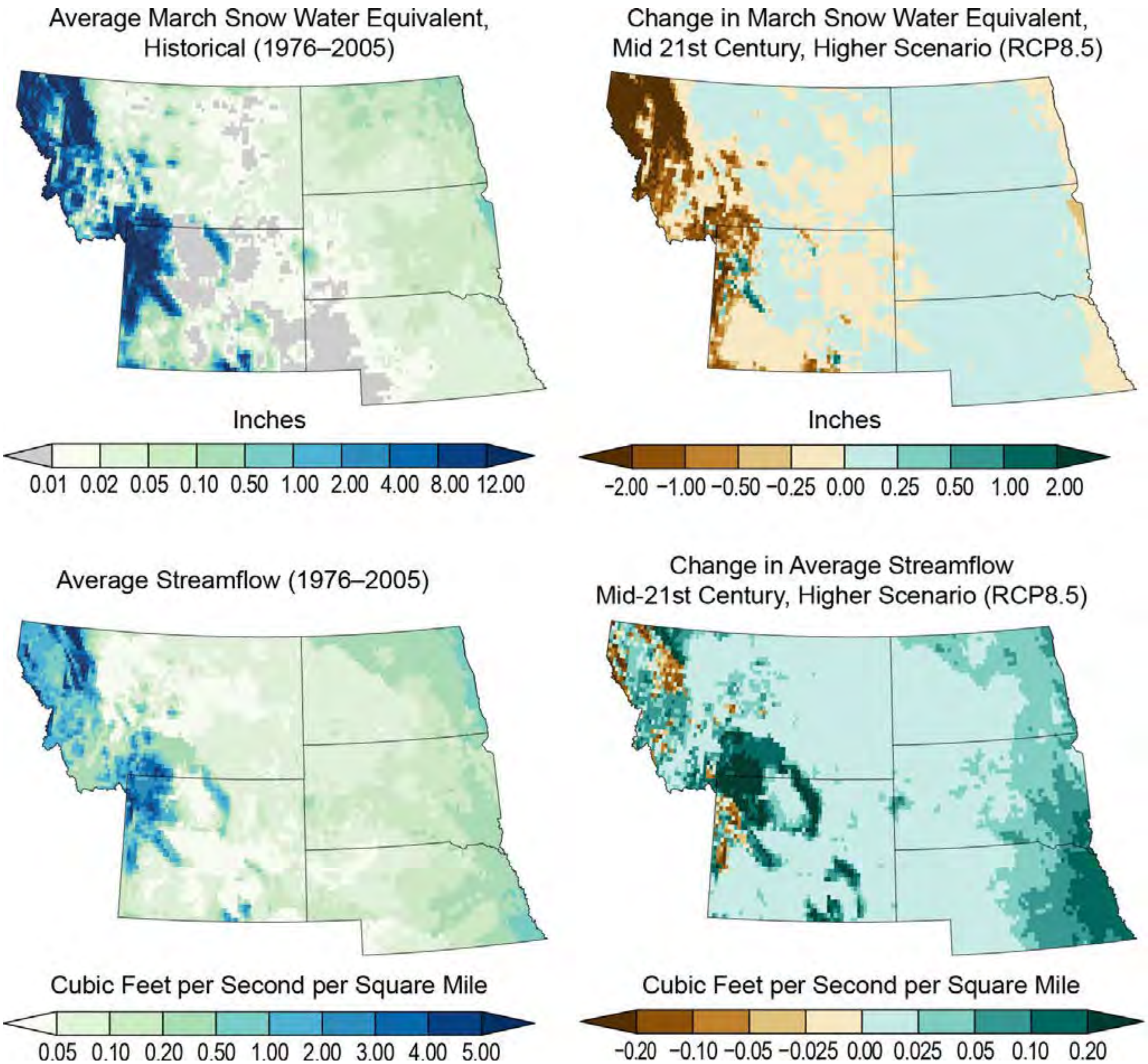


Figure 22.3 These maps show historical (left; 1976–2005) and projected changes (right; 2036-2065) under a higher scenario (RCP8.5) in average snowpack (top row) and annual streamflow (bottom row). Snowpack is measured in terms of snow water equivalent, or SWE—the depth in inches of the amount of water contained in the snowpack. The top two maps show average values for March to provide historical and future end-of-season estimates of SWE. This illustrates projected warming and potential snow loss. Projected decreases in snowpack across montane western regions in the upper-right plot are primarily the result of projected warming at the highest elevations. Projected increases in snow at lower elevations are less important, since those changes are relative to a much lower average (top left) than in montane regions. Similarly, annual streamflows are expected to increase across much of the eastern part of the region, with isolated but important decreases in the western highlands. In this context, streamflow refers to the sum of surface runoff and subsurface flow for each location in space. Sources: NOAA NCEI and CICS-NC.

Climate model projections paint a clear picture of a warmer future in the Northern Great Plains, with conditions becoming consistently warmer in two to three decades and temperatures rising steadily towards the middle of the century, irrespective of the scenario selected (Figure 22.2). This warming is projected to occur in conjunction with less snowpack and a mix of increases and reductions in the average annual water availability (Figure 22.3). Precipitation and streamflow projections show only modest changes, but many areas within the region are already subject to a high degree of year-to-year variability—both wet and dry years. Low-probability, but high-severity and high-impact, events are the result of large variability, including both extreme flood events like in 2011 and drought events like in 2012. This interannual variability implies greater uncertainty about future climate and about the potential for future flooding and drought.

An important takeaway is that the magnitude of variability overshadows the small projected decrease in average streamflow.[35] Changes in extreme events are likely to overwhelm average changes in both the eastern and western regions of the Northern Great Plains (Figure 22.2). Overall, climate models project an increase in the number of heavy precipitation events (events with greater than 1 inch per day) for much of the region, with the exception of the high-mountain areas in the southwestern portion. Societal risk increases any time natural conditions differ greatly from historical conditions,[43] with larger changes representing greater risks. Therefore, any large projected changes will require rethinking infrastructure design and operation. The probability for more very hot days (days with maximum temperatures above 90°F; Figure 22.2) is expected to increase, with potential impacts on agriculture, energy production, human health, streamflows, snowmelt, and fires. There are projected to be many fewer cool days (days with minimum temperatures less than 28°F, an indicator of damaging frost; Figure 22.2), with decreases of 30 days or more per year by mid-century. These changes would have important implications for the region's snowpack and consequently streamflow and water use.

Reservoir and groundwater storage are expected to be increasingly important as buffers against the impacts of increasing variability and to meet water demands during periods of shortage, especially in light of warming-driven losses in snowpack water and higher evapotranspiration rates, which reduce the total amount of water availability. It may be possible to move water between basins to alleviate flooding impacts, but this raises a new set of challenging hydrological and environmental issues. Future activities that increase water demand (population growth, expansion, or alteration of agriculture) will increase dependence on reservoir capacity and infrastructure integrity.

Key Message 2

Agriculture

Agriculture is an integral component of the economy, the history, and the culture of the Northern Great Plains. Recently, agriculture has benefited from longer growing seasons and other recent climatic changes. Some additional production and conservation benefits are expected in the next two to three decades as land managers employ innovative adaptation strategies, but rising temperatures and changes in extreme weather events are very likely to have negative impacts on parts of the region. Adaptation to extremes and to longer-term, persistent climate changes will likely require transformative changes in agricultural management, including regional shifts of agricultural practices and enterprises.

The Northern Great Plains region plays an important role in U.S. food security (see Tables 22.1 and 22.2), and agriculture has been integral to the history and development of the region. Agricultural uses in the region are diverse, including the largest remaining tracts of native rangeland in North America, substantial areas of both dryland and irrigated cropland and pasture, and mosaics of cropland and grazed grassland and forested lands. This region is home to 7.2% of U.S. farms (152,663) but 23.8% of the U.S. land in farms, encompassing 218 million acres with 22.4% of the total cropland, 21.9% of irrigated lands, 29.3% of U.S. pasture and rangeland, and nearly one-third (30.1%) of lands in conservation/wetland reserve programs.[44] Livestock production (beef and dairy cattle and hogs) is dominant in the region. Important crops include corn, soybeans, wheat, barley, alfalfa, hay, and a diversity of other crops such as potatoes, sugar beets, dry beans, sunflowers, millet, canola, and barley (see Tables 22.1 and 22.2).[44] The Northern Great Plains region contributes 12.7% of the market value of agricultural products sold in the United States despite having only 1.5% of the U.S. population.

Extensive precipitation and temperature gradients and inherently high climatic variability, both within and between years, result in highly variable conditions for agricultural enterprises in the Northern Great Plains. The region receives the majority of its precipitation during the spring months (April, May, and June), with a high degree of year-to-year variability.[45] A mix of private, state, federal, tribal, and other land ownership across the region promotes heterogeneity at landscape-to-regional scales, which enhances the provision of numerous ecosystem goods and services, such as wildlife habitat, including for pollinators.

Percent of National Total Livestock Animals in the Northern Great Plains (2012)

	Beef cows	Hogs and pigs	Sheep and lambs	Milk cows	Egg layers
% of National Total	21.9%	6.9%	18.4%	2.0%	3.5%

Table 22.1: The table shows the percent of the national total of livestock animals living in the Northern Great Plains in 2012. Source: U.S. Agricultural Census 2012.[44]

Percent of National Total Crop Commodities in 2012

	Corn for grain (bu)	Corn for silage/ greenchop (tons)	Wheat for grain (bu)	Spring wheat (bu)	Durum wheat (bu)	Oats for grain (bu)
% of National Total	20.2%	11.5%	30.4%	70.6%	72.2%	20.3%

	Barley (bu)	Soybeans (bu)	Dry edible beans and lentils (cwt)	Forage (tons)	Sunflower seed (pounds)	Sugarbeets (tons)
% of National Total	48.4%	16.3%	48.6%	13.8%	83.6%	27.2%

Table 22.2: The table shows the percent of the national total production for crop commodities produced in the Northern Great Plains in 2012. Units are bushels (bu), tons, hundredweight (cwt), or pounds. Source: USDA National Agricultural Statistical Survey 2012.[44]

The Northern Great Plains is currently experiencing a marked transition in agricultural land use involving the conversion of grassland to annual crops[46,47] and an increased prevalence of monoculture cropping.[48] From peak enrollment in the Conservation Reserve Program (10 million acres in 2007), enrollment declined by half by 2017, with the majority of these lands returning to cropland (60%), thereby losing ecosystem service benefits such as wildlife habitat and improved water and soil quality.[49] Changing land use in the eastern part of this region is an outcome of trends of above-average precipitation over the last 10–20 years, with some of those precipitation trends having been driven by expansion of agricultural land use.[50] In the western part of the region, genetic developments in crop cultivars and varieties that enhance suitability of drier land for crop production have led to expansion of dryland cropping.

Despite a long history of high year-to-year variability,[45] producers are experiencing a changing climate and increasing weather variability and extreme conditions that are outside the ranges they have dealt with in the past.[51] Producers' daily and annual decision-making depends on market conditions for seeds and products, agronomic constraints, and climate change-related variables.[52] The decision-making process is challenged by a lack of experience with analogous climatic conditions in the past, thus increasing risks for land managers. This dependence on historical experience highlights the importance of the human element in the resilience of social–ecological systems, which have traditionally been viewed from the biophysical perspective.[53]

Temperature increases of 2°–4°F projected by 2050 for the Northern Great Plains under the lower scenario (RCP4.5) are expected to result in an increase in the occurrence of both drought and heat waves; these projected trends would be greater under the higher scenario (RCP8.5). The amount, distribution, and variability of annual precipitation in the Northern Great Plains are anticipated to change, with increases in winter and spring precipitation of 10%–30% by the end of this century and a decrease in the amount of precipitation falling as snow under a higher scenario (RCP8.5).[54] Summer precipitation is expected to vary across the Northern Great Plains, ranging from no change under a lower scenario (RCP4.5) to 10%–20% reductions under a higher scenario (RCP8.5).[54] Further, the frequency of heavy precipitation events is projected to increase, with an increase of about 50% in the frequency of two-day heavy rainfall events by 2050 under the higher scenario (RCP8.5). The amount falling in single-day heavy events is projected to increase 8%–10% by mid-century depending on scenario.[54] Although fewer hail days are expected, a 40% increase in damage potential from hail due to more frequent occurrence of larger hail is predicted for the spring months by mid-century under a higher scenario (RCP8.5).[55] Even with increases in precipitation, warmer temperatures are expected to increase evaporative demand, leading to more frequent and severe droughts.[56] Some of the negative effects of drying in a warmer climate are likely to be offset by elevated atmospheric carbon dioxide (CO_2) concentrations, which directly stimulate plant growth and increase plant water-use efficiency.[3]

The warmer and generally wetter conditions projected for some of the Northern Great Plains, coupled with elevated atmospheric CO_2 concentrations, are expected to

1. increase soil water availability during the primary growing season in the northern part of the region and decrease it the southern parts;[1,9]

2. increase the number of extreme temperature events (high daytime highs or nighttime lows) during critical pollination and grain fill periods, which will very likely reduce crop yields;[6,9]

3. lead to declining yield for crops[6] and forages[7,8] due to increasing temperatures, some of which will be offset by increasing CO_2;

4. increase the abundance and competitive ability of weeds and invasive species;[1,2]

5. alter plant phenology–for example, earlier onset of spring (Ch. 1: Overview, Figure 1.2j)[57] and earlier flowering of plants;[58]

6. decrease the quality of forage available to livestock;[3,59,60]

7. increase livestock production and efficiency of production due to greater net primary productivity and longer growing seasons;[3]

8. result in longer growing seasons at mid- and high latitudes;[4,5] and

9. increase the range and fecundity of crop pests.[9]

All of these changes will require increased flexibility in resource management.[61,62,63]

Adaptation for agricultural land use for the next 20–30 years, or to the mid-21st century, will be most effective when decision-making integrates biophysical, social, and economic components. Proactive learning opportunities that integrate experimental and experiential knowledge—such as lessons learned from early adopters—can help enhance decision-making. After all, many adaptations have already been implemented by a subset of producers in this region, providing opportunities for assessment, further development, and adoption. Context-specific decision-making for operations can also be improved through science–management partnerships, which aim to build adaptive capacity while being sensitive to multiple production, conservation, and environmental goals. Transfer of this adaptive knowledge in a timely manner to producers in the field through novel, multipronged communication efforts will assist land managers in more effectively and resiliently responding to the changes to come (see Case Study "Adaptive Rangeland Management"). The climate changes projected over the longer term (through the end of this century) are likely to require transformative changes in agricultural management, including regional shifts of agricultural practices and enterprises.[61,64]

Case Study: Adaptive Rangeland Management

Highly variable precipitation in the Northern Great Plains makes it difficult for managers to balance forage availability with animal demand. An emergent focus is on management strategies that are adaptive rather than prescriptive. But adaptive solutions require collaboration, often among stakeholders with different production and conservation goals. For example, grassbanking, in which ranchers lease land from property owners at a discount in exchange for carrying out conservation-related projects on their pastures, requires management strategies that can successfully deal with this variability. They can also require engagement between different land ownership types, including privately owned land, leased land, state lands, and federal lands. At The Nature Conservancy's Matador Ranch in north central Montana, local ranchers pay reduced grazing fees to graze their cattle on the Matador in exchange for wildlife-friendly and ecologically sound practices on their own operations, where a ranch management plan is required and sodbusting is prohibited. Each year, Conservancy staff and the ranchers develop a grazing plan for the Matador to reach production and ecologically based management goals, including the diverse vegetation structure needed by imperiled grassland birds and greater sage-grouse. In 2017, the Matador Grassbank ranches encompassed over 280,000 acres of private and public leased land. Working cooperatively, the Conservancy and grassbank members improved habitat for imperiled wildlife species on more than 340,000 acres, all while creating conditions that allow for sustainable ranch operations across variable and changing climatic conditions.

Learning how better decisions are made in the face of climate variability is a challenging research topic and one that also requires close collaboration—in this case between stakeholder groups and scientists. Another project, the Collaborative Adaptive Rangeland Management (CARM) experiment, which started in 2012 with a series of meetings involving ranchers, conservation/environmental organizations, and public land managers, is an example of such a research project. Conducted at a ranch-level scale for relevance to producers and managers, the research seeks to determine how adaptive rangeland management can be implemented in a manner that effectively responds to current and changing rangeland and weather/climatic conditions, incorporates active learning, and includes management decisions from a diverse stakeholder group based on quantitative, repeatable measurements collected at multiple spatial and temporal scales. An 11-person stakeholder group determined goals for vegetation, livestock, and wildlife. Specific objectives were developed for each, and testable hypotheses were derived for the scientists. The group also identified the need for baseline data and subsequent monitoring data to inform decisions made within the year, as well as from year to year. Following the implementation of more sustainable grazing management and prescribed fire treatments in 2014, interpretation of the monitoring data regarding progress towards accomplishing the desired objectives provided the opportunity for stakeholders and scientists to engage in shared learning and co-production of knowledge. CARM is a promising model for collaborative research that develops science-based management recommendations for multiple rangeland goals and objectives.

Key Message 3

Recreation and Tourism

Ecosystems across the Northern Great Plains provide recreational opportunities and other valuable goods and services that are at risk in a changing climate. Rising temperatures have already resulted in shorter snow seasons, lower summer streamflows, and higher stream temperatures and have negatively affected high-elevation ecosystems and riparian areas, with important consequences for local economies that depend on winter or river-based recreational activities. Climate-induced land-use changes in agriculture can have cascading effects on closely entwined natural ecosystems, such as wetlands, and the diverse species and recreational amenities they support. Federal, tribal, state, and private organizations are undertaking preparedness and adaptation activities, such as scenario planning, transboundary collaboration, and development of market-based tools.

Ecosystems across the Northern Great Plains provide recreational opportunities and other valuable goods and services that are ingrained in the region's cultures and at risk in a changing climate. Recreationists enjoyed roughly 13.1 million days of fishing in the region in 2011, along with 10.8 million days of hunting and 8.7 million days of wildlife-watching. The region contains two dozen national parks, monuments, and historic sites. This subset of outdoor recreationists alone—among a wider population who pursue additional outdoor recreation activities in the region—spent over $4.9 billion on these activities during 2011 ($5.2 billion in 2015 dollars).[65,66,67,68,69]

Climate change affects recreation through three pathways: 1) direct impacts to the ecosystems and wildlife or fish populations of interest (for example, increasing water temperature impacting coldwater fish survival); 2) changes in environmental conditions that directly affect recreationists (for example, increased water temperatures resulting in brief river closures for angling to minimize additional stress on sensitive fish species); and 3) effects of adaptation policies on habitat quality or recreational enjoyment (for example, energy policies that result in higher fuel costs, making distant trips more expensive).[70] These three pathways have not been fully quantified for most recreational systems, within or beyond the Northern Great Plains, and the third pathway is only speculative—it has not yet been documented in the scientific literature. Scientific understanding is most complete for the first pathway—the extent and ways in which climate change affects ecosystems that support outdoor recreation.[70]

Climate-related impacts are already being felt in the region's terrestrial and aquatic ecosystems, as well as the local economies that depend upon them. Climate-driven changes in snowpack, spring snowmelt, and runoff have resulted in more rapid melting of winter snowpack and earlier peak runoff due to rapid springtime warming.[71,72,73] These effects have resulted in lower streamflows, especially in late summer.[74] Lower flows, combined with warmer air temperatures, have caused stream temperatures to rise.[75,76,77] These conditions are negatively affecting aquatic biodiversity (e.g., Hotaling et al. 2017[78]) and ecosystem functions of riparian areas (areas along the banks of rivers and streams; e.g., Tonkin et al. 2018[79]), with important consequences for local economies that depend upon river-based recreation. For example, higher stream temperatures are accelerating the hybridization and genetic dilution of native trout species with nonnative trout species.[80] Similarly, shifts in habitat suitability in favor of warmwater fish species are projected to reduce the value of coldwater fishing in the Northern Great Plains by $25 million per year under RCP4.5 by the end of the century and by $66 million per year under RCP8.5 (in 2015 dollars).[81] Higher stream temperatures are already increasing the vulnerability of coldwater fish species to diseases, such as proliferative kidney disease (PKD).[82,83,84] PKD killed thousands of native mountain whitefish in Montana during 2016, which triggered a month-long closure of 180 miles of the Yellowstone River to all water-based recreation.[85] Economic impacts to local communities are still being quantified, but initial estimates range from $360,000 to $524,000 (in 2014 dollars; range is from $363,600 to $529,240 in 2015 dollars).[86]

In the mountainous areas of the region, climate change is impacting snow-dependent ecosystems and economies. In Wyoming and Montana, for example, higher-than-normal winter and fall temperatures and low summer precipitation are enabling severe mountain pine beetle outbreaks in whitebark pine.[87] Whitebark pine is a keystone species of high-elevation ecosystems, providing a critical seed source for more than 20 wildlife species, creating microenvironments that allow other tree species to establish, and influencing snowpack dynamics.[88,89] Whitebark pine is also an important cultural resource for some tribes in the region.[90]

In the future, warmer temperatures and changes in precipitation are expected to decrease the extent and duration of snow cover across much of the northern hemisphere. In the mountains of western Wyoming and western Montana, the fraction of total water in pre- cipitation that falls as snow (from October 1 to March 31) is expected to decline by 25% to 40% by 2100 under a lower scenario (RCP4.5).[10] The last day of the snow season is also expected to arrive earlier in the spring. Under a lower scenario (RCP4.5), it is expected to occur roughly 20 days sooner by 2050 and 30 days sooner by 2100. Under a higher scenario (RCP8.5), it is expected to occur 80 days sooner by 2100.[10] This would negatively affect the region's winter recreation industry, including snowmobiling, cross-country skiing, and downhill skiing.[11]

Under a lower scenario (RCP4.5), the season length for cross-country skiing and snowmobiling in northwestern Wyoming and western Montana is expected to decline by 20% to 60% by 2090.[11] Under the higher scenario (RCP8.5), the projected decline is more severe: 60% to 100%.[11] Similar losses in season length are projected for the region's downhill skiing industry—a $275 million industry.[11] The number of visitors to downhill ski areas is, therefore, expected to decline. Under RCP4.5, visitors are projected to decline by 13% by 2050 and 22% by 2090 (holding population constant); under RCP8.5, projected declines are 19% by 2050 and 49% by 2090.[11] Similar declines are projected for the region's $4.6 million cross-country ski industry and $2.3 million snowmobiling industry (in 2015 dollars).[11] Such reductions in visitor numbers would cause ripple effects across the local economies of snow-dependent communities.

At lower-elevation areas of the Northern Great Plains, natural ecosystems are often embedded within agricultural landscapes. Climate-induced land-use changes in agriculture can, therefore, have cascading effects on closely entwined natural ecosystems, such as wetlands,[12] and the diverse species and recreational opportunities they support. Technological and economic forces within agriculture are also driving land-use changes, which accelerate the degradation of wetlands. For example, in South Dakota and North Dakota, changing climatic and market conditions have enabled agriculture shifts from pasture to small grains, or small grains to corn and soybeans.[12] Nearly 40% of these land-use changes have occurred within 300 feet of neighboring wetlands, reducing the quantity of wetlands and the quality of their ecological functions (see Case Study "Wetlands and the Birds of the Prairie Pothole Region").[46] For example, conversion of pasture to cropland or of winter-seeded crops to spring-seeded crops reduces waterfowl nest survival by increasing habitat fragmentation, which makes nests more vulnerable to predation.[91,92] Tillage in newly converted fields also increases the risk of soil being washed into nearby wetlands, reducing their biological productivity and floodwater storage capacity.[93] These changes have cascading effects not only on wetland-dependent waterfowl but also on shorebirds, fish, amphibians, aquatic insects, and plants. Waterfowl hunting and watching are important cultural and economic activities in rural communities of the Northern Great Plains.[94] In South Dakota alone, hunters spent $84.7 million in 2015–2016 on migratory bird hunting (in 2016 dollars; $83.9 in 2015 dollars).[95]

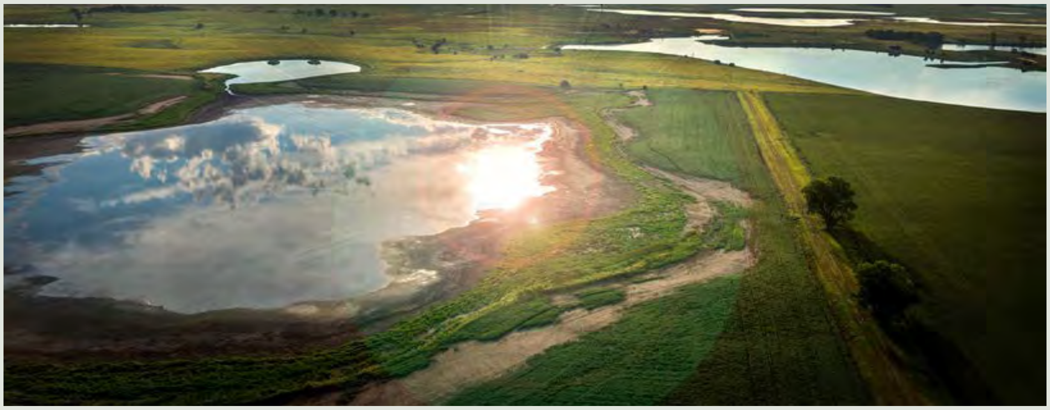
Higher temperatures, reduced snow cover, and more variable precipitation would make it increasingly challenging to manage the region's valuable wetlands, rivers, and snow-dependent ecosystems to sustain today's levels of natural amenities and associated recreational opportunities. Federal, tribal, state, and private organizations are undertaking preparedness and adaptation activities, including scenario planning, to discuss current climate-driven challenges and envision future challenges and responses. The North Central Climate Adaptation Science Center, for example, has facilitated scenario planning exercises for southwestern South Dakota in the vicinity of Badlands National Park and for central North Dakota in the vicinity of Knife River Indian Villages National Historic Site.[96] The Crown Adaptation Partnership—a transboundary team of scientists and resource managers from the United States, Canada, and Tribes/First Nations—is collaborating on climate change adaptation strategies across multiple jurisdictions to enhance resilience of the Crown of the Continent Ecosystem in northern Montana, southwestern Alberta, and southeastern British Columbia.[97] Finally, private organizations have been partnering with researchers to develop "payments-for-ecosystem services," an emerging tool to address land-use change on private agricultural acreage.[98] This market-based tool, when designed appropriately, can encourage private landowners to provide wetlands, wildlife habitat, pollinator habitat, and other valued ecosystem services rather than converting land to uses that produce fewer ecosystem services.[99,100]

Photo taken along the White River in Badlands National Park, South Dakota in September 2016. Photo credit: Christian Collins (CC BY-SA 2.0).

The region's valued ecosystems and recreational opportunities are being affected by climate change to an extent not fully understood, but increasingly being studied. Existing knowledge is primarily based on local and regional case studies, often about specific recreational activities or individual wildlife species. This makes comprehensive assessment a challenge and highlights the need for additional work to fill remaining gaps.[101]

Case Study: Wetlands and the Birds of the Prairie Pothole Region

The North American Prairie Pothole Region (PPR) is a globally important natural resource, a portion of which covers northern and eastern North Dakota, eastern South Dakota, and far northern Montana. The PPR hosts nearly 120 species of wetland-dependent birds representing 21 families[102] and provides prime nesting and migratory habitat for waterbirds, including ducks and shorebirds.[103,104] Estimates suggest that 50% to 75% of all North American waterfowl hatch in the PPR.[105]



Aerial view of the Prairie Pothole Region in South Dakota. Photo credit: © Patrick Ziegler/iStock/GettyImages.

Climate change is affecting wetlands and the bird species they support in the Northern Great Plains, both directly and indirectly. Changes in spring precipitation affect wetlands directly because spring snowmelt, runoff, and refill influence wetland hydrology (including the number of days with standing water and water depth) and plant cover.[106] A warmer climate, if not offset by enough additional precipitation, will shrink wetland areas in the PPR and reduce waterfowl and shorebird habitat. To offset a temperature increase of 5.4°F (3°C), precipitation would need to increase by 20% or more.[106] If a 5.4°F (3°C) increase in average annual temperature occurs and is only offset by a 10% increase in average annual precipitation, much of the wetland habitat in the PPR will be lost.[107,108] Densities of wetlands are predicted to decline on average by 20% to 25% by mid-century under a higher scenario (RCP8.5).[109] In a warmer and drier climate, much of the PPR will be too dry to support historical levels of waterfowl nesting and production,[106] with one study projecting that 28 of 29 species studied will lose range in the future under the higher scenario (RCP8.5).[102]

Wetland and bird losses due to climate change are exacerbated by agricultural land-use change in the PPR, with grasslands and pastures being converted to wheat, corn, and soybeans.[12,46] The degradation of wetland function due to land-use change (Figure 22.4) is driven in part by the increasing profitability of row crops under higher temperatures and increased precipitation in the eastern Dakotas.[12] Land-use change in agriculture to less wetland-friendly crops is also driven by policy and market forces tied indirectly to climate. The ethanol industry's rise in the mid-2000s, for example, contributed to increases in corn prices.[110] Rising prices triggered a north-westward expansion of the historical Western Corn Belt into the PPR, and into close proximity to wetlands.[46] As a result, grassland nesting bird populations are declining faster than any other group of birds in North America.[111,112] Grassland conversion rates such as these (Table 22.3) have not been seen in the Corn Belt since the rapid mechanization of U.S. agriculture in the 1920s and 1930s.[113]

Case Study: Wetlands and the Birds of the Prairie Pothole Region, *contin*

Land-Cover and Land-Use Changes for the Prairie Pothole Region

	Changes in Area (thousands of acres)		
State	**Grassland to Corn/Soy**	**Corn/Soy to Grassland**	**Grassland Net Loss**
Nebraska	309	247	62
North Dakota	320	100	220
South Dakota	632	181	451
Montana	n/a	n/a	n/a
Total	**1,261**	**528**	**733**

Table 22.3: This table shows changes in land cover and land use in the Northern Great Plains portion of the Prairie Pothole Region (PPR), by state, from 2006 to 2011. Note: Montana was not included in the analysis of changes in the PPR cited here, so comparable statistics are not available. Map-based estimates of grassland conversion in Montana from 2008–2012, though not specifically for the PPR, are available from other studies.[47,114] Source: adapted from Wright and Wimberly 2013.[46]

Reductions in Grassland Area in the Prairie Pothole Region

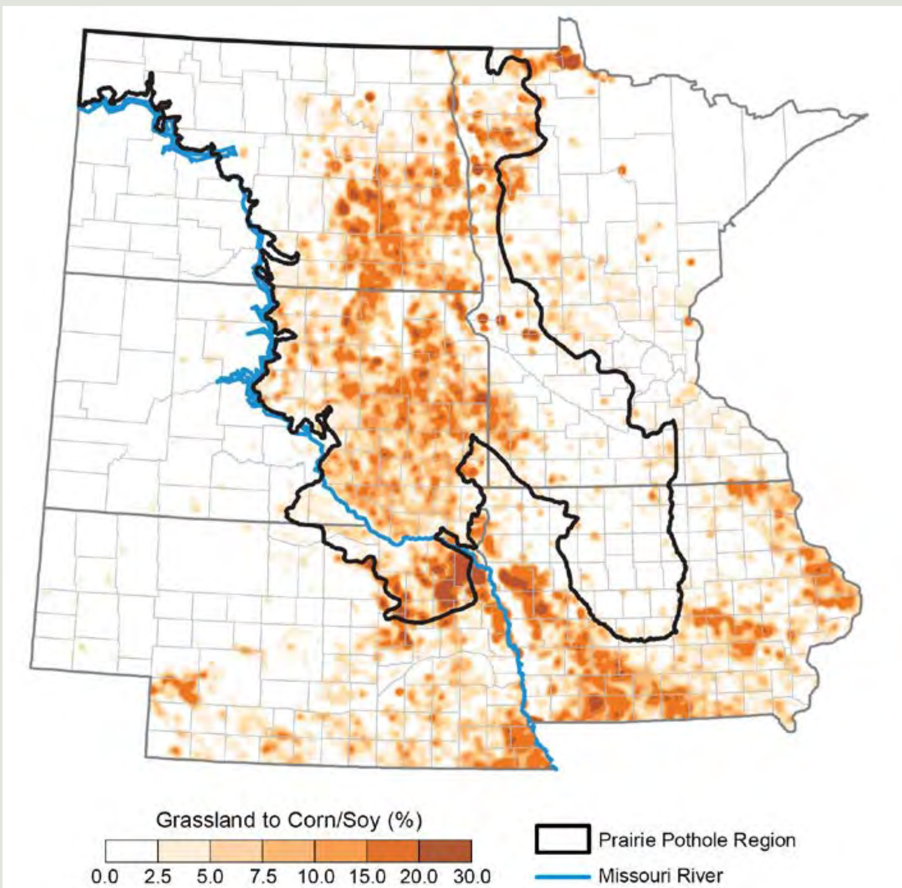


Figure 22.4: The figure shows the loss of grassland to corn/soy between 2006 and 2011 in the eastern states of the Northern Great Plains (Nebraska, South Dakota, and North Dakota), expressed as a percentage of 2006 grassland acres. Outlined in black is the boundary of the U.S. portion of the Prairie Pothole Region, a substantial portion of which was converted from grassland to corn/soy between 2006 and 2011. Source: adapted from Wright and Wimberly 2013.[46]

Key Message 4

Energy

Fossil fuel and renewable energy production and distribution infrastructure is expanding within the Northern Great Plains. Climate change and extreme weather events put this infrastructure at risk, as well as the supply of energy it contributes to support individuals, communities, and the U.S. economy as a whole. The energy sector is also a significant source of greenhouse gases and volatile organic compounds that contribute to climate change and ground-level ozone pollution.

Energy resources in the Northern Great Plains include abundant crude oil, natural gas, coal, wind, stored water, and, to a lesser extent, corn-based ethanol, solar energy, and uranium. The infrastructure associated with the extraction, distribution, and energy produced from these resources is vulnerable to the impacts of climate change, including increasing average temperatures and heat waves, decreasing water availability in the summer, and an increase in the frequency and severity of heavy precipitation events leading to floods.[13]

Energy infrastructure vulnerabilities relate to how fuel is transported and how energy is produced, generated, transmitted, and used. For example, railroads and pipelines are vulnerable to damage or disruption from increasing heavy precipitation events and associated flooding and erosion.[13] Summer heat waves also damage railroad tracks and are expected to reduce thermoelectric power plant and transmission line capacity,[13] though estimates of the likelihood, timeframe, or magnitude of such impacts are limited. Higher temperatures are likely to lower the yields of crops used for biofuels while shifting northward the range in which certain biofuel crops (such as corn) can be cultivated.[13] Biorefineries are vulnerable to decreasing water availability during drier summers and periods of drought.[13] Declining water availability in the summer would likely increase costs for oil production operations, which require freshwater resources.[13] These cost increases will lead either to reduced production or be passed on to consumers. Finally, higher maximum temperatures, longer and more severe heat waves, and higher overnight lows are expected to increase electricity demand for cooling in the summer, further stressing the power grid.[13] Increasing demands for electricity in response to increasing temperatures are projected to increase costs to the power system by approximately $13–$18 million per year by 2050 under the higher scenario (RCP8.5) and $42–$80 million per year by 2090 under the same scenario (in 2015 dollars).[81]

These risks to the energy sector are likely to negatively impact individuals, communities, and the economy, and are also likely to require new planning and preparedness options for the short and long term. While such efforts have already begun, more widespread and coordinated strategies would help maximize risk reduction to the energy sector.

Examples of energy sector resilience solutions include actions like railroad preventive maintenance, upgrades, and reliability standards; water-efficient cooling technologies for thermoelectric power plants, such as recirculating or wet–dry hybrid systems; and programs that reduce total and peak electricity demand.[13] Such programs, often run by electric utilities, use rebates and cash incentives to encourage customers to purchase more efficient appliances and equipment like lighting, pumps, water heaters, and air conditioners.

The energy sector is also a significant source of greenhouse gas emissions in the Northern Great Plains, as illustrated in Figure 22.6.[81] Methane is released during the production, processing, transmission, storage, and distribution of natural gas. CO_2 and methane are released during the production, transportation, and refining of petroleum. Coal mining also releases methane. CO_2 is emitted from the combustion of coal and natural gas to produce electricity and from the combustion of petroleum for transportation.[117] Natural gas and petroleum systems also emit volatile organic compounds, or VOCs, that contribute to the formation of ground-level ozone pollution. Climate change is generally expected to increase such ozone pollution in the future throughout much of the United States, in part due to higher temperatures and more frequent stagnant air conditions (Ch. 13: Air Quality). Unless offset by additional emissions reductions of ozone precursors, these climate-driven increases in ozone are forecast to cause premature deaths, hospital visits, lost school days, and acute respiratory symptoms.[118]

Floodwaters Surround Nuclear Power Plant in Nebraska

Figure 22.5: Floodwaters from the Missouri River surround the Omaha Public Power District's Fort Calhoun Station, a nuclear power plant just north of Omaha, Nebraska, on June 20, 2011. The flooding was the result of runoff from near-record snowfall totals and record-setting rains in late May and early June (NWS 2012).[115] A protective berm holding back the floodwaters from the plant failed, which prompted plant operators to transfer offsite power to onsite emergency diesel generators. Cooling for the reactor temporarily shut down, but spent fuel pools were unaffected.[116] Photo credit: Harry Weddington, U.S. Army Corps of Engineers.

Greenhouse Gas Emissions from Fuel Production

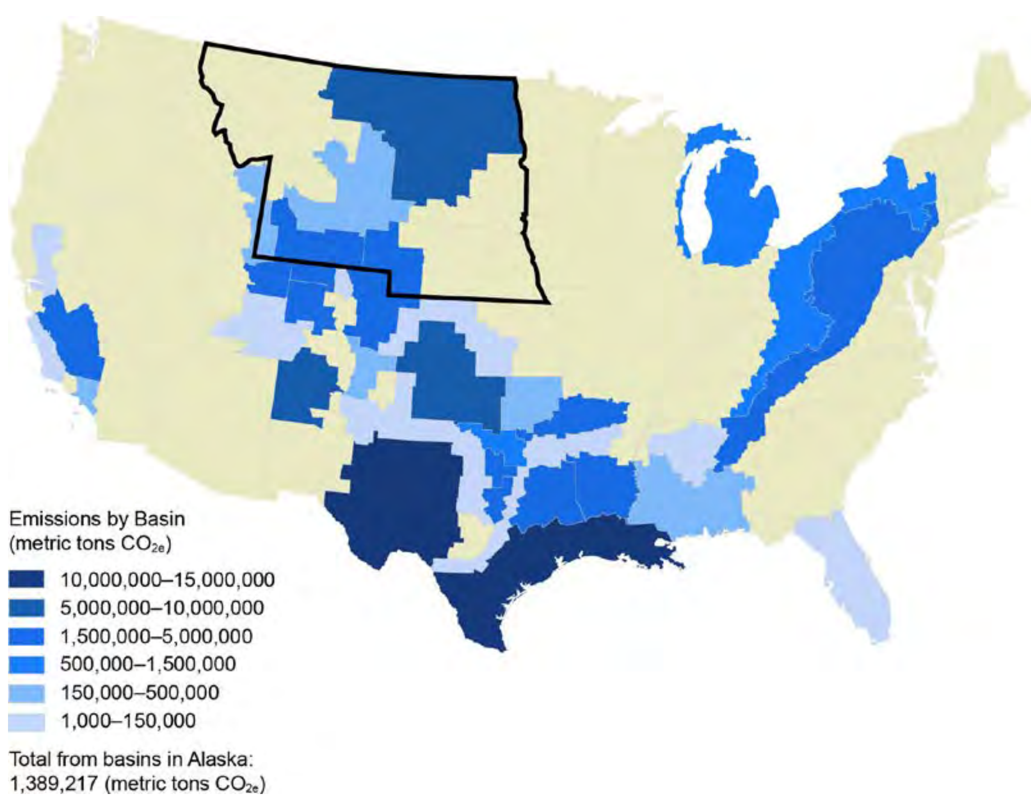


Figure 22.6: Greenhouse gas emissions (shown here in metric tons of carbon dioxide equivalent, or CO_{2e}, per geologic basin) from petroleum and natural gas production facilities in the Northern Great Plains are among the highest in the United States. The data used to produce this map are from EPA's Greenhouse Gas Reporting Program, which only includes facilities that emit 25,000 metric tons of CO_{2e} or more annually.[117] Each production facility must provide the total emissions from all their well pads in a geologic basin. Source: adapted from EPA 2017.[117]

Strategies being employed in the region to reduce greenhouse gas emissions from the energy sector include increasing the performance of coal-fired power plants; offsetting fossil fuel-fired generation with renewable energy; conducting methane leak detection and repair programs using remote sensing technologies at natural gas operations; upgrading the equipment used to produce, store, and transport oil and gas; and demand-side management of electricity use.

Key Message 5

Indigenous Peoples

Indigenous peoples of the Northern Great Plains are at high risk from a variety of climate change impacts, especially those resulting from hydrological changes, including changes in snowpack, seasonality and timing of precipitation events, and extreme flooding and droughts as well as melting glaciers and reduction in streamflows. These changes are already resulting in harmful impacts to tribal economies, livelihoods, and sacred waters and plants used for ceremonies, medicine, and subsistence. At the same time, many tribes have been very proactive in adaptation and strategic climate change planning.

The rich cultural heritage of the Northern Great Plains began with the region's Indigenous peoples who are now in 27 federally recognized tribes, 1 state-recognized tribe in Montana, and several unrecognized tribes in addition to the myriad Native Americans spread throughout the towns, cities, and rural areas of the region (Figure 22.7). Because tribes and Indigenous peoples are among those in the region with the highest rates of poverty and unemployment, and because many are still directly reliant on natural resources, they are among the most at risk to climate change.[24,25,27,28,29,30,31]

Indigenous peoples in the region are observing many climate and seasonality changes to their natural environment and ecosystems, many of which are impacting livelihoods as well as traditional subsistence and wild foods, wildlife, plants and water for ceremonies and medicines, and health and well-being (see Case Study "Crow Nation and the Spread of Invasive Species").[14,15,16,17,18,19,20,21,22,23,24,25,26] Specifically, tribal elders and natural resource managers in the region have observed seasonal changes, such as those in hydrological cycles, phenology, bird migrations, and bear hibernation cycles, as well as reduced availability of traditional plant-based foods and the decline in pine tree species. There is also a mismatch between traditional stories and current climate and seasons.[14,19] They are also experiencing significant impacts to subsistence fisheries and riparian ecosystem health, including declines in salmon, trout, frogs, and mussels as a result of reduced streamflow and warmer water temperatures.[19,26,119,120] Extreme heat and declines in traditional plants (such as sage, cottonwoods, and cattails) are already impacting summer outdoor ceremonies when participants fast and camp for days.[19] In addition, tribes are experiencing increased fire frequency and intensity, and climate projections that show increased fire risks for the region are causing concern for the health of forests, wildlife, freshwater systems and fisheries, and human health.[14,19]

Northern Great Plains Tribal Lands

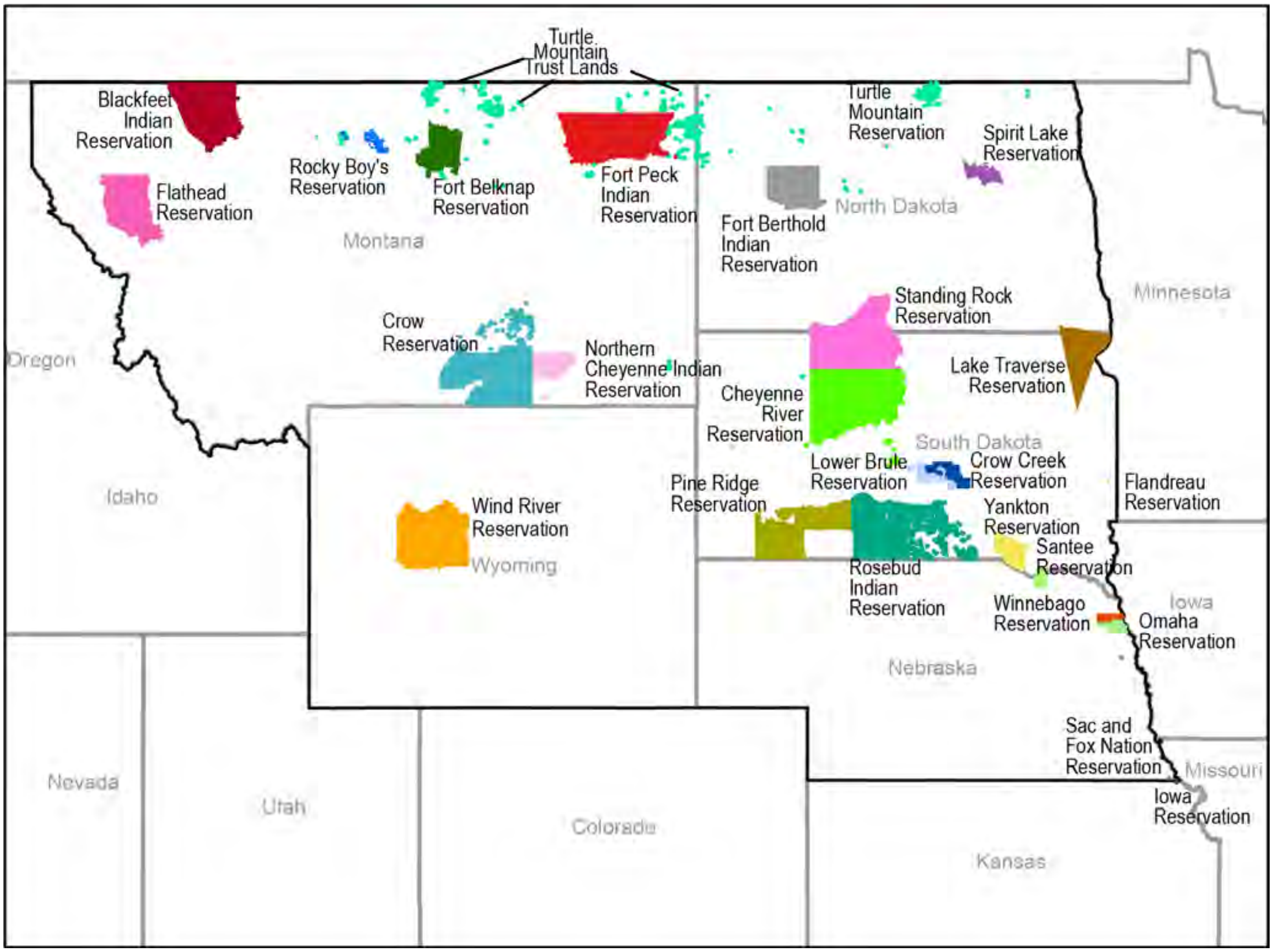


Figure 22.7: The map outlines reservation and off-reservation tribal lands in the Northern Great Plains, which shows where the 27 federally recognized tribes have a significant portion of lands throughout the region. Information on Indigenous peoples' climate projects within the Northern Great Plains is described in Chapter 15: Tribes and Indigenous Peoples. Sources: created by North Central Climate Science Center (2017) with data from the Bureau of Indian Affairs, Colorado State University, and USGS National Map.

To the Indigenous peoples of the Northern Great Plains, the Lakota phrase Mni wiconi means "water is life." Water plays significant cultural, religious, and economic roles across tribal communities that transcend consumptive water use. Because water is so integral, these communities are particularly sensitive to climate change impacts on water in the form of extreme flooding and droughts, changes in snowpack, and changes in the timing of precipitation events. These climate sensitivities, along with substandard water infrastructure and complex institutions and water rights, all combine to create water insecurity.[14,18,19,20,23,24,28,120,121,122,123,124] In the Northern Great Plains, just under 29,000 (76%) Indigenous households are in need of new or improved sanitation facilities, and approximately 5,000 households lack safe water supply, sewage facilities, or both.[125] The total cost to remediate sanitation facility deficiencies in the region was estimated at around $280 million according to a 2015 annual report from the Indian Health Service.[125] Climate change has already begun to exacerbate the problem of disruptions to water supplies from decreased water availability, as happened in 2003 when Standing Rock Reservation ran completely out of water during drought.[28]

Case Study: Crow Nation and the Spread of Invasive Species

A warming climate is projected to hasten the spread of invasive species within riparian ecosystems.[134,137,138,139] Indigenous populations who harvest and hold sacred flora and fauna along rivers within the semiarid region of south central Montana are particularly vulnerable.[140] Post-reservation settlement of Treaty Tribes and multiple land policies aimed at assimilation of Native American Tribes in the United States created a checkerboard of land ownership within reservation boundaries. The Apsaalooké, or Crow, Reservation was established after the Fort Laramie Treaty of 1886 and is located within the mountains and valleys along the Little Bighorn and Bighorn Rivers in south central Montana.[141] Promotion of agriculture in the late 19th century, along with the establishment of divergent dams for floodplain irrigation, resulted in decreased water flows, affecting the natural pulse of these river systems and their associated native riparian species. Cascading effects of river regulation, along with intentional planting of the invasive species Russian olive (*Elaeagnus angustifolia* L.) during the Indian Emergency Conservation Work era of the 1930s, have drastically altered natural vegetation within these watersheds (Figure 22.8). These complex networks of policy and culture determine the ways in which land and riparian regimes were drastically changed. The resulting conditions favored invasive plants and ecosystem degradation.[142]

The Apsaalooké, or Crow, people regularly harvest riparian plant species for food, ritual, and ceremonial uses. For example, plains cottonwood (*Populus deltoides*, Marsh) and willow (*Salix sp.* L.) are used for ceremonial (sweat lodge and Sun Dance) purposes. Crow Elders indicated that they must travel on average more than 15 miles farther now than they did 25 years ago to locate cottonwoods of specific sizes. They also find it difficult to locate and harvest traditional food sources such as chokecherry (*Prunus americana* L.) and buffalo berry (*Shepherdia argentea* Pursh., Nutt.). What was once a cottonwood- and willow-dominated river system is now dominated by Russian olive. Populations of salt cedar are likewise increasing along both the Bighorn and Little Bighorn Rivers and associated floodplains. Projections using habitat species distribution models suggest that Russian olive plants will continue to spread in the next 10 years as a result of increasing temperatures and precipitation (Figure 22.8). Continued spread of Russian olive species ultimately threatens the ability of the Crow people to harvest culturally important riparian species that provide subsistence, medicine, and plant species used in ceremony.[140]

The Russian olive invasion is a challenge throughout the Northern Great Plains. Here, the trees grow on ranchland on the Crow Indian Reservation. Photo credit: Kurrie Jo Small.

Case Study: Crow Nation and the Spread of Invasive Species, *continued*

Projected Expansion of Russian Olive Habitat

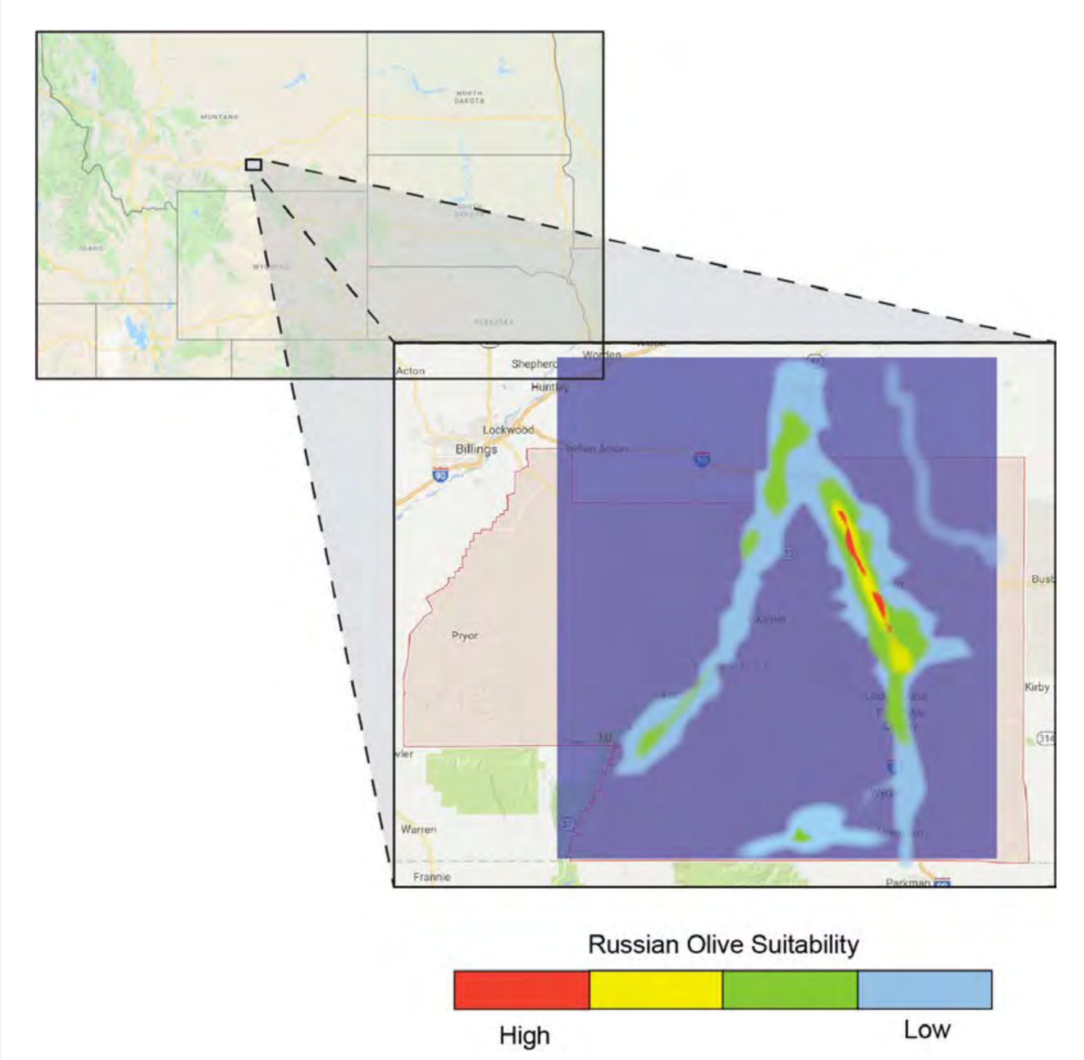


Figure 22.8: The map shows the projected expansion by 2021 of Russian olive habitat. Warmer colors indicate favorable habitat for future spread of Russian olive based on mapped presence points along the Little Bighorn and Bighorn Rivers within the Crow Indian Reservation in south central Montana. The Crow Reservation is outlined and shaded in red. Purple areas are outside of the suitability zone. Source: University of Arizona. Map data © 2018 Google, INEGI.

Reservation Irrigation Projects: Deferred Maintenance and Replacement Costs

Irrigation Project	Deferred Maintenance for FY 2014	Replacement Value
Blackfeet	$26,000,000	$50,000,000
Flathead	$82,000,000	$237,000,000
Fort Belknap	$8,000,000	$19,000,000
Fort Peck	$13,000,000	$33,000,000
Crow	$17,000,000	$59,000,000
Wind River	$30,000,000	$93,000,000
Total	**$176,000,000**	**$491,000,000**

Table 22.4: This table shows deferred maintenance and replacement costs for U.S. Bureau of Indian Affairs irrigation projects on six Northern Great Plains reservations (in 2014 dollars). Source: U.S. Government Accountability Office 2015.[126]

Agriculture, particularly livestock ranching, is a primary tribal livelihood in the region, and warmer temperatures and changes to water cycles (for example, reduced snowpack, earlier transition from snow to rain, and reduced or early runoff) pose a large threat and are already drying soils, reducing forage production, increasing livestock stress, and reducing water availability for irrigation systems throughout the region.[20,120] Reservations in the region would require a combined $176 million in maintenance or $491 million to replace neglected and failing Bureau of Indian Affairs irrigation systems (Table 22.4).[126] High leakages and inefficiencies in these systems hinder effective management of water and irrigation systems for climate change.[20]

Tribes have unique water rights and layers of relevant state and federal laws (for example, the Winters Doctrine and state water rights adjudication, and Prior Appropriation laws in the West). Climate change impacts on water resources are very likely to be compounded by these legal complexities, especially in cases where state water laws supersede tribal water codes and water rights during times of scarcity, such as at Wind River Reservation, where the Wyoming Supreme Court ruled that the state has primary authority.[20,123,127,128] Indigenous people in the region are also very concerned about the consequences of major oil pipelines passing through the region. Their concerns are in part focused around potential leaks, which would impact water resources already stressed by climate change. This concern is further intensified by the reality that climate change is projected to damage infrastructure in the region, including pipelines, through extreme storm or precipitation events that cause flooding.[54,56,121]

Disaster management is another area of great concern for the Northern Great Plains tribes. Over the last two decades, tribes have experienced unusually catastrophic fires, floods, and droughts that are already straining response capacities,[25] and climate change is expected to increase the need for the ability to fight fires, floods, and droughts.[14,16,25,129,130,131] Severe droughts in this century have resulted in serious impacts, such as tribal ranchers liquidating herds and reservations possessing no water at all.[28] Extreme hydrological events on the region's reservations are also happening in quick succession, such as the 2011 floods followed by severe drought and fire in 2012.[19,20,25,28] Each event strains the response capacity, and for the many tribes struggling with a lack of disaster preparedness, successive events compound the challenge.[25,28] This has widespread impacts on tribal economies and livelihoods, domestic and municipal water supplies, and health and well-being.

Many climate adaptations are underway in Northern Great Plains Indigenous communities, but tribes also face unique legal and regulatory barriers because of post-colonial resettlement and reservation impacts of land fragmentation and uneven regulation by federal agencies. For example, the trust relationship with the Federal Government, where the Federal Government holds the titles of tribal lands "in trust" for the tribes, requires federal permission for many aspects of land and resource management.[14,15,16,17,18,20,25,131,132,133,134,135] Outside of these limitations, however, the tribes do have control over the reservations' built environment and housing. For example, the Oglala Lakota Nation (Pine Ridge) in South Dakota has created a sustainability plan that includes off-grid, climate-resilient housing and sustainable agriculture.[16,17,122,136] Other climate adaptation examples include Flathead Reservation's strategic climate planning for multiple sectors and species of cultural and economic importance; several South Dakota tribes' climate vulnerability assessment and drought planning; Wind River Reservation's drought assessment and preparedness; Northern Cheyenne Tribe's Integrated Resource Management Planning that will include climate change; and Fort Belknap's climate adaptation plan, which integrated planning with fire, forestry, and invasives management.[14,20,25] The InterTribal Buffalo Council also has drought and climate adaptation grants to prepare tribal bison herd managers in the region and beyond for climate impacts to bison pastures and water sources. There are multiple tribal initiatives that focus on climate and Indigenous knowledge-based education, outreach, and information sharing between tribes. For example, the Northern Cheyenne Indigenous land-based science learning program offers apprenticeships for youth interested in bio-cultural restoration science. The program, which sits in the tribe's Department of Environmental Protection and Natural Resources, aims to increase tribal knowledge around Indigenous and western sciences and thus enable youth to reclaim their responsibility to the land. Also, the Blackfeet and Confederated Salish and Kootenai Tribes collaborated on a regional workshop with First Nations throughout the region to share ideas and strategies and provide support for tribal climate adaptation planning.[25] Tribes are increasingly drawing on their deep, place-based connections to natural cycles and Indigenous knowledge, combined with western technical sciences, to respond to and prepare for climate change.[14,15,16]

Acknowledgments

USGCRP Coordinators

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Opening Image Credit

Cameron, Montana: Paul Cross/U.S. Geological Survey.

Traceable Accounts

Process Description

The chapter lead (CL) and coordinating lead author (CLA) developed a list of potential contributing authors by soliciting suggestions from the past National Climate Assessment (NCA) author team, colleagues and collaborators throughout the region, and contributors to other regional reports. Our initial list of potential authors also included CL nominees submitted to the U.S. Global Change Research Program (USGCRP). The CL and CLA discussed the Northern Great Plains, which was part of the larger Great Plains region for the Third National Climate Assessment (NCA3), with each of these nominees and, as part of that discussion, solicited suggestions for other nominees. This long list of potential contributing authors was pared down by omitting individuals who could not contribute in a timely fashion, and the list was finalized after reconciliation against key themes within the region identified by past NCA authors, the CL and CLA, and contributing author nominees. The team of contributing authors was selected to represent the region geographically and thematically, but participants from some states who had agreed to contribute were eventually unable to do so. Others were unable to contribute from the start. The author team is mostly composed of authors who did not contribute to NCA3.

The CL and CLA, in consultation with past NCA authors and contributing author nominees, identified an initial list of focal areas of regional importance. The author team then solicited input from colleagues and regional experts (identified based on their deep ties to scientific and practitioner communities across the region) on their thoughts on focal areas. This list informed the agenda of a region-wide meeting held on February 22, 2017, with core locations in Fort Collins, Colorado, and Rapid City, South Dakota. The main purpose of this meeting was to seek feedback on the proposed list of focal areas. With this feedback, the author team was able to refine our focal areas to the five themes comprising the Key Messages of the Northern Great Plains regional chapter. Of these, recreation/tourism is a focus area that is new from NCA3.

Key Message 1

Water

Water is the lifeblood of the Northern Great Plains, and effective water management is critical to the region's people, crops and livestock, ecosystems, and energy industry. Even small changes in annual precipitation can have large effects downstream (*very high confidence*); when coupled with the variability from extreme events, these changes make managing these resources a challenge (*very high confidence*). Future changes in precipitation patterns, warmer temperatures, and the potential for more extreme rainfall events are very likely to exacerbate these challenges (*very likely*, *high confidence*).

Description of evidence base

Multiple lines of research have shown that as a result of its high aridity, changes in water availability in the Northern Great Plains region are highly sensitive to small changes in climate.[35,36,143,144] Despite large differences in climate from the western mountains to the eastern plains, the reliance upon reservoir storage to regulate water supplies is ubiquitous—to provide water during times of drought and to mitigate flood waters during deluges.

Natural reservoirs, groundwater, and snowpack are at risk to varying degrees. Reservoir vulnerability was recently analyzed to assess sustainable pumping rates,[42] while snow and especially glaciers appear to be in steady decline in recent decades,[38] attributed to global climate warming[39] that is projected to continue.[145]

Major uncertainties

While there is high confidence in future increases in temperature, uncertainties exist as to the changes in precipitation and runoff. Perhaps most important are the uncertainties in the degree of precipitation variability from year to year and within season (based on information dating to the 1950s).[35,52] These uncertainties are very likely to overwhelm the projected modest increases in precipitation.

Uncertainties exist in agricultural demands for water, reservoir operation protocols, and changes in extreme events.

Description of confidence and likelihood

There is *high confidence* that temperatures will rise in the region, which will *likely* produce less snowfall and smaller mountain snowpacks. There is *very high confidence* in the downstream consequences of these changes.

Key Message 2

Agriculture

Agriculture is an integral component of the economy, the history, and the culture of the Northern Great Plains. Recently, agriculture has benefited from longer growing seasons and other recent climatic changes (*very high confidence*). Some additional production and conservation benefits are expected in the next two to three decades as land managers employ innovative adaptation strategies (*very likely*, *high confidence*), but rising temperatures and changes in extreme weather events are very likely to have negative impacts on parts of the region (*very likely*, *very high confidence*). Adaptation to extremes and to longer-term, persistent climate changes will likely require transformative changes in agricultural management, including regional shifts of agricultural practices and enterprises (*very likely*, *high confidence*).

Description of evidence base

Several lines of research have shown that agricultural productivity is likely to increase in rangelands across the region with increasing atmospheric carbon dioxide (CO_2) and warming,[3,7,8] with no yield changes likely for small grain crops (for example, wheat) and yield reductions likely for row crops (for example, corn) in dryland croplands.[6] The competitive ability of weeds (primarily perennial forbs such as *Linaria dalmatica* and annual grasses such as *Bromus tectorum*) is likely to increase as well, with corresponding impacts to forage production,[1,2] as phenology is altered[57,58] and the growing season lengthens.[4,5] Forage quality is expected to decline,[3,59,60] and crop yields are likely to decrease if extreme temperature events (high daytime highs or nighttime lows) occur during critical pollination and grain fill periods.[9]

Numerous lines of research have addressed adaptation strategies for various parts of the agricultural sector[9,61,63,146,147,148]

Major uncertainties

While there is high confidence in future increases in temperature, uncertainties exist as to the changes in extreme events, including the spatiotemporal aspects of high-intensity rainfall events, snowstorms, and hailstorms. Perhaps most important are the uncertainties in the degree of precipitation variability from year to year[35] that influence decision-making calendars for agricultural producers.

Description of confidence and likelihood

There is *very high confidence* that longer growing seasons have already benefited agriculture in parts of the Northern Great Plains. There is *very high confidence* that increases in temperatures and atmospheric CO_2 will *likely* increase production potential for the agricultural sector in the short term (the next 10–20 years) and that current adaptations already being implemented by a subset of producers in this region provide opportunities for assessment, further development, and adoption by the larger population of agricultural managers. There is *very high confidence* that rising temperatures and changes in extreme weather events are very *likely* to have negative impacts on parts of the region. Over the longer-term (through the end of the 21st century), predicted climate changes may require transformative changes in agricultural management, including regional shifts of agricultural practices and enterprises (*very likely, high confidence*).[61,64]

Key Message 3

Recreation and Tourism

Ecosystems across the Northern Great Plains provide recreational opportunities and other valuable goods and services that are at risk in a changing climate (*very high confidence*). Rising temperatures have already resulted in shorter snow seasons, lower summer streamflows, and higher stream temperatures and have negatively affected high-elevation ecosystems and riparian areas, with important consequences for local economies that depend on winter or river-based recreational activities (*high confidence*). Climate-induced land-use changes in agriculture can have cascading effects on closely entwined natural ecosystems, such as wetlands, and the diverse species and recreational amenities they support (*very high confidence*, *likely*). Federal, tribal, state, and private organizations are undertaking preparedness and adaptation activities, such as scenario planning, transboundary collaboration, and development of market-based tools.

Description of evidence base

State-level surveys, conducted roughly every five years, have consistently documented that the public spends millions of days each year (over $30 million in 2011) participating in nature-based recreation activities in the Northern Great Plains (e.g., U.S. Department of the Interior and U.S.

Department of Commerce 2008, 2013a, 2013b, 2014a, 2014b[65,66,67,68,69]). The implications of climate change for outdoor recreation, and tourism more broadly, have been studied extensively around the globe (see summaries in Scott et al. 2012, Rosselló and Santana-Gallego 2014, Brice et al. 2017[101,149,150]). Region-specific studies are only a small subset of this large body of literature, so our understanding of potential impacts of climate change on outdoor recreation in the Northern Great Plains is sometimes inferred from other regions with similar characteristics (e.g., Hari et al. 2006[83]). Region-inclusive studies are available (e.g., Wobus et al. 2017[11]) for the sectors most obviously affected by climate change (such as winter recreation). Our understanding is most complete about the implications of climate change for the ecosystems upon which outdoor recreation in the Northern Great Plains depends.[70] For example, the implications of climate change for wetlands and waterbirds in the Prairie Pothole Region, upon which much bird hunting and bird watching in the region depend,[104,105] have been studied extensively over the past several decades (e.g., Johnson and Poiani 2016, Wright and Wimberly 2013[46,106]). The role of agricultural land-use change (as a function of climate change as well as complex technological, policy, and market factors) in the degradation of wetland function in the region—for example through increased soil erosion and resulting wetland sedimentation or upland habitat fragmentation and resulting increases in waterfowl nest predation—has also been thoroughly assessed (e.g., Rashford et al. 2016, Sofaer et al. 2016[12,109]).

Major uncertainties

Climate change is expected to disrupt local economies that depend on winter-based or river-based recreational activities. However, the magnitudes of these effects are uncertain. This is due largely to uncertainties about the preferences of recreationalists and the extent to which they will adapt by shifting the timing and location of their activities or by substituting towards a different set of recreational activities. For example, although climate change will make it more difficult to supply high-quality downhill skiing opportunities, this effect will be stronger in lower-elevation areas. Therefore, some skiers might adapt by simply traveling to higher-elevation downhill ski areas. Others might compensate for the shorter ski season at their favorite lower-elevation mountain by shifting some of their recreational time to an alternative outdoor activity, such as winter mountain biking. Given the potential diversity of individual preferences for adapting outdoor recreation activities to climate change, it is challenging to project with certainty the future potential impacts to recreation-dependent economies, but the impact will be larger and more immediate for some industries and companies (e.g., low-altitude ski resorts).

Another source of uncertainty is the reliance, in some cases, on scientific studies from other geographic locations to infer what the impacts of climate change might be for ecosystems, species, or recreationalists within the Northern Great Plains. For example, the effects of increased stream temperature on the susceptibility of coldwater fish species to diseases in the region are based largely on studies conducted in European coldwater fisheries.

Regarding wetlands in the Prairie Pothole Region, uncertainty about their abundance in the future arises from uncertainty about future government policies that would either exacerbate or mitigate climate-induced losses. For example, future versions of the Farm Bill may contain language that directly encourages wetland preservation (e.g., through conservation-compliance requirements) or unintentionally leads to wetland degradation (e.g., through higher subsidies for row crop insurance).

Description of confidence and likelihood

We know with *very high confidence* that ecosystems across the Northern Great Plains provide recreational opportunities and other valuable goods and services. We know with *very high confidence* that climate change is *very likely* affecting abiotic factors that influence these ecosystems, such as snowfall, spring snowmelt, runoff, and stream temperatures. There is *high* confidence that these abiotic factors are *likely* to affect high-elevation ecosystems and riparian areas in the Northern Great Plains. Greater confidence could be gained by conducting studies specifically within the Northern Great Plains, as opposed to drawing inferences from studies conducted in other regions of the world with similar characteristics. The consequences of ecosystem changes for local economies in the region that depend on winter-based or river-based recreational activities are currently being debated in the scientific literature, due to uncertainty about potential individual behavioral responses to changes in the recreational environment. Based on a limited number of case studies, effects of climate change on outdoor recreation-based economies are *as likely as not* to be negative, but this is only known with *medium confidence*. We know with *very high confidence*, however, that some natural ecosystems that local economies depend upon—in this specific case, wetlands in the Northern Great Plains—are *likely* to be negatively affected by climate-induced changes in agricultural land use. In turn, we know with *high confidence* that wetland declines will *very likely* harm the diverse species and recreational amenities they support. Uncertainty about future policies that could influence agricultural land-use decisions and wetland conservation outcomes precludes a higher confidence level or higher likelihood.

Key Message 4

Energy

Fossil fuel and renewable energy production and distribution infrastructure is expanding within the Northern Great Plains (*very high confidence*). Climate change and extreme weather events put this infrastructure at risk, as well as the supply of energy it contributes to support individuals, communities, and the U.S. economy as a whole (*likely*, *high confidence*). The energy sector is also a significant source of greenhouse gases (*very likely*, *very high confidence*) and volatile organic compounds that contribute to climate change and ground-level ozone pollution (*likely in some areas*, *very high confidence*).

Description of evidence base

Fossil fuel and renewable energy production/distribution infrastructure is expanding within the Northern Great Plains, including oil and natural gas pipelines, natural gas compressor stations and storage tanks, natural gas processing plants, natural gas-fired power plants, high-voltage power lines and substations, wind farms, and even a new oil refinery and a new biorefinery in recent years (both began operations in 2015).

A number of oil and natural gas pipelines are being constructed or have been completed in recent years. In particular, the Dakota Access Pipeline began commercial service June 1, 2017, transporting crude oil from the Bakken/Three Forks production areas in North Dakota, through South Dakota and Iowa, to Pakota, Illinois. While pipelines are vulnerable to damage or disruption from heavy precipitation events and associated flooding and erosion,[13] their increased use could eliminate hundreds of rail cars and trucks needed to transport crude every day. This reduces the exposure of these modes of transportation to rising temperatures, heat waves, and floods.[13] Other oil and gas production and distribution infrastructure is similarly vulnerable to heavy precipitation events and flooding.

The region relies on rail lines to transport coal, and these lines are vulnerable to rising temperatures, heat waves, and floods.[13] There is ample evidence of rail line vulnerability to extreme weather.[151]

Damage to thermoelectric power plants and electric power transmission lines from extreme weather such as heat waves and wildfires has been documented, and the risk is expected to increase.[13,152]

The U.S. Department of Energy (DOE) Energy Risk Profiles (1996–2014) highlight the risks to energy infrastructure in the United States from natural hazards. For example, in North Dakota, thunderstorms and lightning had the highest frequency of occurrence and property loss during this timeframe. DOE also has a series of comprehensive documents on U.S. energy sector vulnerabilities to climate change[13,153] that identify important climate-related vulnerabilities for fuel transport, electricity generation, and electricity demand.

There is substantial evidence that the energy sector is a significant source of greenhouse gases that contribute to climate change, in particular from power plants, oil and gas systems, and refineries.[117]

Major uncertainties

Cold waves are projected to be less intense in the future, reducing the risk of disruptions from cold to energy infrastructure.[13]

There is not yet substantial agreement among sources as to how a changing climate will ultimately affect wind resources in the United States in general and in the Northern Great Plains in particular.[153]

Projected increases in precipitation in the Northern Great Plains are likely to benefit hydropower production, but this will vary by location. For example, it is known that in the Columbia River Basin, decreasing summer streamflows will reduce downstream hydropower production, and increasing winter and early spring streamflows will increase production.[13] In the Missouri River Basin, projected seasonal declines in precipitation in the southern and western portion of the region are likely to reduce the water available to generate hydropower.[13]

Biofuel feedstocks from crops and forage grown in the Northern Great Plains are vulnerable to climate change, but the net impacts on biofuel production are uncertain.[13]

It is well understood that ground-level ozone (O_3) is created by chemical reactions between volatile organic compounds in the presence of sunlight and would be exacerbated by climate change. What is less understood is the sensitivity of regional climate-induced O_3 changes, and the science of modeling climate and atmospheric chemistry to understand future conditions.

Description of confidence and likelihood

There is *high confidence* that climate change and extreme weather events will *likely* put energy supply and infrastructure of various types at risk. There is *high confidence* that the energy sector is a *very likely* a significant source of greenhouse gases contributing to climate change. There is *very high confidence* that volatile organic compounds contribute to climate change and ground-level ozone pollution, and it is *likely* that this will worsen in the future in some areas.

Key Message 5

Indigenous Peoples

Indigenous peoples of the Northern Great Plains are at high risk from a variety of climate change impacts, especially those resulting from hydrological changes, including changes in snowpack, seasonality and timing of precipitation events, and extreme flooding and droughts as well as melting glaciers and reduction in streamflows (*likely*, *very high confidence*). These changes are already resulting in harmful impacts to tribal economies, livelihoods, and sacred waters and plants used for ceremonies, medicine, and subsistence (*very high confidence*). At the same time, many tribes have been very proactive in adaptation and strategic climate change planning (*very likely*, *very high confidence*).

Description of evidence base

Multiple lines of research have shown that hydrological changes and changes in extremes have resulted in deleterious impacts to Indigenous peoples.[14,18,19,20,23,24,28,121,122,123,124] During times of drought, decreased water availability negatively impacts tribal communities and livelihoods such as ranching, and already stressed water systems and infrastructure do not provide the necessary water to sustain Indigenous communities and reservations.[20,28,154]

Major uncertainties

The impacts of climate change in the Northern Great Plains are expected to increase risks to Indigenous reservations, communities, and livelihoods. However, there is uncertainty about how Indigenous people will be able to respond. Much of this uncertainty is due to unsettled water rights, multijurisdictional complexities, and federal funding and policies.

Description of confidence and likelihood

There is *very high confidence* that rising temperature and increases in flooding, runoff events, and drought are *likely* to lead to increases in impacts to reservations and other Indigenous communities. There is *very high confidence* that climate changes are already resulting in harmful impacts on tribal economies, livelihoods, and culture. However, the actual impacts and response capacities will depend on the response of regulatory systems and funding amounts.

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23 Southern Great Plains

Whooping cranes in the Aransas National Wildlife Refuge in Texas

Key Message 1

Food, Energy, and Water Resources

Quality of life in the region will be compromised as increasing population, the migration of individuals from rural to urban locations, and a changing climate redistribute demand at the intersection of food consumption, energy production, and water resources. Agrowing number of adaptation strategies, improved climate services, and early warning decision support systems will more effectively manage the complex regional, national, and transnational issues associated with food, energy, and water.

Key Message 2

Infrastructure

The built environment is vulnerable to increasing temperature, extreme precipitation, and continued sea level rise, particularly as infrastructure ages and populations shift to urban centers. Along the Texas Gulf Coast, relative sea level rise of twice the global average will put coastal infrastructure at risk. Regional adaptation efforts that harden or relocate critical infrastructure will reduce the risk of climate change impacts.

Key Message 3

Ecosystems and Ecosystem Services

Terrestrial and aquatic ecosystems are being directly and indirectly altered by climate change. Some species can adapt to extreme droughts, unprecedented floods, and wildfires from a changing climate, while others cannot, resulting in significant impacts to both services and people living in these ecosystems. Landscape-scale ecological services will increase the resilience of the most vulnerable species.

Key Message 4

Human Health

Health threats, including heat illness and diseases transmitted through food, water, and insects, will increase as temperature rises. Weather conditions supporting these health threats are projected to be of longer duration or occur at times of the year when these threats are not normally experienced. Extreme weather events with resultant physical injury and population displacement are also a threat. These threats are likely to increase in frequency and distribution and are likely to create significant economic burdens. Vulnerability and adaptation assessments, comprehensive response plans, seasonal health forecasts, and early warning systems can be useful adaptation strategies.

Key Message 5

Indigenous Peoples

Tribal and Indigenous communities are particularly vulnerable to climate change due to water resource constraints, extreme weather events, higher temperature, and other likely public health issues. Efforts to build community resilience can be hindered by economic, political, and infrastructure limitations, but traditional knowledge and intertribal organizations provide opportunities to adapt to the potential challenges of climate change.

Executive Summary

The Southern Great Plains experiences weather that is dramatic and consequential; from hurricanes and flooding to heat waves and drought, its 34 million people, their infrastructure, and economies are often stressed, greatly impacting socioeconomic systems. The quality of life for the region's residents is dependent upon resources and natural systems for the sustainable provision of our basic needs—food, energy, and water. Extreme weather and climate events have redistributed demands for consumption, production, and supply across the region. Adaptation strategies that integrate climate services and early warning systems are improving our abilities to develop sustainable infrastructure and increase agricultural production, yet include the flexibility needed to embrace any changing demand patterns.

Regional adaptation efforts that harden or relocate critical infrastructure will reduce the risk of climate change impacts. Redesigns of coastal infrastructure and the use of green/gray methodologies are improving future coastal resilience. Energy industry reinvention is ensuring operations and reliability during extreme climatic events. Increasingly robust considerations of economic resilience allow us to anticipate risk, evaluate how that risk can affect our needs, and build a responsive adaptive capacity.

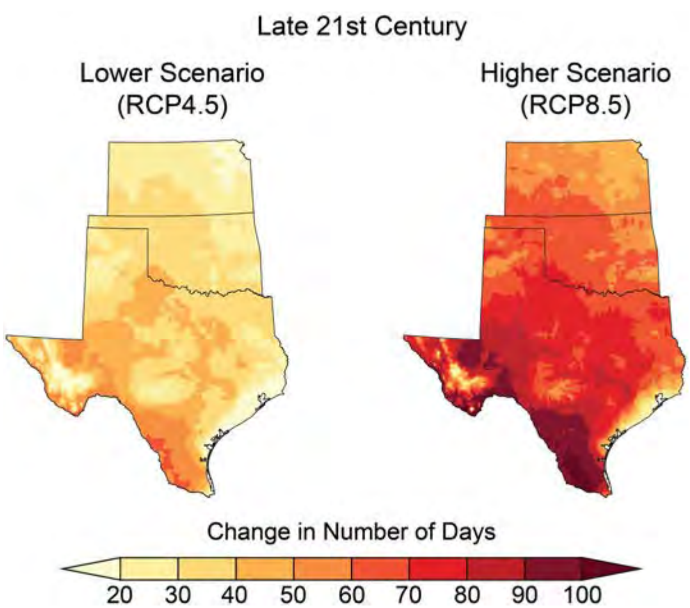
With climate change, terrestrial and aquatic ecosystems, and species within them, have winners and losers. Those that can adapt are "increasers," while others cannot, resulting in impacts to traditional services and the livelihoods of the people who depend on those resources. The warming of coastal bay waters has been documented since at least the 1980s, and those increases in water temperature directly affect water quality, leading to hypoxia, harmful algal blooms, and fish kills—thus lowering the productivity and diversity of estuaries. Natural wetlands like the playa lakes in the High Plains, which have served for centuries as important habitat for migrating waterfowl, are virtually nonexistent during drought.

Direct human health threats follow a similar pattern of species within our natural ecosystems. Extreme weather results in both direct and indirect impacts to people; physical injury and population displacement are anticipated to result with climate change. Heat illness and diseases transmitted through food, water, and insects increase human risk as temperature rises. Acute awareness of these future impacts allows us to plan for the most vulnerable and adapt through response plans, health forecasting, and early warning strategies, including those that span transboundary contexts and systems.

The impacts of climate change in general become more acute when considering tribal and Indigenous communities. Resilience to climate change will be hindered by economic, political, and infrastructure limitations for these groups; at the same time, connectivity of the tribes and Indigenous communities offers opportunities for teaching adaptably through their cultural means of applying traditional knowledge and intertribal organization. These well-honed connections of adapting through the centuries may help all of us learn how to offset the impacts and potential challenges of climate change.

The role of climate change in altering the frequency of the types of severe weather most typically associated with the Southern Great Plains, such as severe local storms, hailstorms, and tornadoes, remains difficult to quantify.[1,2] Indirect approaches suggest a possible increase in the circumstances conducive to such severe weather,[3] including an increase in the instances of larger hail sizes in the region by 2040,[4] but changes are unlikely to be uniform across the region, and additional research is needed.

Projected Increase in Number of Days Above 100°F



Under both lower- and higher-scenario climate change projections, the number of days exceeding 100°F is projected to increase markedly across the Southern Great Plains by the end of the century (2070–2099 as compared to 1976–2005). *From Figure 23.4 (Sources: NOAA NCEI and CICS-NC)*.

Background

The Southern Great Plains, composed of Kansas, Oklahoma, and Texas, experiences weather that is dramatic and consequential. Hurricanes, flooding, severe storms with large hail and tornadoes, blizzards, ice storms, relentless winds, heat waves, and drought—its people and economies are often at the mercy of some of the most diverse and extreme weather hazards on the planet. These events cause significant stress to existing infrastructure and socioeconomic systems and can result in significant loss of life and the loss of billions of dollars in property.

Climate conditions in the Southern Great Plains vary dramatically from the arid, high-elevation borders with the mountainous states of Colorado and New Mexico on the west, to the humid states of Missouri, Arkansas, and Louisiana in the Mississippi River valley on the east. Average annual precipitation ranges from less than 10 inches in the western reaches of the region to over 60 inches in the southeastern corner (Figure 23.1).

A large west-to-east contrast in surface water availability results, with large reservoirs in eastern parts of the region and few reservoirs in the west. Except for the Missouri River (a portion of the border for the Southern Great

Monitoring Precipitation Across the Southern Great Plains

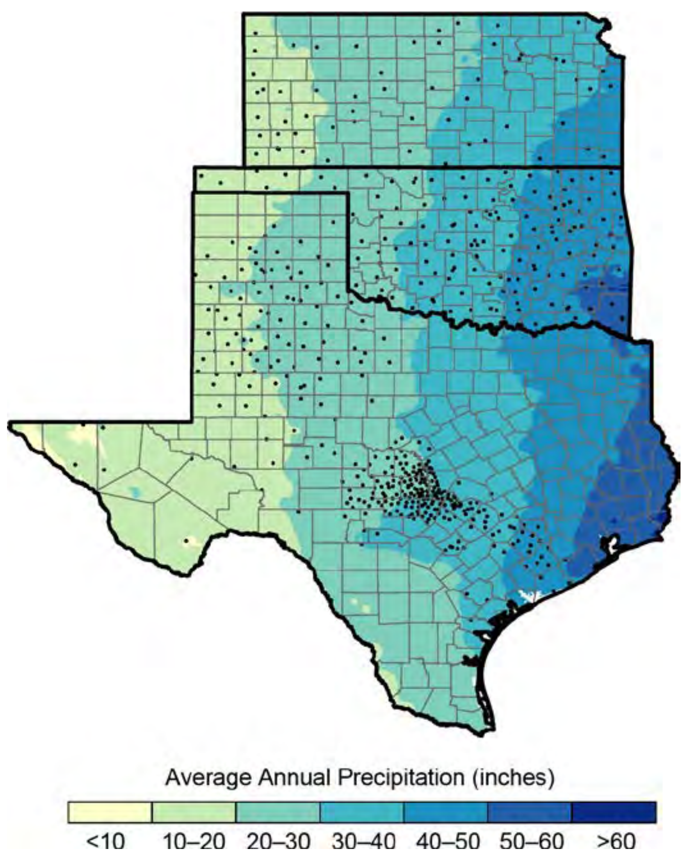


Figure 23.1: The Southern Great Plains is characterized by a pronounced east–west gradient of precipitation, with wetter conditions prevailing to the east and arid conditions to the west. Precipitation monitoring is critical in this region; state-level Mesonet station networks in Kansas, Oklahoma, and Texas are shown here to illustrate a key aspect of current monitoring capacity. Sources: NOAA NCEI, CICS-NC, and ERT Inc. Data from PRISM Climate group, Oregon State University, http://prism.oregonstate.edu, created July 10, 2010.

Plains), the Arkansas River, and the upper reaches of the rivers such as the Rio Grande, rivers in the region do not draw from mountain snowpack and are sensitive to seasonal rainfall amounts. The region is vulnerable to periods of drought, historically prevalent during the 1910s, 1930s, 1950s, and 2010–2015, and periods of abundant precipitation, particularly the 1980s and early 1990s. The region has experienced an increase in annual average temperature of 1°–2°F since the early 20th century, with the greatest warming during the winter months.

With the Gulf of Mexico to its southeast, the coastal Southern Great Plains is vulnerable to hurricanes and sea level rise. Relative sea level rise along the Texas Gulf Coast is twice as large as the global average, and an extreme storm surge in Galveston Bay would threaten much of the U.S. petroleum and natural gas refining capacity. Variations in freshwater flows and evaporation affect the salinity of bays and estuaries along the coast and have the potential to alter coastal ecosystems and affect the fishing industry. Tropical cyclones are also responsible for exceptional rainfall rates in the region. The U.S. record for greatest single-day rainfall is 43 inches, set in Alvin, Texas, in July of 1979, as Tropical Storm Claudette moved through the area. Houston, Texas, in particular, experienced several record-breaking floods in 2015, 2016, and 2017, with Hurricane Harvey rewriting the continental U.S. record for total rainfall from a tropical cyclone. Cedar Bayou, Texas (30 miles from Houston), recorded 51.88 inches of rain during the multi-day onslaught of Hurricane Harvey (see Box 23.1 for further discussion).

Box 23.1: Hurricane Harvey

Hurricane Harvey was a Category 4 hurricane on the Saffir-Simpson scale when it made landfall on the central Texas coast near Rockport late in the evening of August 25, 2017. It then moved inland, stalled, and eventually moved back over the coastal Gulf of Mexico waters before making landfall a final time as a tropical storm several days later in southwestern Louisiana.

Preliminary damage estimates place Harvey as one of the two most costly U.S. natural disasters in inflation-adjusted dollars, rivaling Hurricane Katrina. Flooding from Harvey resulted in the overflow of sewage systems and breaches at numerous waste treatment facilities,[5] resulting in untreated infectious human waste entering surface waters and resulting in a spike in skin and gastrointestinal infections.[6]

Widespread flooding affected dozens of communities, including those in the Houston and Beaumont metropolitan areas. Immediate effects included deaths from drowning and trauma that claimed the lives of at least 63 individuals. Additionally, more than 30,000 people were evacuated. Displacement of patients from their communities and healthcare providers led to interruptions in medical treatment. Texas has one of the lowest rates of health insurance in the country, and more than 11% of the population of Texas is diabetic.[7] Additionally, chronic kidney disease rates in Texas are higher than the national average, with a prevalence of over 17% in the adult population, and 1,524 per one million inhabitants require routine dialysis.[7] In the aftermath of the hurricane, dialysis centers struggled with staffing shortages, and centers in outlying areas worked around the clock to attempt to meet the needs of evacuated patients.[8] Hospitals and pharmacies faced critical shortages of essential medications (including insulin and respiratory inhalers) due to the inability of suppliers to make deliveries. Hospitals faced critical power shortages and loss of indoor air and temperature controls. At least 15 area hospitals evacuated their patients.[9]

Box 23.1: Hurricane Harvey, *continued*

Based on past trends and recent sea surface temperatures, the heaviest rainfall amounts from intense storms such as Harvey are about 5%–7% greater now than what they would have been a century ago.[1] As discussed in detail in Chapter 2: Climate, several studies have already quantified the human contribution to the record-breaking rainfall associated with Hurricane Harvey. Additional information is available in Chapter 17: Complex Systems, Box 17.1.

In an attempt to recover from Hurricane Harvey and help prepare for future hurricanes, leaders in government, education, business, and nonprofit organizations gathered to identify unmet needs across all of the affected communities. For example, the Rebuild Texas Fund has a special focus on serving low-income communities and their most vulnerable members (https://www.rebuildtx.org). It was developed to support organizations that provide services in four focus areas: health and housing, schools and child care, workforce and transportation, and capital for rebuilding small businesses.

Figure 23.2: Texas Army National Guard assisting in flood rescues associated with Hurricane Harvey, August 27, 2017. Photo credit: Lt. Zachary West, Texas National Guard.

Box 23.1: Hurricane Harvey, *continued*

Figure 23.3: This visible satellite image shows Hurricane Harvey approaching the Texas coast on August 25, 2017. Image credit: NASA Earth Observatory.

Over the past 50 years, significant flooding and rainfall events followed drought in approximately one-third of the drought-affected periods in the region when compared against the early part of the 20th century.[10] Understanding this rapid swing from extreme drought to flood is an important and ongoing area of research in the region. As major metropolitan areas in the region continue their rapid population growth, overall exposure to extreme rainfall events will increase. Yet, even while record-breaking flooding events increased over the past 30 years, the Southern Great Plains experienced an overall decrease in flood frequency,[11] possibly related to the decrease in total precipitation over the same period.

The Southern Great Plains is a critical thoroughfare for rail and road freight, supports numerous ocean and river ports within its borders, and is a major energy producer and exporter.[12] Combined, the three-state region accounts for 25% of all U.S. energy production. The world's largest oil-storage tank facility is located in Cushing, Oklahoma, with 13% of total U.S. storage and a convergence of several major pipelines. More than 550,000 miles of roads connect rural and urban communities and serve as vital infrastructure supporting state and local economies.[13,14,15] The vast and dispersed nature of the region's infrastructure makes investment in maintenance and rehabilitation of deficient and aging infrastructure difficult. Infrastructure is typically designed to withstand historical climate extremes and is exposed to the environment year-round. Therefore, as the intensity and frequency of climate-related extremes (such as heat, drought, flooding, and severe storms) increase, impacts to the region are usually adverse and costly. The Southern Great Plains ranks near the top of states with structurally deficient or functionally obsolete bridges, while other bridges are nearing the end of their design life.[16,17,18] Road surface degradation in Texas urban centers is linked to an extra $5.7 billion in vehicle operating costs annually (dollar year not reported).[15] The region has tens of thousands of dams and levees; however, many are not subject to regular inspection and maintenance and have an average age exceeding 40 years.[16,17,18] Most state and local budgets are unable to meet the funding needs for infrastructure improvements, particularly in rural towns where funding is largely derived from municipal revenue. In urban centers, population growth is anticipated to require expansion of transportation infrastructure and services and revisions to flood control structures and policies[16,17,18] and result in increased water resource needs and a growth in building demand.[19,20]

Understanding the potential for future changes in the frequency and severity of weather events and their impacts will ultimately determine the sustainability of economies, cultures, ecosystems, health, and life in the region. Over the past two decades, state and local governments have invested in the creation of weather monitoring networks ("Mesonets") that are designed to measure important weather and climate parameters (Figure 23.1).[21] Mesonet stations are critical infrastructure required to establish the long-term climate record for the region. Mesonet observations have been especially critical for predicting and preparing for extreme weather events like droughts, floods, ice storms, and severe convective storms, as well as for developing value-added products. These data are used daily by decision-makers, public safety officials, educational institutions, the agricultural sector, and researchers, generating societal and economic benefits that greatly exceed the investments made in these systems.[22,23]

Projections

Climate change is expected to lead to an increase in average temperatures as well as frequency, duration, and intensity of extreme heat events and a reduction in extreme cold events. Annual average temperatures in the Southern Great Plains are projected to increase by 3.6°–5.1°F by the mid-21st century and by 4.4°–8.4°F by the late 21st century, compared to the average for 1976–2005, and are dependent on future scenario, with higher levels of greenhouse gas emissions leading to greater and faster temperature increases. Extreme heat will become more common. Temperatures similar to the summer of 2011 will become increasingly likely to reoccur, particularly under higher scenarios. By late in the 21st century, if no reductions in emissions take place, the region is projected to experience an additional 30–60 days per year above 100°F than it does now (Figure 23.4).[24]

Projected Increase in Number of Days Above 100°F

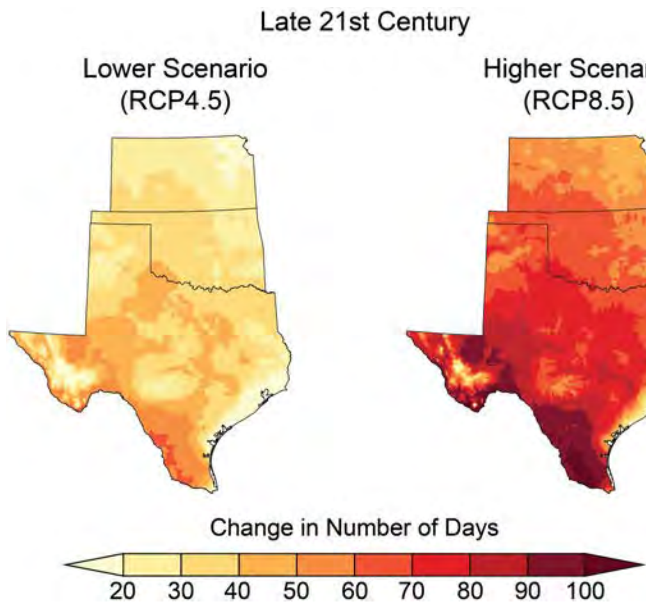


Figure 23.4: Under both lower- and higher-scenario climate change projections, the number of days exceeding 100°F is projected to increase markedly across the Southern Great Plains by the end of the century (2070–2099 as compared to 1976–2005). Sources: NOAA NCEI and CICS-NC.

The role of climate change in altering the frequency of the types of severe weather most typically associated with the Southern Great Plains, such as severe local storms, hailstorms, and tornadoes, remains difficult to quantify.[1,2] Indirect approaches suggest a possible increase in the circumstances conducive to such severe weather,[3] including an increase in the instances of larger hail sizes in the region by 2040,[4] but changes are unlikely to be uniform across the region, and additional research is needed.

Along the Texas coastline, sea levels have risen 5–17 inches over the last 100 years, depending on local topography and subsidence (sinking of land).[25] Sea level rise along the western Gulf of Mexico during the remainder of the 21st century is likely to be greater than the projected global average of 1–4 feet or more.[26] Such a change, along with the related retreat of the Gulf coastline,[27] will exacerbate risks and impacts from storm surges.

Average annual precipitation projections suggest small changes in the region, with slightly wetter winters, particularly in the north of the region, and drier summers.[1] However, the frequency and intensity of heavy precipitation are anticipated to continue to increase, particularly under higher scenarios and later in the century.[1] The expected increase of precipitation intensity implies fewer soaking rains and more time to dry out between events, with an attendant increase in soil moisture stress. Studies that have attempted to simulate the consequences of future precipitation patterns consistently project less future soil moisture, with future conditions possibly drier than anything experienced by the region during at least the past 1,000 years.[28]

While past hydrologic extremes have been driven largely by climate variability, climate change is likely to exacerbate aridity in the Southern Great Plains, largely associated with drying soils due to increased evapotranspiration caused by higher temperatures.[1,29]

Key Message 1

Food, Energy, and Water Resources

Quality of life in the region will be compromised as increasing population, the migration of individuals from rural to urban locations, and a changing climate redistribute demand at the intersection of food consumption, energy production, and water resources. A growing number of adaptation strategies, improved climate services, and early warning decision support systems will more effectively manage the complex regional, national, and transnational issues associated with food, energy, and water.

Food, energy, and water systems are inseparable. Any change in demand for one will impact demand on the other two. The quality of life of the 34 million people residing in the Southern Great Plains is dependent upon the resources and natural systems for the sustainable provision of food, energy, and water. At least 60% of the region's population is clustered around urban centers, which are experiencing population growth that exceeds that of rural communities. The remaining population is spread across vast areas of rural land.[14,30,31,32,33] As the population in the region grows, rapid urbanization and economic development opportunities will drive an increase in the demand for food, energy, and water. Water is used in every aspect of agricultural production and electricity generation. Energy is required to extract and deliver water of sufficient quality for diverse human and agricultural use, as well as healthy consumption and wastewater treatment. Both water and energy are required to irrigate and process agricultural products and livestock to feed the region's increasing population. The complex interdependencies at the food–energy–water nexus create enormous challenges.

When severe drought affected the Southern Great Plains in 2011, limited water availability constrained the operation of some power plants and other energy production activities. Contention for water developed between consumers associated with the food–energy–water nexus. The recent boom in domestic unconventional oil and gas development brought on by hydraulic fracturing and horizontal drilling represents another stressor to this nexus. This development has added complexity to the regional dialog about the relationship between food, energy, and water resources.

Superimposed on the existing complexities at the intersection of food, energy, and water is the specter of climate change. During 2010–2015, the multiyear regional drought severely affected both agricultural and aquatic ecosystems. One prominent impact was a reduction of irrigation water released for the Texas Rice Belt farmers on the Texas coastal plains, as well as a reduction in the amount of water available to meet instream flow needs in the Colorado River and freshwater inflow needs to Matagorda Bay. The Lower Colorado River Authority (LCRA), through its Water Management Plan (WMP), balances the needs of competing water demands in the Lower Colorado River Basin of Texas. Depending upon the amount of water stored in lakes, the WMP requires that LCRA reduce or cut off interruptible stored water for most downstream agriculture so firm water supplies are available to meet the basic needs of cities, businesses, and industries during drought.

In one year, planted acres of rice in Matagorda County, Texas, dropped from 22,000 acres to 2,100 acres.[34] The ripple effect on the local economy was severe, with a 70% decline in sales of farm implements and machinery. Some family-owned establishments that had survived for decades closed permanently.[35] Irrigation strategies shifted from river-based to pumping

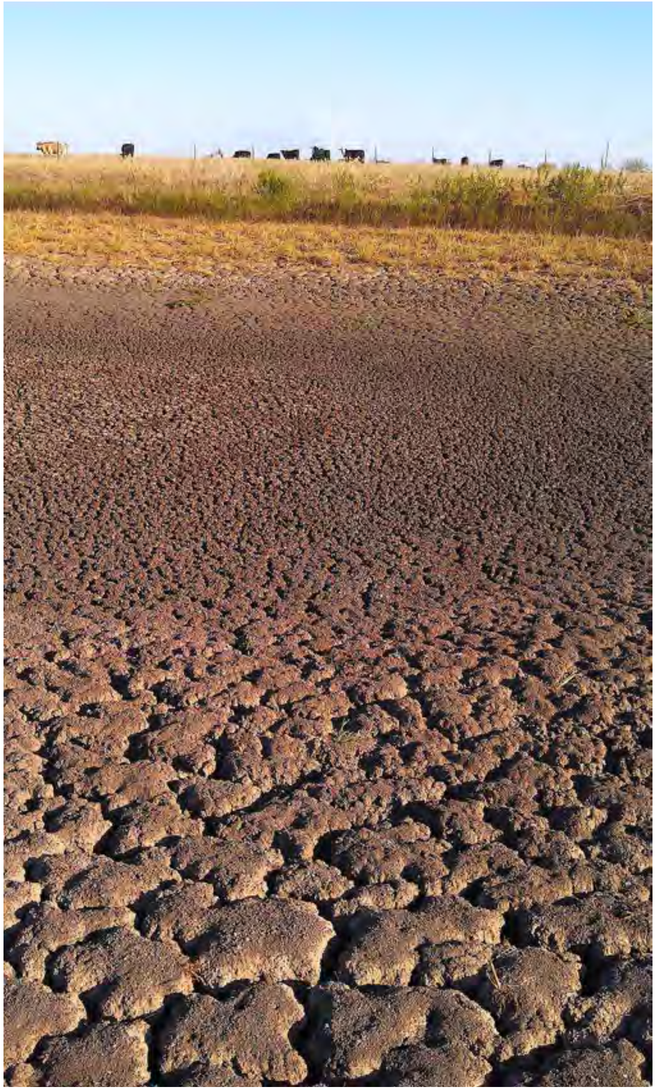


Figure 23.5: The photo shows the drought impact on a stock pond near Kurten, Texas, in 2011. Photo credit: John Nielson-Gammon.

water from the Gulf Coast Aquifer, and dozens of new wells were drilled. Drilling water wells then resulted in declining groundwater levels, adding stress to water levels that had historically been falling in the region.[36] Some farmers attempted to adapt by making the difficult transition to other crops such as corn. However, when flooding rains inundated the region in 2016, 15% of the corn crop was swept away in flood waters.[37] Thus the 2010–2015 drought simultaneously affected agriculture, energy, recreation, and economic activity, eventually leading to increased groundwater development and potential future overexploitation. Projected increases in drought duration and severity imply even more pervasive direct and indirect effects. These impacts might have been even more severe had it not been for adaptation actions taken by the City of Austin, including implementation of drought contingency plans and water-use cutbacks in coordination with the City Council and community.

Climate change has significant negative impacts on agriculture in the United States, causing substantial economic costs (Ch. 10: Ag & Rural).[38,39] The effects of drought and other occurrences of extreme weather outside the Southern Great Plains also affect the food–energy–water nexus in the region. The neighboring Southwest region is especially vulnerable to climate change due to its rapidly increasing population, changing land use and land cover, limited water supplies, and long-term drought (Ch. 25: Southwest).[40] States in the Southern Great Plains import over 20% of their food-related items from Arizona, and El Paso, Texas, receives 25% percent of its consumable foods (mostly vegetables) and 18% of its animal feed supplies from Arizona.[41] In addition, relationships across the border of the Southern Great Plains with Mexico will be critical to a better understanding of the food–energy–water nexus (see Case Study "Rio Grande Valley and Transboundary Issues") (see also Ch. 16: International, KM 4).

Case Study: Rio Grande Valley and Transboundary Issues

In the U.S.–Mexico transboundary region of the Southern Great Plains, no hydrologic resource is more critical than the Rio Grande and its attendant tributaries. Partnered, binational management of the basin's water supply is essential to supporting the agricultural, industrial, and community infrastructure in place along the Rio Grande valley. Proactive and collaborative water management strategies allow for effective flood control, mitigation of drought impacts, and maximization of water quality, among other benefits.[42]

The Rio Grande is highly sensitive to variations and changes in the climate of the Southern Great Plains, where changes can have marked impacts on the valley's extensive agricultural productivity.[43,44] Increasing regional temperatures,[45] consistent with global trends, will enhance the severity of drought impacts via the acceleration of surface water loss driven by evaporation, particularly in large Rio Grande reservoirs such as Lake Amistad. Changes in regional precipitation patterns, including observed increases in extreme rainfall events as part of a regional "dipole" dry-wet-dry-again pattern,[10] will affect both drought and flood occurrence and intensity along the Rio Grande channel. Other climate-driven impacts, such as changes in wildfire frequency[46] and increased vulnerability to heat events,[40] will further challenge the preparedness and resilience of communities on both sides of the border.

The Rio Grande Gorge near Taos, New Mexico. Photo credit: © flickr.com/josephmccowie.

A growing number of adaptation strategies[47] and an increasing provision of regional climate services in the Southern Great Plains[48] bode well for an improved future ability to effectively manage the Rio Grande's transboundary water interests. This is particularly true in the context of early warning decision support systems. Frequently, extreme weather and climate events, such as the 2011–2012 La Niña and 2015–2016 El Niño episodes, serve as catalyzing opportunities to develop new and refine existing information delivery pathways from climate services providers to stakeholder audiences. One recent application in the Rio Grande transboundary region is bilingual seasonal climate outlooks and impact assessments,[49] which are utilized by stakeholders to strengthen regional drought and wildfire outlooks[46] and which augment other ongoing efforts to strengthen bilingual climate services delivery.[50]

Case Study: Rio Grande Valley and Transboundary Issues, *continued*

Highlighting Seasonal-Scale Extreme Events in a Transboundary Setting

AT A GLANCE

1. **New Mexico, North Texas**
Severe to extreme drought conditions developed over the past month, and drought is likely to persist in these regions through May.

2. **Rio Grande/Bravo Region**
High fuel loads from warm, dry conditions, coupled with the increasing frequency of wind events common during early spring in the region, will increase the risk of intense, fast-spreading fires through April.

3. **New Mexico, North Texas**
Precipitation was 0-25% of average from November – January.

UN VISTAZO

1. **Nuevo México, Norte de Texas**
Condiciones severas a extremas de sequía se desarrollaron durante el mes pasado, y es probable que la sequía persista en estas regiones hasta mayo.

2. **Región de Rio Grande / Bravo**
Las altas cargas de combustible provenientes de las condiciones cálidas y secas, junto con la frecuencia cada vez mayor de los eventos de viento comunes a comienzos de la primavera en la región, aumentarán el riesgo de incendios intensos y de rápida propagación hasta abril.

3. **Nuevo México, Norte de Texas**
La precipitación fue 0-25 % del promedio de noviembre a enero.

Figure 23.6: Shown here are the English- and Spanish-language versions of the February 2018 Climate Assessment for the Southwest Rio Grande-Bravo Climate Impacts and Outlook "At a Glance" summary. Source: Garfin et al. 2018.[44,51]

The 2017 Texas State Water Plan[52] indicates that the growing Texas population will result in a 17% increase in water demand in the state over the next 50 years. This increase is projected to be primarily associated with municipal use, manufacturing, and power generation, owing to the projections of population increase in the region. Likewise, the Oklahoma Water Plan indicates that water use projections in Oklahoma are expected to increase by 21% for municipal use, 22% for agricultural use, and 63% for energy use.[53] The Kansas Water Plan's preliminary assessment of projected water demand in Kansas also shows an increase of 20%, but with the expected variability depending upon rural versus urban areas.[54] Throughout much of western Kansas, western Oklahoma, and the Texas Panhandle, groundwater from the Ogallala Aquifer is the dominant water source,[17,55] benefitting the agricultural sector in particular. This resource is known to be shrinking faster than it is replenishing, and some portions are likely to become an insufficient source or become completely depleted within the next 25 years, particularly at its southernmost extent.[17] Drought more persistent than that experienced in the region's recent history would trigger large social and economic consequences, including shifting agriculture, migration, rising commodity prices, and rising utility costs.[20]

The importance of groundwater as a resource will increase under a changing climate as the intensification of hydrologic extremes decreases the reliability of precipitation, soil moisture, and surface water, and as surface water supplies are becoming increasingly over-allocated.[56,57,58]

Research into the food–energy–water nexus is in its early stages and historically tends to examine only one or two components.[59,60,61,62, 63, 64, 65] It is clear that tradeoffs and cascading complexities exist between sectors, and changes in one sector are likely to propagate through the entire system (Ch. 17: Complex Systems). There are significant gaps in the scientific understanding regarding the role that climate change will play as a disruptive force and a threat to food, energy, and water security.[60,63,66,67,68]

Wind turbines near Kansas farmland. Photo credit: © flickr.com/Kansas State Research and Extension.

Case Study: The Edwards Aquifer

The Edwards Aquifer is a "karst" aquifer, composed of limestone and characterized by solution features such as large pores, caves, sinkholes, and conduits that channel groundwater flow. The Edwards provides groundwater to the central Texas region. It serves more than two million people, including the cities of San Antonio, San Marcos, and Austin, which are three of the fastest-growing cities in the country.[69] The aquifer is a source of water for drinking, industry, agriculture, livestock, and recreation. In particular, San Antonio relies nearly entirely on the Edwards for its drinking water. The aquifer is also a habitat for a number of endemic and endangered species. As a shallow karst aquifer, the Edwards is especially sensitive to climate change. Its shallow depth and karst features allow for rapid infiltration and recharge during wet periods, and discharge is similarly responsive, making the Edwards vulnerable to climate extremes of droughts and floods. This high susceptibility and exposure to climate change is a major challenge for managing the Edwards Aquifer as a resource.[70] The probable impacts of climate change for the Edwards Aquifer include a decrease of water supply during droughts, a degradation of habitat for species of concern, economic effects, and the interconnectivity of these impacts. These climate change impacts will be exacerbated in central Texas's rapidly urbanizing regions, as increasing impervious cover will affect water quality and rates of runoff and recharge.

Water availability and demand: The population of Texas is projected to grow by more than 70% between 2020 and 2070, with the majority of the increase projected to occur in urban centers.[52] Increased demand for water will come from municipal, power generation, agriculture, manufacturing, and livestock uses.[52] Over this same period, water availability in the U.S. Southwest is projected to decrease due to a shift to a more drought-prone climate state.[28,71] History shows that increases in population and pumpage from the Edwards led to unsustainable use of water from the aquifer during the drought of the 1950s.[72] The lessons learned from the 1950s drought and the more intense 2011 drought provide a well-suited application for models of how the aquifer and associated ecosystems will respond to further climate change.[73]

Cross Section of Edwards Aquifer

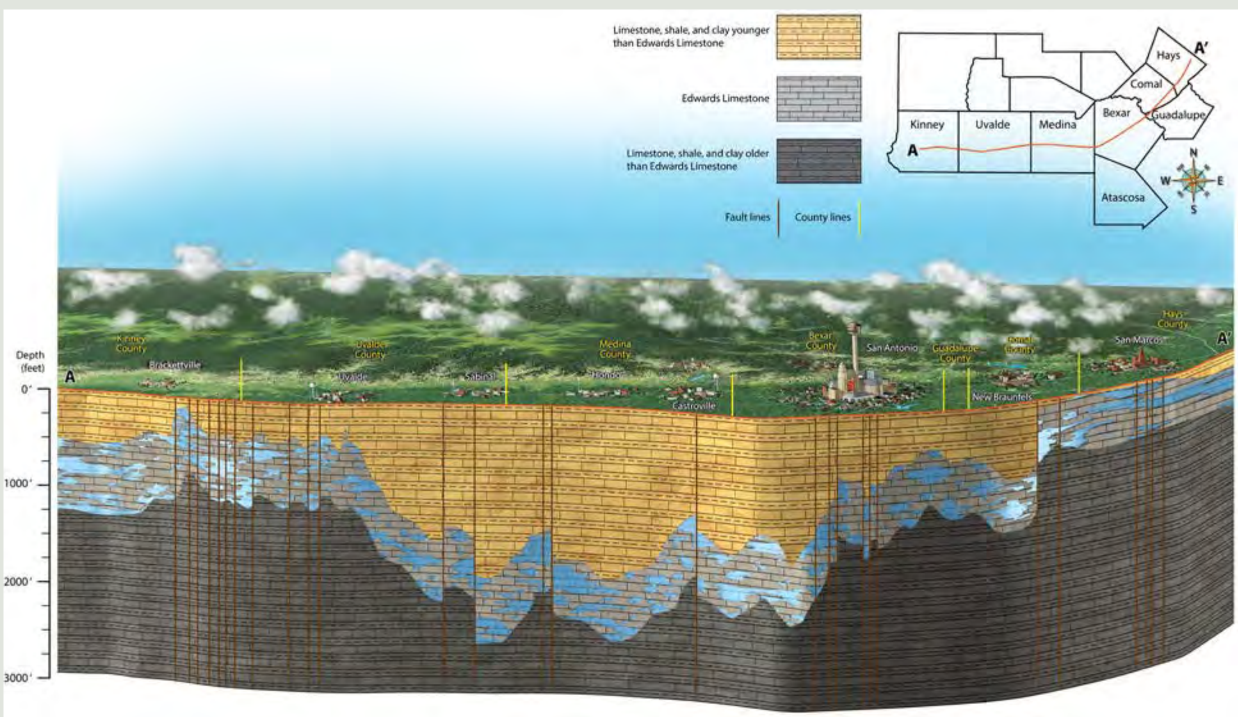


Figure 23.7: Key characteristics of the Edwards Aquifer, such as relative shallowness and karst features, make it vulnerable to the impacts of both climate variability and climate change. Its importance as a major supplier of groundwater in central Texas makes these vulnerabilities even more pronounced. Source: Edwards Aquifer Authority.[79] Used with permission.

Case Study: The Edwards Aquifer, *continued*

Habitat: Plants and animals are sensitive to a variety of changes related to the Edwards Aquifer groundwater system, including changes in habitat, water levels, spring flows, and water quality. An example of the last is an analysis of dissolved oxygen concentrations (DO) in water in Barton Springs, a major point of discharge from the Edwards Aquifer. Most notable are water quality effects on the Barton Springs salamander (*Eurycea sosorum*), a federally listed endangered species native to these springs. An analysis of DO, discharge, and temperature measurements at the springs indicates that low DO episodes that correspond to salamander mortality could result from 1) lower discharge from the springs resulting from increased water withdrawals or decreased recharge as a result of drought, and/or 2) increased water temperature as a result of climate change.[74] A key challenge is understanding and modeling the extent to which endangered and native species can be protected in their habitats associated with the aquifer.[73,75,76]

Impacts: Dramatic drawdowns of groundwater levels by human activity combined with climate change in many regions illustrate the challenges of the nonrenewable nature of groundwater and the multiple dependencies of some ecosystems and agricultural systems on groundwater.[77] Multiple, integrated solutions will be needed to address the impacts on the Edwards Aquifer. These will necessarily involve ways to increase supply through technological approaches, such as desalination of brackish groundwater and aquifer storage and recovery; ways to decrease demand, such as conservation and regulation; and ways to reduce the impact of urbanization through sustainable design. For example, The Edwards Aquifer Recovery Implementation Program Habitat Conservation Plan[78] balances water pumping and use of the aquifer with protection of eight federally listed threatened and endangered species that depend on San Marcos Springs and Comal Springs, two of the largest springs in the southwestern United States. The plan incorporates a number of innovative water supply strategies including Aquifer Storage and Recovery and advanced water conservation, along with market-based solutions for voluntary suspension of groundwater pumping rights during drought periods.

Key Message 2

Infrastructure

The built environment is vulnerable to increasing temperature, extreme precipitation, and continued sea level rise, particularly as infrastructure ages and populations shift to urban centers. Along the Texas Gulf Coast, relative sea level rise of twice the global average will put coastal infrastructure at risk. Regional adaptation efforts that harden or relocate critical infrastructure will reduce the risk of climate change impacts.

Climate change is anticipated to lead to higher average temperatures year-round and an increase in the frequency of very hot days (days with maximum temperatures above 100°F), with the number of such days possibly doubling by mid-21st century (Figure 23.4).[80] An increase in temperatures is *virtually certain* for the Southern Great Plains. Longer, hotter summers will place strain on cooling systems and energy utilities, road surfaces, and water resources, particularly during drought, although warmer winters are likely to reduce heating demands and winter road maintenance costs. The rate of temperature rise will be especially large within urban centers due to possible intensification of the urban heat island (UHI) effect, although the degree of heating will likely vary by city, and it is difficult to obtain precise quantitative estimates. Warmer temperatures will likely lead to an increase in evaporation and therefore an increase in moisture in the air[81,82] and an increase in heat stress, especially during the summertime.[83] During excessive heat in July 2011, downtown

Dallas experienced late-evening temperatures 6.1°F higher than rural Kaufman, Texas, 36 miles away.[84] Population growth, increased urban density, and expansion will intensify the UHI effect for many Southern Great Plains cities, necessitating more energy use for cooling. This strains energy utilities and can further enhance the UHI effect.[85] If prolonged power failure occurs during high heat conditions, the impact to human health and comfort is projected to be notably more detrimental in a warmer climate.[86]

Increased aridity (or dryness) is also projected for the Southern Great Plains with climate change, due to enhanced evapotranspiration and depleted soil moisture associated with increased temperatures.[1,29] In the past, drought conditions have decreased surface water availability (such as from reservoirs), leading to an increase in the use of groundwater. In some cases, new pipelines were needed and water had to be imported.[20] Compounding infrastructure challenges for the region include aging and over-capacity water pipelines.[53] The Texas Water Development Board[87] projected that by 2060, municipal water use will increase to 41% of available supply (versus 9% in 2010). Therefore, a record drought scenario occurring in 2060 would result in as much as half of the state's population facing a water supply shortage. Additionally, water infrastructure can be damaged by drought. During summer 2011, water main breaks were common, with 200 breaks in Fort Worth, Texas, in one month and over 1,000 in one month in Houston, Texas,[20] associated with shrinkage of clay soil, a common soil type throughout the Southern Great Plains. Soil shrinkage can damage both surface and subsurface infrastructure, including roads, water and sewer lines, and building foundations. Periods of abundant precipitation followed by drought and high temperatures are also linked to increased wildfire activity in the region.[88] Texas experienced several major wildfire outbreaks during the drought of 2011, including the Bastrop Fire that destroyed more than 1,500 homes. More recently in 2016 and 2017, fires in Kansas and Oklahoma have exceeded 400,000 acres and were among the largest in the region's history. These events killed thousands of cattle, contributed to several human fatalities, and damaged, displaced, or isolated rural communities.[89] Model simulations indicate that wildfire risk will increase throughout the region as temperatures rise, particularly in the summer, and the duration of the fire season increases.[90]

Following the abrupt end to the persistent drought in 2015, the region suffered extensive damage associated with river and flash flooding.[10,91,92] Precipitation totals for a 120- day period during the spring of 2015 in south-central Oklahoma were above 40 inches, approximately the average annual amount in many locations,[93,94] largely associated with multiple episodes of very heavy rain. Numerous state and U.S highways experienced regional detours or closures.[94] A rockslide on Interstate Highway 35 closed portions of the road for several weeks.[94,95] Flooding in Oklahoma and Texas caused an estimated $2.6 billion in damage in 2015,[95] with $1 million in emergency relief funds provided by the U.S. Department of Transportation's Federal Highway Administration to assist in the repair of damaged roads.[96] The increasing frequency of extreme precipitation that is projected by climate models is anticipated to contribute to further vulnerability of existing highway infrastructure, although the magnitude and timing of projected precipitation extremes remain uncertain.[1]

Changing precipitation frequency and increases in the magnitude and frequency of heavy precipitation will place more stress on existing water resource infrastructure. The region has a large number of older dams and levees, many of which have received poor grades from the American Society of Civil Engineers.[16,17,18] Between 1982 and 2012, 82 dams failed in Texas, and during 2015 the high-hazard Lewisville Dam was of concern due to observed seepage.[18,97] As climate conditions continue to change, rare events such as 100-year floods (those that currently have a 1% chance of occurring in any given year) are likely to become more common.[1,29] Future extremes may exacerbate flooding and wear and tear on existing flood control infrastructure and will necessitate revisions to design standards for flood infrastructure and a reevaluation of floodplains. Floodplain management and mitigation of flooding are currently left largely to local governments and cities and are thus reliant on local funding and resources for successful implementation.[16,17,18] While there are clear implications of more variable and extreme precipitation on infrastructure, the precise links between specific events and their resulting damage are uncertain as most infrastructure is exposed to both climatic and non-climatic stressors whose effects are difficult to separate without a high degree of monitoring.

As the energy industry undergoes, to some extent, a reinvention, it is taking climate and extreme weather events into consideration in design, operations, and reliability. An Edison Electric Institute (2008) study estimated that by 2030, the U.S. electric utility industry will need to make a total infrastructure investment of between $1.5 trillion and $2.0 trillion, of which transmission and distribution investment is expected to account for about $900 billion.[98] These investments increasingly include renewable energy and distributed generation, smart grid technologies, and storage. From 2008 to 2013, the amount of electricity generated from wind has more than tripled and the amount from solar has increased more than tenfold.[99] These enhancements would need to be reliable (able to operate within limits so that instability, uncontrolled events, or cascading failures do not result if there is a disturbance), resilient (able to adapt to changing conditions and withstand and rapidly recover from disruptions), safe, flexible, and affordable.

Coastal regions are among the most vulnerable to climate change due to their direct exposure to rising sea levels and damaging storm surge. Global mean sea level is very likely to rise by 1–4 feet (0.3–1.3 m) by 2100 relative to 2000 levels. Under certain future conditions, a rise exceeding 8 feet (2.4 m) by 2100 is physically possible, although the probability of such an extreme outcome cannot currently be assessed (Ch. 2: Climate, KM 4). Since the early 20th century, areas of the Texas coast have experienced sea level rise (SLR) higher than the global average, associated with extraction of both fossil fuels and groundwater.[25] Within Texas alone, 1,000 square miles of land is within 5 feet of the high tide line, including $9.6 billion in current assessed property value and homes to about 45,000 people. Sensitive assets include 1,600 miles of roadway, several hospitals and schools, 4 power plants, and 254 EPA-listed contamination sites (hazardous waste and sewage).[100] Up to $20.9 billion in coastal property is projected to be flooded at high tide by 2030, and by 2050, property values below the high-water mark are projected to be in excess of $30 billion, assuming current trends of greenhouse gas emissions.[101] The coastline in the vicinity of Galveston and Texas City is also a critical oil refining and transport hub. SLR will affect numerous coastal assets, including residential communities, roads, waterways, and energy generation facilities, and move the risk of damaging storm surge well inland of present areas of impact. With 2 feet of SLR, cities such as Galveston and Corpus Christi will be exposed to more frequent flooding.[100,102,103,104] Disruption to coastal oil-refining facilities can cause cascading failures throughout the region, including fuel shortages and higher prices. Saltwater intrusion of aquifers has been observed in the Gulf Coast Aquifer, the second most utilized aquifer in Texas, which supports 8 million people. Although this was in part associated with heavy pumping,[105] the Gulf Coast Aquifer remains vulnerable to further saltwater intrusion resulting from SLR and storm surge exacerbated by climate change.[106]

Due to the historical frequency of drought, water conservation activities are already recognized as important and encouraged in many municipalities. Common strategies include rainwater harvesting, encouraging improved residential water-use efficiency, water audits, and restricted water use in times of drought.[20] Other proactive measures currently in place in some communities aim to mitigate longer-term risks and involve wastewater treatment and reuse, aquifer storage and recovery, and desalination (see Case Study "Meeting Current and Future Water Needs in El Paso, Texas").[20]

Climate change is likely to require modification and updating of design standards in order to accommodate changes in risk that cannot be accounted for based on history. For example, in transportation design, these modifications might include changing the minimum and maximum temperature rating for binders used in asphalt roads to improve durability; structural modifications to bridges to meet the demands of higher summer temperatures; updating the data used for calculating flooding of dams and neighborhoods; restricting rail speeds during hot temperatures; and shifting timing of maintenance activities. Many technological solutions exist or are in development to build resilience to these climate-related challenges. However, the aforementioned stressors and budgetary challenges will continue to present notable challenges to adaptive capacity in the Southern Great Plains (Ch. 12: Transportation).

Many studies have documented economic impacts of climate change on different sectors in the United States).[1111,112,113,114,115] For example, predictive analyses estimate that climate change and coastal development will cause hurricane damage to increase faster than the U.S. economy is expected to grow. The number of people expected to face substantial damage will, on average, increase more than eightfold over the next 60 years.[116] Although economic analyses for specific regions, sectors, and states in the Southern Great Plains are currently limited, active ongoing research is beginning to produce critical metrics regarding the socioeconomic impacts of climate change at regional scales.[117]

The role of economics is increasingly recognized as being critical for advancing the resilience of households, businesses, and local governments, and also for the broader economic adaptation of entire regions. Establishing economic resilience in a local business or a regional economy requires the ability to anticipate risk, evaluate how that risk can impact key economic assets, and build a responsive adaptive capacity. At the regional or community level, economic development practitioners can build capacity for economic resilience.

Case Study: Meeting Current and Future Water Needs in El Paso, Texas

El Paso, Texas, is vulnerable to drought, being situated in the Chihuahuan Desert and with a growing population and limited water resources derived largely from the Rio Grande and regional aquifers. Average annual rainfall is only around 9 inches. The city continues to be a part of the Rockefeller Foundation's 100 Resilient Cities initiative. Prior to, and as part of, El Paso's ongoing climate adaptation planning, the city's water utility program implemented programs on water conservation, reclamation, and supply diversification. In 2007, the city completed construction of the 27.5 million-gallon-per-day Kay Bailey Hutchison Desalination Plant. The desalination is applied to previously unusable brackish waters in the Hueco Bolson Aquifer. Conversion of this brackish water to freshwater increased El Paso's water utilities' production by 25%.[107] The plant is designed to run at capacity only when needed, such as in times of drought. While desalination is expensive due to use of energy-intensive reverse osmosis, the plant was found to be more cost effective in the long term compared with importing water from remote sources. A climate change analysis of the future viability of this infrastructure suggested that it could meet the needs of the city through the next 50 years.[108] Across Texas, brackish water is abundant, estimated at 2.7 billion acre-feet, and an expansion of desalination is recommended in the state's 2017 Water Plan.[109] There are currently 44 public water supply desalination plants in Texas.

Texas Desalination Plants

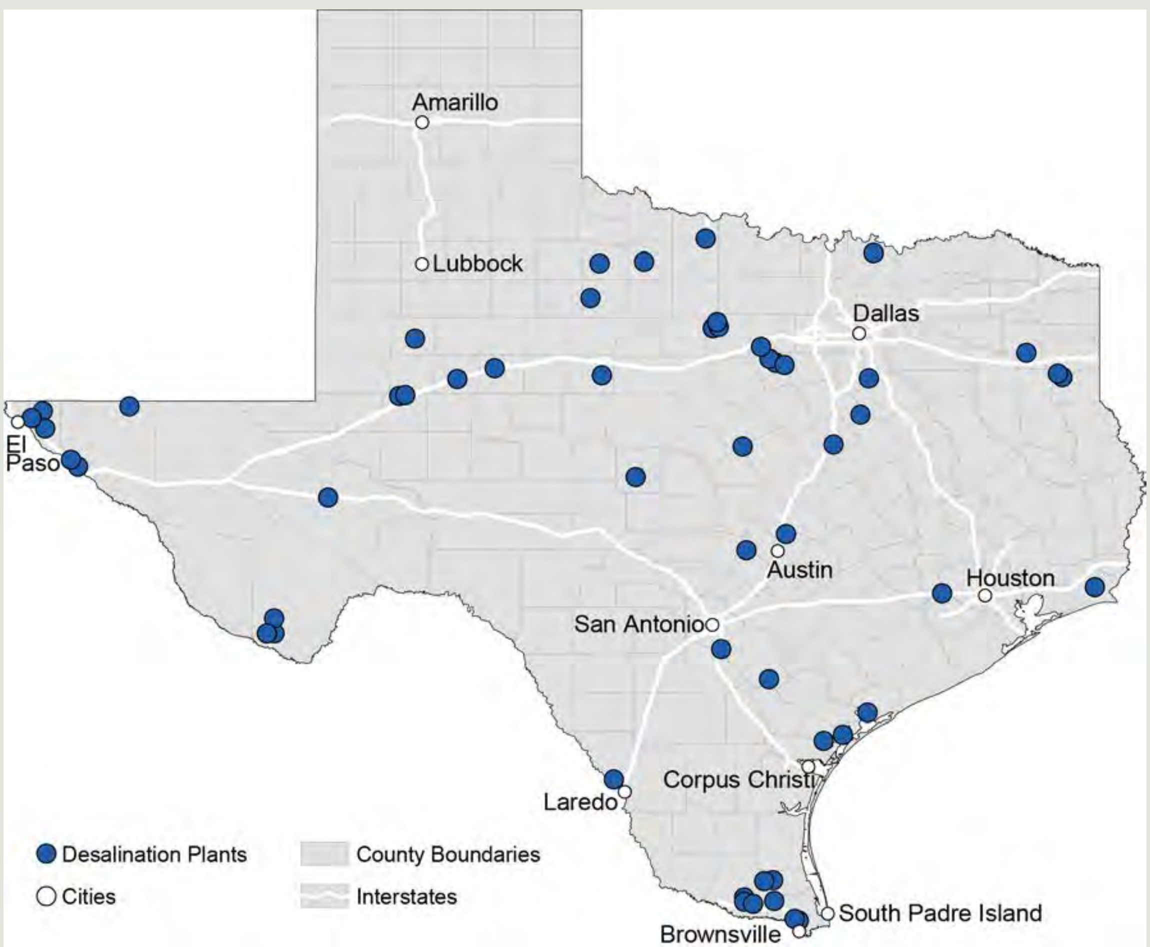


Figure 23.8: Desalination activities in Texas are an important contributor to the state's efforts to meet current and projected water needs for communities, industry, and agriculture. Source: adapted from Texas Water Development Board 2017.[110]

Key Message 3

Ecosystems and Ecosystem Services

Terrestrial and aquatic ecosystems are being directly and indirectly altered by climate change. Some species can adapt to extreme droughts, unprecedented floods, and wildfires from a changing climate, while others cannot, resulting in significant impacts to both services and people living in these ecosystems. Landscape-scale ecological services will increase the resilience of the most vulnerable species.

The Southern Great Plains encompasses diverse ecoregions (areas where ecosystems are generally similar) stretching from the High Plains to the Edwards Plateau and from the Tamaulipan Brushlands to the Gulf Coast Prairie.[118] The region is prone to periods of drought punctuated by heavy rainfall events, with evidence that these events are occurring more frequently.[10] These precipitation patterns influence water availability and aquatic habitats such as lakes, rivers, springs, and streams. Freshwater inflows from rivers flowing to coastal estuaries provide important nutrients and sediments while moderating salinities to create and maintain productive estuarine ecosystems.

Species Distribution and Habitats

Climate plays a key role in the distribution of species (Ch. 7: Ecosystems). Species' response to climate change is complex and variable.[119] As temperatures increase, the geographic distribution of some species tends to shift to areas with temperature ranges where a given species can survive. A notable species of concern in the region is the lesser prairie-chicken, which was listed as threatened under the U.S. Endangered Species Act in May 2014. Currently, the lesser prairie-chicken habitats include Kansas, Texas, and Oklahoma (as well as Colorado and New Mexico) with 70% of the population in Kansas.[120] At this time, it is not clear whether climate change will influence the lesser prairie-chicken in positive or negative ways.[121,122] Rising temperatures are also causing changes to growing seasons and migration patterns of birds and butterflies.[123] In Texas, white-wing doves, originally confined to the Lower Rio Grande valley, have been expanding northward [124] and are now common across Oklahoma. Other factors such as habitat loss also influence species distributions, making it difficult to pinpoint a single cause for these distribution changes.

While it is unclear how climate change will affect species directly, the effects of increased aridity will likely have negative impacts. In addition, ecosystem services—the materials and processes that ecosystems produce that benefit people—will also be affected.[123] In general, drought forces wildlife to travel farther to locate food, water, and shelter, which can deplete body condition going into winter or spring migration, when food sources are typically scarcer, making them more vulnerable to other stresses. The highly endangered Houston toad was negatively impacted during the 2011 drought and devastating wildfire in Bastrop County, Texas. Whooping crane numbers, which depend on sufficient freshwater inflows for a reliable food source (primarily blue crabs), were also reduced. In addition, a lack of freshwater can force whooping cranes to fly to uplands to drink, using more energy and exposing birds to more threats from predators and other mortality factors.

Aridification exacerbates stress in highly isolated habitats and fragmented lands, diminishing the ability for species to persist if they cannot move to better conditions. Migratory birds are better able to move to areas with better habitat conditions but could be in a weakened condition to do so. Migratory waterfowl can also be negatively impacted by reductions in wetland habitat areas due to aridification. Loss of irrigated rice fields in Texas contributed to significant declines in wintering waterfowl along the Gulf Coast. The most significant decline was documented for snow geese, with a 71% decline for 2011–2014 as compared to the long-term average.[125] Playa lakes in the High Plains serve as important habitat for migrating waterfowl, but during the drought these wetlands were virtually nonexistent.

Plant community changes are also occurring, possibly due to climate change and other factors, and these changes in turn affect fish and wildlife. In the Southern Great Plains region, winters are warmer and spring is arriving earlier. Along the Texas coast, black mangroves, which are sensitive to cold, are expanding northward along the coast, and red mangroves, formerly not found in Texas, are now appearing there.[126] Warmer winters with fewer freezes are also conducive to pests and diseases. Woody shrubs invading prairie grasslands are favored by increases in concentrations of carbon dioxide (CO_2), changes in soil moisture cycles, fire suppression activities, and soil disturbances.[125] The 2011 drought produced a direct and indirect tree mortality rate of over 6%—many times the normal rate.[127]

Aquatic Ecosystems

Climate change impacts to aquatic ecosystems include higher water temperatures in lakes, wetlands, rivers, and estuaries that can result in lower dissolved oxygen, leading to more fish kills. Impacts to reservoirs include fluctuating lake levels, loss of habitat, loss of recreational access, increase in harmful algal blooms, and disconnectedness from upstream and downstream riverine habitats.[128] Localized declines in fish populations have been documented in rivers due to lack of water or water confined to increasingly narrow pools; in some cases, these declines prompted biologists to capture and relocate some endangered species to fish hatcheries.[129] Aridification (a gradual change to a drier climate) can have a number of negative impacts on freshwater mussel populations, including increased predation pressures, hypoxia (low oxygen conditions), increasing water temperature, and, ultimately, anoxia (no dissolved oxygen in water) or emersion (stranding the organism out of water and exposing it to air).

Coastal Areas, Bays, and Estuaries

The Texas coast, with 6.5 million people contributing over $37 billion to the region's economy, relies on its natural features, bays, and estuaries that serve as storm barriers to protect coastal infrastructure, and on its climate amenities to spur ecosystem services, such as fishing, ecotourism, and the ocean economy. These coastal ecosystems provide protection not only for people but also for 25% of the Nation's refining capacity, four crucial ports, much of the strategic petroleum reserves, and strategic military deployment and distribution installations. This protection was clearly on display with the recent impacts of Hurricane Harvey, where it has been estimated that natural coastal habitats protected about $2.4 billion worth of property in Texas and thousands of lives, with the suggestion that these habitats are potentially our first lines of defense.[130]

A rising sea level impacts more than 74% of Gulf-facing beaches in the upper Texas coast. The average rate of beach erosion is almost 10 feet per year.[131] Sea level rise means more frequent and longer-lasting flooding of marshes that eventually could be permanently flooded, becoming open water.[126,132] Higher tides and storm surges cause inundation of freshwater areas and beach erosion, leading to a potential decrease or loss of barrier islands and coastal habitats, including nesting habitats and submerged habitat such as seagrass beds affected by changes in water quality and changing water depths. A significant percentage of fishery species in the Gulf of Mexico are dependent upon estuaries for some portion of their life cycle.[133]

The warming of bay waters on the Texas coast has been documented for at least 35 years. This mostly reflects warmer winters, not warmer summers. The increase in water temperature directly affects water quality, leading to the higher potential for low levels of dissolved oxygen, or hypoxia. Hypoxic events and harmful algal blooms have caused fish kills, leading to lower productivity and diversity of estuarine ecosystems.[126]

Freshwater inflows are critical to both aquatic ecosystems and wetlands in the Southern Great Plains. Both surface and groundwater depletion have led to dramatic changes of the aquatic and wetland communities in Kansas[134] that not only impact inland species but have a dramatic effect on coastal species relying on the freshwater inflow to ensure the integrity of the coastal ecosystem. Whooping crane and many other migratory species flying through this region during both spring and fall are impacted.[135] Climate change and human use have impacted these aquatic systems and wetlands and, ultimately, the vital flow of freshwater to the coastal marshes and estuaries.

Changes to freshwater inflows to estuaries lead to changes in salinity and inflows of nutrients and sediment, resulting in impacts to oysters and other sensitive estuarine species. In addition, harmful algal blooms have become more frequent, more intense, and more widespread.[123] Reduced freshwater inflows during 2011 led to record high salinities in Texas estuaries that contributed to a coastwide "red tide" harmful algal bloom event. Red tides, a type of harmful algal bloom, most commonly occur during drought years, as the organism that causes red tide does not tolerate low salinity. Red tide blooms cause fish kills and contaminate oysters. In addition, oysters and other shellfish can accumulate red tide toxins in their tissues. People who eat oysters or other shellfish containing red tide toxins become seriously ill with neurotoxic shellfish poisoning. Once a red tide appears to be over, toxins can remain in the oysters for weeks to months. The 2011 bloom started in September and lasted into 2012. Fish mortality was estimated at 4.4 million. The commercial oyster season was closed and disaster declarations issued. The total economic loss was estimated at $7.5 million (dollar year not reported).[136]

Climate Winners and Losers (Gray Snapper and Southern Flounder)

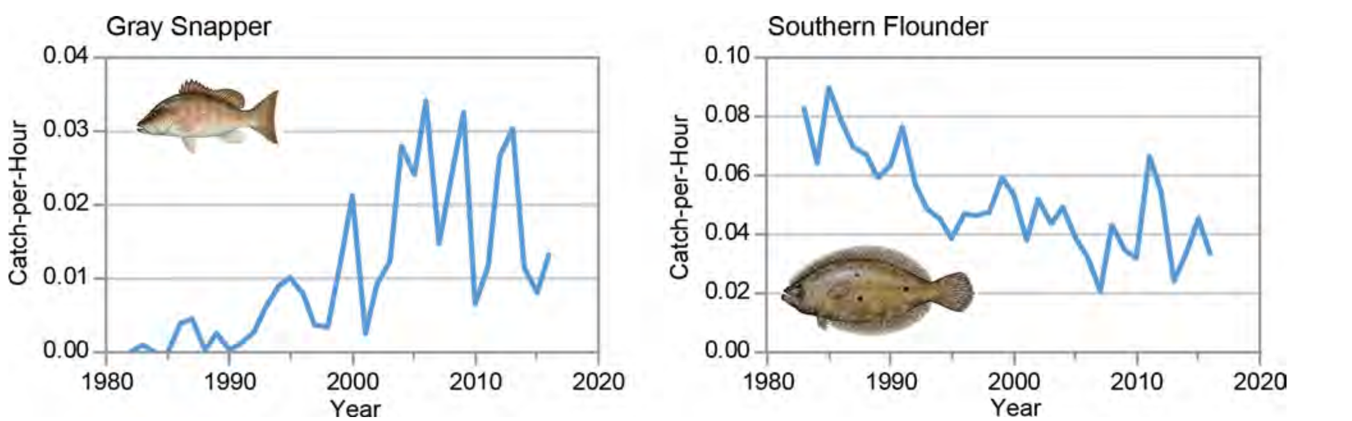


Figure 23.9: The graphs show trends in annual abundance of (left) gray snapper and (right) southern flounder as the number of fish caught per hour along the Gulf Coast of Texas between 1982 (snapper)/1983 (flounder) and 2016. As water temperatures increase along the Texas Gulf Coast, gray snapper are expanding northward along the Texas coast, while southern flounder, a popular sport fish, are becoming less abundant, impacting the recreational and commercial fishing industries. Source: Texas Parks and Wildlife Department.

Gray snapper have been ranging farther north since the 1990s; once found only in the lower Laguna Madre and off the extreme southern shore of Texas, they are now migrating northward along the upper Texas Coast. Conversely, flounder abundance has been declining due to the warmer winters,[137,138] since sex ratios (the number of males versus females) are influenced by temperature during flounder development and increases in temperature produce increasingly male-dominated sex ratios in southern flounder from Texas (See Figure 23.9).

Existing Options for Managing Risk

The National Fish, Wildlife, and Plants Climate Adaptation Strategy[123] was developed to provide natural resource managers and decision-makers the strategies and tools to address climate change impacts. The Strategy offers a guide for actions that can be taken in spite of remaining uncertainties over how climate change will impact living resources.

The Texas Edwards Aquifer Recovery Implementation Program Habitat Conservation Plan[78] balances water pumping and use of the aquifer with protection of eight federally listed threatened and endangered species that depend on San Marcos Springs and Comal Springs, two of the largest springs in the southwestern United States. These springs are the headwaters of the San Marcos and Comal Rivers and provide important water flow, especially during drought, to the Guadalupe River and Estuary.

Environmental flows—instream flows and freshwater inflows to bays and estuaries—are critical for sustaining aquatic ecosystems. In 2007, the Texas Legislature passed Senate Bill 3, which established a comprehensive, statewide process to protect environmental flows.[136] The process relies upon input from local stakeholder groups, composed of balanced interests ranging from agricultural water users to commercial anglers. The Texas Commission on Environmental Quality has adopted environmental flow standards intended to protect flow regimes that will help ensure healthy rivers, streams, and estuaries for Texas. The focus now is on adaptive management to refine standards, address research needs, and identify voluntary strategies to meet environmental flow standards.

The Texas Coastal Resiliency Master Plan[139] promotes coastal resilience, defined as the ability of coastal resources and coastal infrastructure to withstand natural or human-induced disturbances and quickly rebound from coastal hazards. This definition encompasses the two dimensions of resilience: 1) taking actions to eliminate or reduce significant adverse impacts from natural and human-induced disturbances, and 2) responding effectively in instances when such adverse impacts cannot be avoided. To keep pace with the dynamic Texas coastline, the Plan will be updated regularly to allow the state to continually assess changing coastal conditions and needs and to determine the most suitable way to implement the appropriate coastal protection solutions.

Key Message 4

Human Health

Health threats, including heat illness and diseases transmitted through food, water, and insects, will increase as temperature rises. Weather conditions supporting these health threats are projected to be of longer duration or occur at times of the year when these threats are not normally experienced. Extreme weather events with resultant physical injury and population displacement are also a threat. These threats are likely to increase in frequency and distribution and are likely to create significant economic burdens. Vulnerability and adaptation assessments, comprehensive response plans, seasonal health forecasts, and early warning systems can be useful adaptation strategies.

Extreme heat causes both direct and indirect impacts on human health and acts as a threat multiplier to the medically vulnerable. The increase in extreme heat due to climate change will exacerbate the medical issues associated with heat illness. More detail can be found in Chapter 14: Human Health. Notably, heat stress is strongly correlated with complications of lung disease, such as asthma and emphysema, as well as dehydration and injurious electrolyte abnormalities. It is estimated that each increase of approximately 1.8°F (1°C) in summer temperature increases the death rate for elders with chronic conditions by 2.8% to 4.0%.[140] During heat waves, concrete, blacktop, and the low ventilation capacity of urban "canyons" created by tall buildings can add 7°–12°F to the urban heat load.[141] The heat wave of 2011 exemplifies the human health and healthcare system impacts of extreme heat in the Southern Great Plains. The average temperature in Texas from June to August that year was 86.7°F (30.4°C), which broke all previous single-month records and was 5.2°F (2.9°C) higher than the long-term climatological average.[11] Studies demonstrated a 3.6% increase in emergency room visits and a 0.6% increase in deaths, with the largest effect on the elderly.[142,143] Within the Southern Great Plains, changes in extreme temperatures are projected to result in an additional 1,300 deaths per year under a higher scenario (RCP8.5) by the end of the century. Under a lower scenario (RCP4.5), more than half of these additional deaths could be avoided. Annual losses associated with extreme temperature-related mortality are estimated at $19 billion (2015 dollars) under RCP8.5 in 2090 and $9.4 billion (2015 dollars) under RCP4.5[144] (see the Scenario Products section of App. 3 for more on RCPs).

Rising temperatures and precipitation alter the habitats of vectors (mosquitoes, ticks, rodents, and fleas) that transmit a variety of human diseases. In the Southern Great Plains, hantavirus,[145] Rocky Mountain spotted fever,[146] leptospirosis,[147] and West Nile virus[148] are all currently endemic and could be impacted by climate change.[149,150] A warmer world will create newly hospitable habitats for tropical and subtropical insect vectors and the diseases they carry. Historically disease-free areas have been protected from becoming hazardous by cold environmental temperatures. That is, with extreme low temperatures of winter, insect (in particular, mosquito) populations are decimated. However, as the global average temperature increases, mosquitoes will thrive longer and reproduce more successfully at higher latitudes and altitudes. Tropical diseases, such as dengue virus,[151] chikungunya virus, and Zika virus are transmitted by *Aedes* mosquitoes, which are currently expanding their geographic range in the southern United States.[149] In southern Texas, sporadic, locally acquired outbreaks of dengue have been reported.[152] In 2005, there were 59 cases of dengue virus in southern Texas that met criteria for dengue hemorrhagic fever,[153] indicating that inhabitants were exposed to multiple variations of the virus, a condition necessary for the development of severe manifestations of dengue. In 2014, locally transmitted cases of chikungunya began to be reported in Texas.[154] Zika virus has also recently appeared in the region. In 2016, the Centers for Disease Control and Prevention (CDC) issued a travel warning for Cameron County, Texas, after the first case of local, person-to-person transmission of Zika was reported.[155] The ecology of vector-borne diseases is complex, and the future risk for proliferation and expansion of the ranges of these diseases is possible under future climate scenarios.[156,157] Along the southern Gulf Coast, stronger hurricanes will increase the likelihood of favorable ecologic niches for emerging infectious diseases that infect humans and animals.[158]

As water evaporates during periods of drought, the remaining water can have higher concentrations of chemicals and solid particles, lower dissolved oxygen levels, and a higher density of germs that cause infectious diseases.[128] Drought conditions reduce the number of sources and overall quantity of water available to both human and animal users. Because these users are sharing a reduced supply, germ transmission and outbreaks of infectious disease become more likely. Waterborne diseases that have been linked to drought include amoebiasis, hepatitis A, salmonellosis, schistosomiasis, shigellosis, typhoid and paratyphoid fevers, infection with *E. coli*, cholera, and leptospirosis.[159,160,161,162] Skin infections, such as scabies and impetigo, and eye infections, including conjunctivitis, are also correlated with drought due to a lack of water available for personal hygiene.[163]

Droughts, floods, and higher temperatures will change the balance of ecosystems, allowing invasive species such as animal pests, plant weeds, and algae blooms to proliferate and harm existing agriculture.[164] Such conditions favor fungal species that can overwhelm crops and contaminate animal feedstocks. Additionally, increases in CO_2 are changing the nutritional composition of food crops.[165] Elevated CO_2 levels have been shown to reduce the protein composition of grains, tubers, rice, wheat, and barley.[166] Micronutrient contents are also affected by rising CO_2 levels, with atmospheric CO_2 concentrations of 550 parts per million being associated with reductions in zinc, iron, phosphorus, potassium, calcium, sulfur, magnesium, copper, and manganese across a wide range of crops.[167] Additionally, extreme temperatures and aridity pose health risks to outdoor agricultural workers.[168] Under a higher scenario (RCP8.5), the impact of temperature extremes at a national level are projected to result in the loss of two billion labor hours, equating to an estimated $160 billion (in 2015 dollars) in lost wages by the end of the century. The Southern Great Plains region is projected to experience higher-than-average impacts, with some communities projected to lose more than 6% in annual labor hours by the end of the century.[144]

State-level climate adaptation programs[169] have been developed throughout the Nation. For health, these include vulnerability and adaptation assessments, comprehensive response plans,[170,171] climate-proofing healthcare infrastructure, and implementing integrated surveillance of climate-sensitive infectious diseases. These efforts are outlined in more detail in Chapter 14: Human Health. Incorporating short-term to seasonal forecasts into public health activities can also provide assistance under a warming climate.[172] Although there is momentum to adopt adaptation strategies in the wake of Hurricane Harvey,[173] and adaptation strategies on a general scale (such as for drought) are in progress,[174] large-scale adaptation efforts in the region are lacking[175] and regional planners can learn from activities ongoing outside the region (Ch. 14: Human Health).

Key Message 5

Indigenous Peoples

Tribal and Indigenous communities are particularly vulnerable to climate change due to water resource constraints, extreme weather events, higher temperature, and other likely public health issues. Efforts to build community resilience can be hindered by economic, political, and infrastructure limitations, but traditional knowledge and intertribal organizations provide opportunities to adapt to the potential challenges of climate change.

Box 23.2: The Sun Dance Ceremony

Cheyenne tribal Chief Gordon Yellowman noted that excessive heat, invasive species, and drought threatened the Cheyenne Sun Dance ceremony. He related how natural materials are traditionally gathered for the ceremony by young men, called runners. Most significantly, willow branches for shade arbors were increasingly hard to find given the prolonged drought experienced in western Oklahoma. In areas where natural materials were gathered for the ceremony, invasive poison ivy was now present, with the vines choking out willow saplings and taking over. Many of the young men were poisoned to such an extent that they had to seek medical attention beyond traditional medicines in order to participate in the most important ceremony for the Cheyenne. In addition, an increase in the occurrences of heat illness at these ceremonies is preventing some tribal members from participating in or completing the ceremony.

Figure 23.10: Chief Gordon Yellowman is shown here representing the Cheyenne Tribe at a traditional speaking engagement. Photo courtesy of Gordon L. Yellowman, Sr.

The 45 federally recognized tribes (48 if state-recognized tribal nations are included) located in the Southern Great Plains show considerable economic, social, cultural, and linguistic/language diversity.[176,177,178] The 4 tribes of Kansas (59,130 people), 39 tribes of Oklahoma (482,760 people), including 1 state-recognized tribe, and 5 tribes of Texas (6,210 people), including 2 state-recognized tribes, experience the same climate change impacts as the rest of the Nation.[14] However, these sovereign nations within the United States are faced with infrastructure (social and physical), economic, political, and cultural challenges, as well as unique opportunities, in their response to climate change impacts (Ch. 15: Tribes).

Climate Change Threats to Tribal Cultural Traditions and Community Resilience

No climate change impacts are as significant to the tribes and Indigenous peoples of the Southern Great Plains as those that threaten the ability to procure food, water, shelter, and preserve ancient cultural activities.[179,180,181] Given the ancient symbiotic relationship between environment and culture that shapes tribal identities and life-way practices, climate-induced changes to the seasons, landscapes, and ecosystems pose an existential threat to tribal cultural traditions and community resilience.[182,183,184] For example, climate change, including the impacts of excessive heat, drought, and the disappearance of native species, is already disrupting ceremonial cycles in Oklahoma.[185] However, many climate change adaptation initiatives and strategies are being developed by tribes throughout the United States. Specific examples in the Southern Great Plains can be found in Figure 15.1 in Chapter 15: Tribes.

Physical and Organizational Infrastructure

The region's tribes and Indigenous peoples vary greatly in size, from small nations with fewer than 1,000 enrolled members to larger nations with over 50,000 enrolled members; the largest of the tribes is the Cherokee Nation with more than 317,000 enrolled members.[186] The smaller nations, given their population size and respective size of government, often struggle to exercise their sovereignty to respond to climate change due to a lack of organizational and physical infrastructure.[187,188] The social organizational infrastructure needed to adapt to climate change impacts like extreme weather events, rising temperatures, shifting seasons, invasive species, air and water quality issues, and a host of health impacts is often lacking or underdeveloped in small tribal nations. Consequently, the smaller tribes depend largely on the services, grant programs, and technology transfer capabilities of the Bureau of Indian Affairs and other Federal Government departments, agencies, and bureaus to assist in their climate adaptation efforts. There are exceptions—larger and wealthier tribal nations, such as the Chickasaw Nation, Citizen Band Potawatomi, and Muscogee (Creek) Nation, can develop and shape, to a much larger extent, their own climate adaptation strategies.[169]

Lack of physical infrastructure, tied directly to limited economic resources and power, poses a substantial obstacle to climate change adaptation for the tribes of the region. While cities and other governmental jurisdictions make plans to build resilient physical infrastructure by using bonds, public–private partnerships, and taxes and tax instruments, only a handful of tribal nations have the ability to use these tools for climate adaptation. Most tribes and Indigenous peoples remain dependent on underfunded federal programs and grants for building and construction activities to improve the resilience of their infrastructure in the face of climate change threats. Many larger and wealthier tribes have modeled construction and design of homes and large commercial building best practices on "green" or resilient net-zero carbon footprint designs. Increasing activity in community gardens, food recovery, recycling, water conservation, land-use planning, and investment in climate-resilient community design all signal opportunities for tribal nations to leapfrog significant obstacles other city, county, and state governments face when dealing with the costs of existing physical infrastructure that often make climate change adaptation difficult and incremental.

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Whooping cranes: Jon Noll/U.S. Department of Agriculture.

Traceable Accounts

Process Description

The initial Southern Great Plains author team was selected such that expertise from each of the states' officially recognized climate offices in the region (Kansas, Oklahoma, and Texas) were included. The offices of the state climatologist in Kansas, Oklahoma, and Texas are each members of the American Association of State Climatologists, which is the recognized professional scientific organization for climate expertise at the state level.

One representative from each of several regional hubs of national and regional climate expertise was included on the author team. These regional hubs include the U.S. Department of Agriculture's Southern Plains Climate Hub (El Reno, Oklahoma), the U.S. Department of the Interior's South Central Climate Adaptation Science Center (Norman, Oklahoma), and the National Oceanic and Atmospheric Administration's Regional Integrated Sciences and Assessments Southern Climate Impacts Planning Program (Norman, Oklahoma).

After assessing the areas of expertise of the six authors selected from the state and regional centers, a gap analysis was conducted to prioritize areas of expertise that were missing. Due to the importance of the sovereign tribal nations to the Southern Great Plains, an accomplished scholar with expertise in Indigenous knowledge on the environment and climate change was selected from the premier tribal university in the United States, Haskell Indian Nations University in Lawrence, Kansas. An individual from the Environmental Science Institute at the University of Texas at Austin was selected to bring expertise on the complex intersection of coupled atmosphere–land–ocean systems, climate, and humans (population and urbanization). Expertise in the electric utility industry was gained through the Oklahoma Association of Electric Cooperatives by an individual with a long history of working with rural and urban populations and with researchers and forecasters in weather and climate.

The author group decided to allow Southern Great Plains stakeholders to drive additional priorities. On March 2, 2017, the Fourth National Climate Assessment (NCA4) Southern Great Plains chapter team held a Regional Engagement Workshop at the National Weather Center in Norman, Oklahoma, with a satellite location in Austin, Texas, that allowed a number of stakeholders to participate virtually. The objective of the workshop was to gather input from a diverse array of stakeholders throughout the Southern Great Plains to help inform the writing and development of the report and to raise awareness of the process and timeline for NCA4. Stakeholders from meteorology, climatology, tribes, agriculture, electric utilities, water resources, Bureau of Land Management, ecosystems, landscape cooperatives, and transportation from Kansas, Oklahoma, and Texas were represented. The productive dialog at this workshop identified important gaps in environmental economics, ecosystems, and health. Scientists working at the cutting edge of research in these three areas were selected: an ecosystems expert from the Texas Parks and Wildlife Department, an environmental economist from the department of Geography and Environmental Sustainability at the University of Oklahoma, and health experts from the University of Colorado School of Medicine and the Aspen Global Change Institute.

This diverse collection of medical doctors, academics, researchers, scientists, and practitioners from both federal and state agencies gives the Southern Great Plains chapter a wealth of expertise across the many ways in which climate change will affect people in the region.

Key Message 1

Food, Energy, and Water Resources

Quality of life in the region will be compromised as increasing population, the migration of individuals from rural to urban locations, and a changing climate redistribute demand at the intersection of food consumption, energy production, and water resources (*likely*, *high confidence*). A growing number of adaptation strategies, improved climate services, and early warning decision support systems will more effectively manage the complex regional, national, and transnational issues associated with food, energy, and water (*likely*, *high confidence*).

Description of evidence base

The connection between food, water, and energy also creates great challenges in the management and distribution of resources. People need food, energy, and water, yet all sectors pull from each other and allocation is a challenge. There are many studies focused on the competitive nature revolving around these resources and the demand by people.[41,59,60,61,62,63,64,65] The management and application of these issues are social in context and require significant communication and collaboration to resolve. As demands for these resources become more acute, development of collaborative processes to ensure integrated use and allocation may be required.

Major uncertainties

Research into the intersection of food, energy, and water is in its early stages and historically tends to examine only one or two components.[59,60,61,62,63,64,65] It is clear that tradeoffs and cascading complexities exist between sectors, and changes in one sector are likely to propagate through the entire system. There are significant gaps in the scientific understanding regarding the role that climate change will play as a disruptive force and a threat to food, energy, and water security.[60,63,66,67,68] It is likely, and with significant certainty, that the competition for and use of the resources by people will continue; however, the likelihood of developing a means to manage this situation is challenging. The added complexities of people and cultures, a rapidly growing population (see next section), and the diminishing availability of resources (water especially) in this region will be an important future research topic.

Description of confidence and likelihood

The Southern Great Plains will continue to grow rapidly and with high probability of significant competition. Water is the major concern, and political inability to develop a system to allocate water in an equitable manner will continue to build this competitive and contentious issue among all users—energy, food, and water. Quality of life in the region will be compromised as population increases. At least 60% of the region's population is clustered around urban centers currently, but these population centers are experiencing growth that far exceeds that of rural communities. The remaining population is distributed across vast areas of rural land.[14,30,31,32,33] Therefore, the migration of individuals from rural to urban locations, combined with climate change, redistributes demand at the intersection of food consumption, energy production, and water resources. (*Likely, High confidence*)

A growing number of adaptation strategies, improved climate services, and early warning decision support systems will more effectively manage the complex regional, national, and transnational issues associated with food, energy, and water. Since a changing climate has significant negative impacts on agriculture in the United States and causes substantial economic costs,[38] the effects of drought and other occurrences of extreme weather outside the region will also affect the food–energy–water interconnections within the region. (*Likely, High confidence*)

Key Message 2

Infrastructure

The built environment is vulnerable to increasing temperature, extreme precipitation, and continued sea level rise, particularly as infrastructure ages and populations shift to urban centers (*likely*, *high confidence*). Along the Texas Gulf Coast, relative sea level rise of twice the global average will put coastal infrastructure at risk (*likely*, *medium confidence*). Regional adaptation efforts that harden or relocate critical infrastructure will reduce the risk of climate change impacts.

Description of evidence base

The existing infrastructure and projected models for growth are well established and documented. Demographic and population projections are available from state demographers and are typically included in Long-Term Transportation Plans available from state departments of transportation. Additionally, the present-day infrastructure challenges have been examined in depth by the American Society for Civil Engineers (ASCE), which publishes an Infrastructure Report Card for the Nation and for each state (www.infrastructurereportcard.org).[189] For the Southern Great Plains states, one of the pressing concerns is meeting the funding challenges necessary to maintain critical infrastructure, as well as anticipating future revenue streams, which themselves depend on population and its distribution, and state and federal funding. The ASCE, as well as all state transportation plans in the Southern Great Plains, does not consider future climate projections, and the information contained generally does not explicitly mention climate-related stressors. However, the impacts of climate change have become an issue of concern for agencies such as the Department of Transportation (DOT) and Federal Highways Administration (FHWA), which have in recent years funded projects evaluating the potential impacts of climate change on infrastructure and transportation and possible adaptation strategies. Since 2010, the FHWA has sponsored a series of pilot studies in resilience for municipalities and states across the Nation.[190] Two of these studies took place in Texas, in Dallas and Tarrant Counties and in the City of Austin. These reports provide some of the most comprehensive examples of integrating climate data into assessments of infrastructure vulnerability in the region to date. The potential impacts of temperature and precipitation extremes on transportation and infrastructure were based in part on known vulnerabilities as shown by these aforementioned reports and the larger repository of information and resources supplied by the FHWA.

Estimates of relative sea level rise (SLR) in Texas in the historical period are available from NCA4 Volume I: *Climate Science Special Report*,[24] Runkle et al. (2017),[25] Sweet et al. (2017).[191] Relative SLR along the Texas coastline is some of the highest in the Nation; coupled with its population and critical energy infrastructure, this region has some noteworthy vulnerabilities to SLR. Projections of SLR remain uncertain and depend to some extent on whether the current rates of relative SLR are maintained, in addition to the magnitude and rate of greenhouse gas emissions. Sweet et al. (2017)[191] probabilistically evaluate a number of SLR scenarios, typically noting that the Texas coast SLR is higher than the global mean. The values mentioned in the main text are global mean values obtained from USGCRP (2017)[24] and from the range quoted by Runkle et al. (2017).[25]

Major uncertainties

In the Southern Great Plains there remains uncertainty over the direction of change of average precipitation, although models generally project increases in very heavy precipitation.[1] The expectation of an increase in the frequency of events such as the 100-year storm is uncertain due to the spread of model projections of extreme precipitation and the need to use additional statistical modeling in order to obtain the return period estimates.

There are limited studies that attempt to directly link weather and climate extremes and their impacts to infrastructure. While it is appreciated that infrastructure exposed to adverse conditions will lead to deterioration, studies on specific cause–effect chain of events in these cases are limited (e.g., Winguth et al. 2015[192]).The results are more evident in the case of catastrophic failures associated with floods, for example, but even in those cases, antecedent conditions related to the age, condition, and/or construction quality of infrastructure will affect its resilience (Ch. 12: Transportation).

Description of confidence and likelihood

There is *very high confidence* that extreme heat will increase in frequency and intensity. There is *medium confidence* in an increased frequency of flooding and *high confidence* in the increased frequency of drought. There is *high confidence* of sea level rise of at least 4 feet by 2100 along the Texas coastline if greenhouse gas emissions are not reduced. On the implications for infrastructure, there is *high confidence* that weather-related damage will increase due to inland weather-related hazards. Along the coastline, there is *very high confidence* that infrastructure will be impacted by sea level rise and storm surge.

Key Message 3

Ecosystems and Ecosystem Services

Terrestrial and aquatic ecosystems are being directly and indirectly altered by climate change (*likely*, *high confidence*). Some species can adapt to extreme droughts, unprecedented floods, and wildfires from a changing climate, while others cannot, resulting in significant impacts to both services and people living in these ecosystems (*likely*, *high confidence*). Landscape-scale ecological services will increase the resilience of the most vulnerable species.

Description of evidence base

This Key Message was developed through technical discussions developed within science teams and collaborators of the Gulf Coast and Great Plains Landscape Conservation Cooperatives. Species' response to climate change is complex and variable;[119] this complexity necessitates a multifaceted review of the projected impacts of climate change. In addition, ecosystem services also require assessment, given the impact of climate change on their ability to deliver materials and processes that benefit people.[123]

The following relevant areas of evidence regarding climate change impacts on ecosystems in the Southern Great Plains were therefore considered: species, aquatic ecosystems, coastal bays and estuaries, and risk management. It is unclear how climate change will affect species directly, but the effects of increased aridity will likely have negative impacts (e.g., NFWPCAP 2012[123]). Species migration (e.g., Schmandt 2011[126]) and mortality (e.g., Moore et al 2016[127]) will increase in response to climate change. Climate change impacts to aquatic ecosystems include higher water temperatures in lakes, wetlands, rivers, and estuaries, while impacts to reservoirs include fluctuating lake levels, loss of habitat, loss of recreational access, increase in harmful algal blooms, and disconnectedness from upstream and downstream riverine habitat.[129] Sea level rise will impact coastal bays and estuaries via more frequent and longer-lasting flooding of marshes,[126,132] while higher tides and storm surges cause inundation of freshwater areas and beach erosion, leading to a potential decrease or loss of barrier islands and coastal habitats, including nesting habitats and submerged habitats such as seagrass beds affected by changes in water quality and changing water depths.[133] Other ecosystem-centered impacts include surface and groundwater depletion (e.g., Perkin et al. 2017[134]) and changes in migratory species pathways.[135]

Major uncertainties

Ecosystems and the species that exist in these ecosystems have experienced a rapid decline in many "common species" as well as certain rare species.[123,137,138] Increases in many nonnative species have led to both concern and opportunity. Continued habitat and population shifts and the impact of interactions between people, other resources, and available habitat stressors are vague. Indirect impacts to livestock and agricultural systems are also unknown. The likelihood of animal and plant diseases and parasites impacting commercial production and the interaction with wild species is anticipated but uncertain.

Description of confidence and likelihood

There is *high confidence* that rising temperatures and increases in flooding, runoff events, and aridity will *likely* lead to changes in the aquatic and terrestrial habitats supporting many regional species. Flooding has changed the complexity of many riparian habitats. Increases already seen in extreme drought occurrence have caused downturns in the fish- and wildlife-related industries, with losses in traditional fish (crab and oysters) and wildlife species (waterfowl) important for both recreational and commercial purposes.

In contrast, habitat created by invasive species due to climate change has improved populations of other species including fungi. The expanded stress due to a rapidly growing population in this region increases the likelihood (*high confidence*) of negative natural resource and ecosystems outcomes in the future.

Key Message 4

Human Health

Health threats, including heat illness and diseases transmitted through food, water, and insects, will increase as temperature rises (*very likely*, *high confidence*). Weather conditions supporting these health threats are projected to be of longer duration or occur at times of the year when these threats are not normally experienced (*likely*, *medium confidence*). Extreme weather events with resultant physical injury and population displacement are also a threat (*likely*, *high confidence*). These threats are likely to increase in frequency and distribution and are likely to create significant economic burdens (*likely*, *high confidence*). Vulnerability and adaptation assessments, comprehensive response plans, seasonal health forecasts, and early warning systems can be useful adaptation strategies.

Description of evidence base

This Key Message was developed in close coordination with the Human Health (Ch. 14) author team and incorporated applicable inputs from the U.S. Climate and Health Assessment.[168] Multiple lines of evidence demonstrate statistically significant associations between temperature, precipitation, and other climatologic variables with adverse health outcomes, including heat-related illness, respiratory disease, malnutrition, and vector-borne disease.[168] Regionally specific examples of these well-documented impacts were identified through literature reviews conducted to identify regionally specific studies of these impacts.

There is strong evidence that increasing average temperatures as well as increasing frequency, duration, and intensity of extreme heat events will occur in the Southern Great Plains by the middle and end of this century, with higher CO_2 emissions leading to greater and faster temperature increases.[80] Extreme temperatures are shown with *high confidence* to have substantial effects on morbidity and mortality [142,143,168] by causing heat-related illness and by increasing the risk of cardiovascular events, cerebrovascular events, respiratory disease, renal failure, and metabolic derangements.[193,194] In addition to impacting health and well-being, extreme heat is likely to lead to a significant economic impact through an increase in healthcare costs, premature mortality, and lost labor.[195] Within the Southern Great Plains, climate change is likely to exacerbate aridity due to drying of soils and increased evapotranspiration caused by higher temperatures.[80] Such aridity is likely to negatively impact the agricultural sector, contributing to food insecurity and increased pesticide use.[165] Extreme temperatures are projected to further impair food production in the region by significantly impacting the health and work capacity of outdoor workers.[144] Additionally, shifting temperature and precipitation patterns are making habitats more suitable for disease-carrying vectors to move northward towards the Southern Great Plains region.[149,150] In southern Texas, sporadic, locally acquired outbreaks of dengue, chikungunya, and Zika have been reported.[152,154,155] These diseases are transmitted by the *Aedes agypti* mosquitoes, which are currently expanding their geographic range into the Southern Great Plains region.[149,196]

Climate change is expected (with *medium to high confidence*) to increase the frequency of extreme rainfall and hurricanes, although impacts in the Southern Great Plains remain difficult to quantify.[2] The Gulf Coast of Texas in particular has experienced several record-breaking floods and tropical cyclones in recent years, including Hurricane Harvey. Hurricanes and resultant flooding result in significant health impacts, including deaths from drowning and trauma, critical shortages of essential medications, critical healthcare system power shortages, and forced patient evacuations.[9] Such events strain healthcare resources not only within regions of direct hurricane impact but also within the entire region due to displacement of patient populations.[8]

Major uncertainties

The ability to quantitatively predict specific health outcomes associated with projected changes in climate is limited by long-term public health data as well as meteorological data. While assessments consistently indicate that climate change will have direct and indirect impacts on human health (*high confidence*), quantifying specific health metrics, such as incidence and community level prevalence, remains difficult. The uncertainty develops when there are many connected actions that influence health outcomes. For example, the future impact of climate change on human health is likely to be reduced by adaptation measures that take place on local and national scales. Additionally, the role of non-climate factors, including land use, socioeconomics, and population characteristics (such as immigration), as well as health sector policies and practices, will affect local and regional health impacts. The magnitude of impact of these variables on health at local and regional scales is difficult to predict. The estimation of future economic impacts is limited by difficulties in estimating the true cost of healthcare delivery and additionally only partially captures the actual impacts on health and livelihood of individuals and communities. Thus, existing projections likely underestimate the entirety of the economic impact.

Description of confidence and likelihood

There is *very high confidence* that rising temperatures and changes in precipitation leading to flooding, runoff events, and aridity will *likely* lead to negative impacts on human health in the Southern Great Plains. There is *high confidence* that certain populations, such as very young and old and socioeconomically disadvantaged individuals, will *likely* be disproportionately affected.

Key Message 5

Indigenous Peoples

Tribal and Indigenous communities are particularly vulnerable to climate change due to water resource constraints, extreme weather events, higher temperature, and other likely public health issues (*likely*, *high confidence*). Efforts to build community resilience can be hindered by economic, political, and infrastructure limitations (*likely*, *high confidence*), but traditional knowledge and intertribal organizations provide opportunities to adapt to the potential challenges of climate change.

Description of evidence base

This Key Message was developed through dialog and discussions among Indigenous communities and within the social sciences discipline. While Indigenous communities vary in size from smaller nations to large well-formed governments, all are in need of communication about the realities of climate change.[14] Climate change threatens the ability of tribes and Indigenous peoples to procure food, water, and shelter and to preserve ancient cultural activities.[179,180,181] The impacts of excessive heat, drought, and the disappearance of native species are already disrupting ceremonial cycles in Oklahoma.[185] There is strong evidence that because of the unique nature of the Indigenous communities, including previous and ongoing experiences of the communities, the collective economic and political power for enacting efficient and effective climate adaptation responses could be limited at best.[182,183,184] There is a consensus among the nations that impacts of climate change will be a direct threat to the symbiotic connection between environment and the tribal traditions connecting the people with the land.

Major uncertainties

There is a great deal of uncertainty regarding how tribal communities will integrate climate change into their cultures, given the variable size of these communities and the challenges of connecting and communicating with clarity among them. It is likely that adaptation strategies will vary greatly as knowledge and communication might not be widely supported within all nations.[169,187,188] Due to disproportionate rates of poverty and access to information and collaborative support, some communities could suffer more than others; however, the degree and the impacts of such are unclear.

Description of confidence and likelihood

There is *high confidence* that extreme events and long-term climate shifts will lead to changes in tribal and Indigenous communities in the Southern Great Plains. Environmental connections will be direct, but the degree of those connections is uncertain and shifts in climate system will impact each nation differently. How changes will be perceived and managed and what steps are taken to adapt are uncertain; thus, there is *low confidence* that adaptation will be a successful mechanism among all tribal and Indigenous peoples.

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24 Northwest

Four Lakes basin in White Cloud Peaks, Sawtooth National Forest, Idaho

Key Message 1

Natural Resource Economy

Climate change is already affecting the Northwest's diverse natural resources, which support sustainable livelihoods; provide a robust foundation for rural, tribal, and Indigenous communities; and strengthen local economies. Climate change is expected to continue affecting the natural resource sector, but the economic consequences will depend on future market dynamics, management actions, and adaptation efforts. Proactive management can increase the resilience of many natural resources and their associated economies.

Key Message 2

Natural World and Cultural Heritage

Climate change and extreme events are already endangering the well-being of a wide range of wildlife, fish, and plants, which are intimately tied to tribal subsistence culture and popular outdoor recreation activities. Climate change is projected to continue to have adverse impacts on the regional environment, with implications for the values, identity, heritage, cultures, and quality of life of the region's diverse population. Adaptation and informed management, especially culturally appropriate strategies, will likely increase the resilience of the region's natural capital.

Key Message 3

Infrastructure

Existing water, transportation, and energy infrastructure already face challenges from flooding, landslides, drought, wildfire, and heat waves. Climate change is projected to increase the risks from many of these extreme events, potentially compromising the reliability of water supplies, hydropower, and transportation across the region. Isolated communities and those with systems that lack redundancy are the most vulnerable. Adaptation strategies that address more than one sector, or are coupled with social and environmental co-benefits, can increase resilience.

Key Message 4

Health

Organizations and volunteers that make up the Northwest's social safety net are already stretched thin with current demands. Healthcare and social systems will likely be further challenged with the increasing frequency of acute events, or when cascading events occur. In addition to an increased likelihood of hazards and epidemics, disruptions in local economies and food systems are projected to result in more chronic health risks. The potential health co-benefits of future climate mitigation investments could help to counterbalance these risks.

Key Message 5

Frontline Communities

Communities on the front lines of climate change experience the first, and often the worst, effects. Frontline communities in the Northwest include tribes and Indigenous peoples, those most dependent on natural resources for their livelihoods, and the economically disadvantaged. These communities generally prioritize basic needs, such as shelter, food, and transportation; frequently lack economic and political capital; and have fewer resources to prepare for and cope with climate disruptions. The social and cultural cohesion inherent in many of these communities provides a foundation for building community capacity and increasing resilience.

Executive Summary

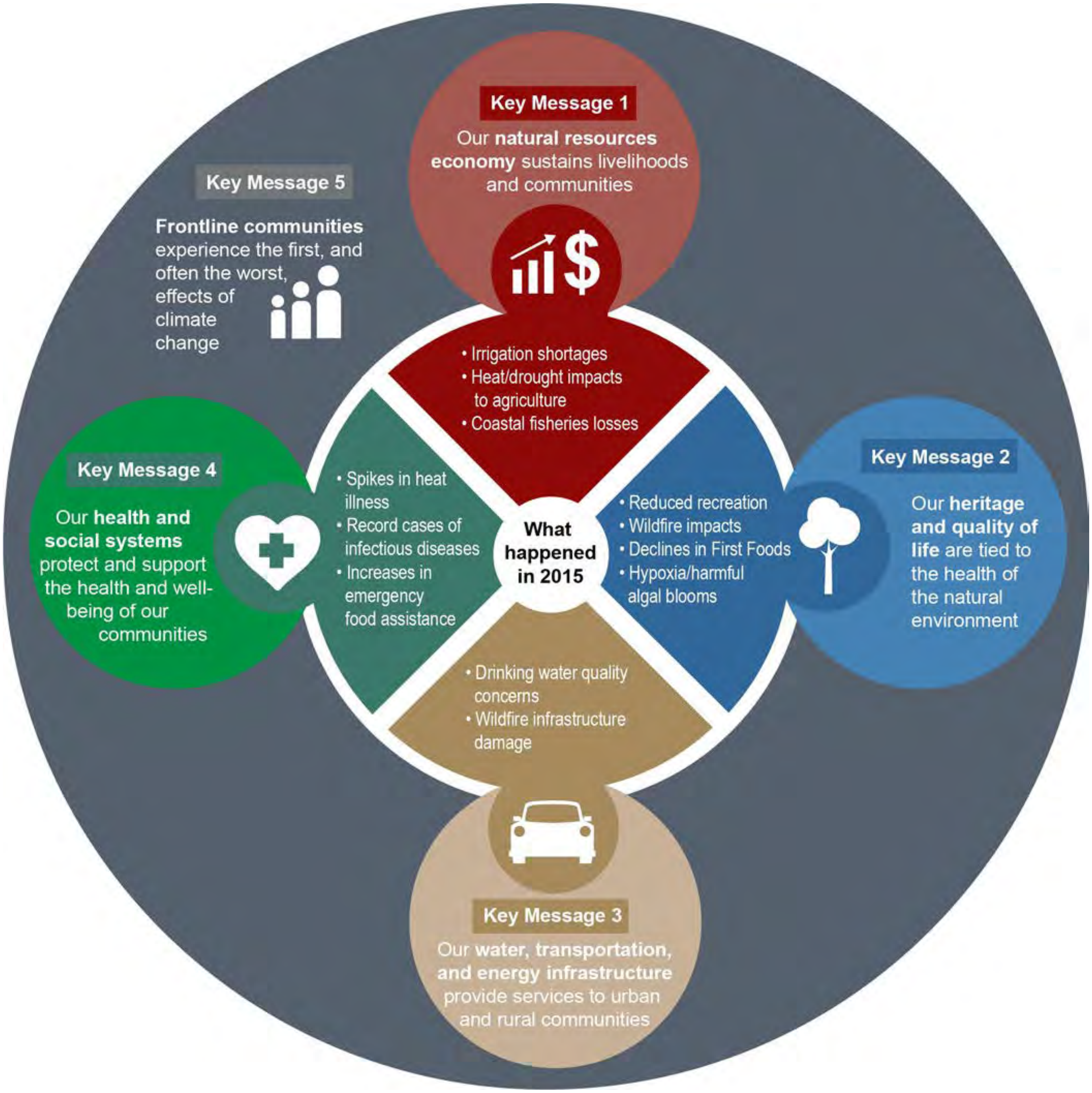
Residents of the Northwest list the inherent qualities of the natural environment among the top reasons to live in the region. The region is known for clean air, abundant water, low-cost hydroelectric power, vast forests, extensive farmlands, and outdoor recreation that includes hiking, boating, fishing, hunting, and skiing. Climate change, including gradual changes to the climate and in extreme climatic events, is already affecting these valued aspects of the region, including the natural resource sector, cultural identity and quality of life, built infrastructure systems, and the health of Northwest residents. The communities on the front lines of climate change—tribes and Indigenous peoples, those most dependent on natural resources for their livelihoods, and the economically disadvantaged—are experiencing the first, and often the worst, effects.

In the Third National Climate Assessment, the Key Messages for the Northwest focused on projected climate impacts to the region.[1] These impacts, many of which are now better understood in the scientific literature, remain the primary climate concerns over the coming decades. In this updated assessment, the Key Messages explore how climate change could affect the interrelationships between the environment and the people of the Northwest. The extreme weather events of 2015 provide an excellent opportunity to explore projected changes in baseline climate conditions for the Northwest. The vast array of climate impacts that occurred over this record-breaking warm and dry year, coupled with the impacts of a multiyear drought, provide an enlightening glimpse into what may be more commonplace under a warmer future climate. Record-low snowpack led to water scarcity and large wildfires that negatively affected farmers, hydropower, drinking water, air quality, salmon, and recreation. Warmer than normal ocean temperatures led to shifts in the marine ecosystem, challenges for salmon, and a large harmful algal bloom that adversely affected the region's fisheries and shellfish harvests.

Strong climate variability is likely to persist for the Northwest, owing in part to the year-to-year and decade-to-decade climate variability associated with the Pacific Ocean. Periods of prolonged drought are projected to be interspersed with years featuring heavy rainfall driven by powerful atmospheric rivers and strong El Niño winters associated with storm surge, large waves, and coastal erosion. Continued changes in the ocean environment, such as warmer waters, altered chemistry, sea level rise, and shifts in the marine ecosystems are also expected. These changes would affect the Northwest's natural resource economy, cultural heritage, built infrastructure, and recreation as well as the health and welfare of Northwest residents.

The Northwest has an abundance of examples and case studies that highlight climate adaptation in progress and in practice—including creating resilient agro-ecosystems that reduce climate-related risks while meeting economic, conservation, and adaptation goals; using "green" or hybrid "green and gray" infrastructure solutions that combine nature-based solutions with more traditional engineering approaches; and building social cohesion and strengthening social networks in frontline communities to assist in meeting basic needs while also increasing resilience to future climate stressors. Many of the case studies in this chapter demonstrate the importance of co-producing adaptation efforts with scien- tists, resource managers, communities, and decision-makers as the region prepares for climate change impacts across multiple sectors and resources.

Climate Change Will Impact Key Aspects of Life in the Northwest



The climate-related events of 2015 provide a glimpse into the Northwest's future, because the kinds of extreme events that affected the Northwest in 2015 are projected to become more common. The climate impacts that occurred during this record-breaking warm and dry year highlight the close interrelationships between the climate, the natural and built environment, and the health and well-being of the Northwest's residents. *From Figure 24.2 (Source: USGCRP).*

Background

Residents of the Northwest list the inherent qualities of the natural environment among the top reasons to live in the region. The Northwest is known for clean air, abundant water, low-cost hydroelectric power, vast forests, extensive farmlands, and an array of outdoor recreation that includes hiking, boating, fishing, hunting, and skiing. Warming and related changes in climate are already affecting aspects of the Northwest's identity such as its natural resource economy and its cultural heritage that is deeply embedded within the natural environment. The built systems that support Northwest residents and the health of residents themselves are also already experiencing the effects of climate change. The communities on the front lines of climate change experience the first, and often the worst, effects. Frontline communities in the Northwest include tribes and Indigenous peoples, the economically disadvantaged, and those most dependent on natural resources for their livelihoods.

The region has warmed substantially—nearly 2°F since 1900—and this warming is partially attributable to human-caused emissions of greenhouse gases.[2,3,4] Warmer winters have led to reductions in the mountain snowpack[5,6] that historically blanketed the region's mountains, increasing wildfire risk (Ch. 6: Forests, KM 1)[7,8] and speeding the usually slow release of water for communities, agriculture, rivers, and soils. In 2015, record winter warmth led to record-low snowpack in much of the Northwest's mountains as winter precipitation fell as rain instead of snow,[9] resulting in drought, water scarcity, and large wildfires that negatively affected farmers, hydropower, drinking water, salmon, and recreation. In addition, warmer ocean temperatures led to shifts in the marine ecosystem, challenges for salmon, and a large harmful algal bloom.[10] The extreme climate-related events of 2015 have prompted Northwest states, cities, tribes, and others to increase and prioritize climate preparedness efforts, as evidenced by the presentations at the 6th and 7th annual Northwest Climate Conference (http://pnwclimateconference.org/CdA2015/ and http://pnwclimateconference.org/Stevenson2016/).

Detroit Lake Reservoir During Multiyear Drought

Figure 24.1: Detroit Lake Reservoir in Oregon at record-low levels in 2015. Photo credit: Dave Reinert, Oregon State University.

Climate change affects the interrelationships between the environment and the people of the Northwest, and extreme climate events, such as those that occurred during 2015, provide a preview of what may be more commonplace under a warmer future climate (Figure 24.2). The Northwest is projected to continue to warm during all seasons under all future scenarios, although the rate of warming depends on current and future emissions.[11] The warming trend is projected to be accentuated in certain mountain areas in late winter and spring,[9] further exacerbating snowpack loss and increasing the risk for insect infestations and wildfires.[12] In central Idaho and eastern Oregon and Washington, vast mountain areas have already been transformed by mountain pine beetle infestations, wildfires, or both, but the western Cascades and coastal mountain ranges have less experience with these growing threats.[13]

Climate Change Will Impact Key Aspects of Life in the Northwest

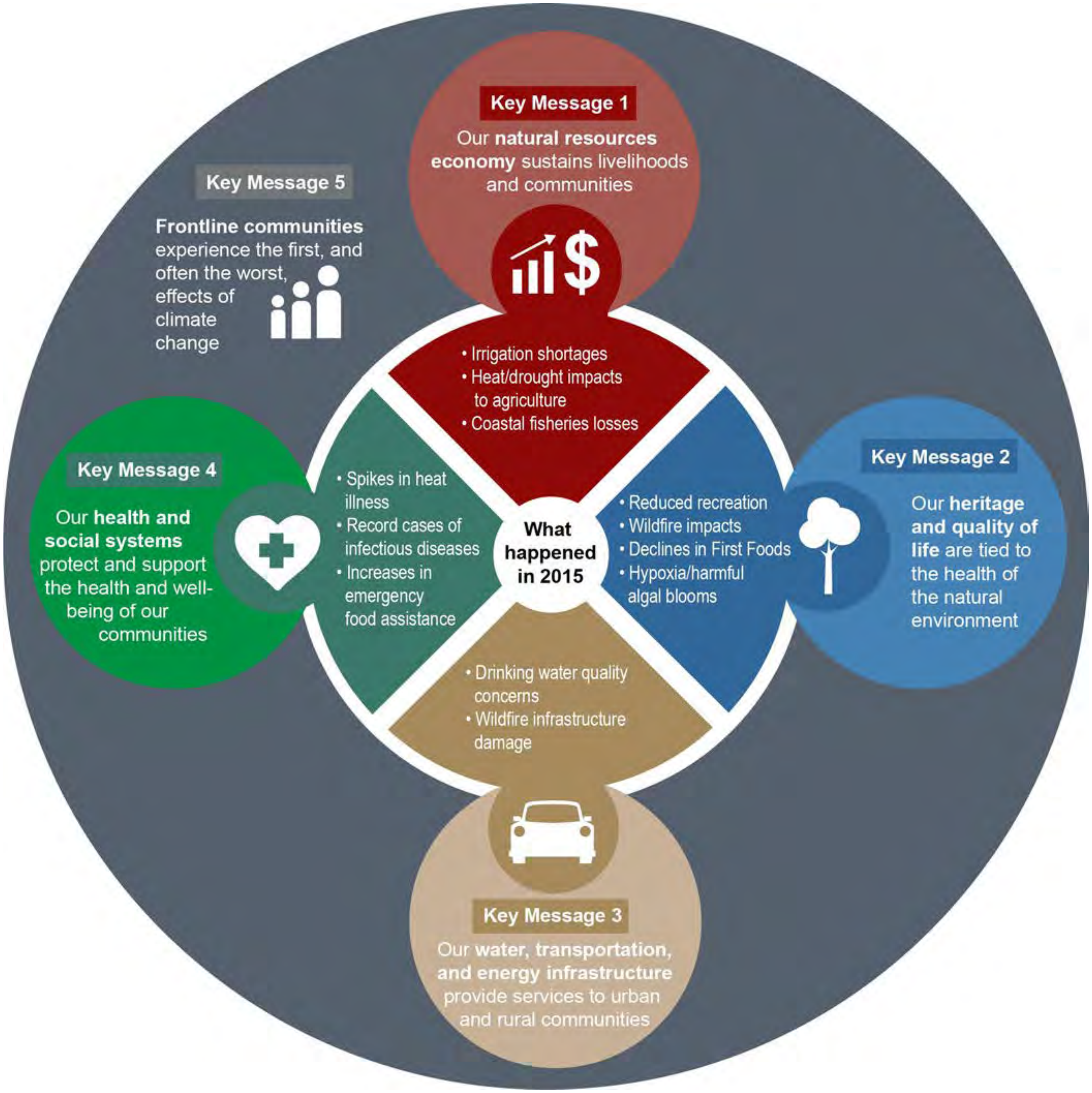


Figure 24.2: The climate-related events of 2015 provide a glimpse into the Northwest's future, because the kinds of extreme events that affected the Northwest in 2015 are projected to become more common. The climate impacts that occurred during this record-breaking warm and dry year highlight the close interrelationships between the climate, the natural and built environment, and the health and well-being of the Northwest's residents. Source: USGCRP.

Average winter precipitation is expected to increase over the long term, but year-to-year variability in precipitation is also projected to increase.[11] Years of abnormally low precipitation and extended drought conditions are expected to occur throughout the century,[11] and extreme events, like heavy rainfall associated with atmospheric rivers, are also anticipated to occur more often.[14] Along the coast, severe winter storms are also projected to occur more often, such as occurred in 2015 during one of the strongest El Niño events on record.[15] El Niño winter storms contributed to storm surge, large waves, coastal erosion, and flooding in low-lying coastal areas (Ch. 8: Coastal, KM 1).[16] Changes in the ocean environment, such as warmer waters, altered chemistry, sea level rise, and shifts in the marine ecosystems are also expected (Ch. 9: Oceans). These projected changes affect the Northwest's natural resource economy, cultural heritage, built infrastructure, recreation, and the health and welfare of Northwest residents.

Key Message 1

Natural Resource Economy

Climate change is already affecting the Northwest's diverse natural resources, which support sustainable livelihoods; provide a robust foundation for rural, tribal, and Indigenous communities; and strengthen local economies. Climate change is expected to continue affecting the natural resource sector, but the economic consequences will depend on future market dynamics, management actions, and adaptation efforts. Proactive management can increase the resilience of many natural resources and their associated economies.

Linkage Between Observed Climate and Regional Risks

The Northwest provides for a diverse natural resource economy, from coastal fisheries, to Douglas fir plantations, to vineyards, to semiarid rangelands, to dryland and irrigated farms. The region is the Nation's top producer of 28 agricultural products, one of the leading national producers of timber products, and is widely recognized for salmon and shellfish fisheries. The agriculture, forestry, and fisheries sectors accounted for over 700,000 jobs and more than $139 billion in sales in 2015 (in 2015 dollars; Figure 24.3).[17]

Natural Resource Industry Jobs and Sales Revenues

Figure 24.3: Natural resources are a key part of the Northwest economy. Climate change is putting natural resource sector jobs and sales revenues at risk. Jobs and sales figures include the agriculture, forestry, and fisheries sectors only, and are presented based on 2015 data for Idaho, Oregon, and Washington.[17] Source: U.S. Forest Service and Boise State University.

The outdoor recreation sector is another important contributor to local economies in the Northwest. The Outdoor Industry Association (2017)[18] estimates that the region's outdoor recreation economy generates $51 billion (based on 2017 data, dollar year not reported) in consumer spending each year and provides around 451,000 jobs. These economic benefits are particularly important in rural and tribal communities whose income base is largely dependent on natural resource economies and supporting industries (Ch. 10: Ag & Rural, KM 4; Ch. 15: Tribes). Outdoor activities, including skiing, boating, rafting, hunting, fishing, hiking, and backpacking, are impacted by climate variability, whether through less summer water, warmer streams, less snowfall, or loss of forests. Comparing high-snowfall to low-snowfall years in the Northwest between 1999 and 2009, each low-snowfall year resulted in more than 2,100 fewer employees and a $173 million reduction in ski resort revenues ($189 million in 2015 dollars) compared to the high-snowfall years.[19] Impacts on the skiing industry were especially prominent during the warm 2015 winter, when snowpack was at record lows (see Box 24.7).

Both the natural resource commodity sector and the outdoor recreation industry are sensitive to short- and long-term climate variability. The record-setting 2015 drought and above-average temperatures were a challenge for agriculture. The reduced availability of water for irrigation coupled with heat stress impacted production and livestock health (see Box 24.7) (see also Ch. 10: Ag & Rural, KM 2 and 3; Ch. 3: Water, KM 3). In Northwest forests, tree mortality driven by wildfires, insects, and disease have been more prevalent over the last two decades due to drought conditions and increased temperatures (e.g., Hicke et al. 2013[13]), and timber managers are adjusting to increased risk of loss by shortening rotation rates, reducing investment in some areas, and changing planted species.[20,21]

Commercial fisheries are also sensitive to climate variability. River temperatures increase during warm and dry years, resulting in fish kills of migrating and spawning salmon; these fish kills have consequences several years in the future.[22,23,24] In 2015, July water temperatures in the lower Columbia River and its tributaries were higher than in any other year on record, leading to a high rate of mortality for endangered sockeye and threatened Chinook.[25,26] The record temperatures in 2015 were part of a long-term trend of declining low flows[27] and warming streams.[28,29] Increasing ocean temperatures and acidity also impact fish survival, species abundance, and predator–prey distribution and timing.[30] In 2015, the increased ocean temperatures were part of an ocean heat wave coined “the Blob,” which fueled a coast-wide harmful algal bloom that affected commercial, recreation, and tribal subsistence fisheries (see Box 24.7) (see also Ch. 9: Oceans).[10]

Future Climate Change Relevant to Regional Risks

Shifts in timing of water supply, such as earlier snowmelt and declining summer flows, can adversely impact irrigated crop productivity, particularly where access to reservoir water storage and/or groundwater is limited (Ch. 10 Ag & Rural, KM 2).[31] Planning studies for Northwest reservoirs suggest a significant increased need for reservoir storage to meet future summer irrigation demands under climate change scenarios.[32,33] Irrigation demands among farmers in the Columbia River Basin are projected to increase 5% in response to climate change by the 2030s; however, actual water demands will vary depending on adaptive management decisions and crop requirements.[34] For dryland wheat production, shifting planting dates and rising temperatures coupled with increased atmospheric carbon dioxide (CO_2) and associated increases in plant water use efficiency are projected to lead to improved wheat yields under both lower and higher scenarios (RCP4.5 and RCP8.5) through the end of the century.[35,36]

Specialty crops, including apples and other tree fruits, are already experiencing changes. Higher spring temperatures have led to earlier flowering, which can lead to a mismatch with the availability of pollinators required for fruit setting (the process of flowers becoming fruit)[37] and can affect fruit quality as well as yield. Additionally, summer heat stress can lead to sunburn scald on apples and softer berry crops that can be damaged in transport and harvest,[37] which can decrease fruit quality and the farmers’ selling price. Heat stress can also decrease livestock health and increase parasite abundance.[38] Projected warmer and drier summer seasons will likely reduce forage quality and quantity,[39] with varied impacts across forage and rangeland types.[40] Impacts to the quality and quantity of forage will also likely impact farmers’ economic viability as they may need to buy additional feed or wait longer for their livestock to put on weight, which affects the total price they receive per animal.

Forests in the interior Northwest are changing rapidly because of increasing wildfire[8] and insect and disease damage,[41,42] attributed largely to a changing climate (Ch. 5: Land Changes).[43] These changes are expected to increase as temperatures increase[44] and as summer droughts deepen.[45] For forests that grow in areas with snowpack, the declining snowpack is projected to worsen summer drought conditions, increasing vulnerability to drought caused by year-to-year precipitation variability.[46] Some forests in the region will increase in potential productivity (growth without consideration of increased disturbance) due to a combination of increased CO_2 and a longer growing season length, while others will decrease due to reduced availability of summer moisture (Ch. 6: Forests).[47] Timber supplies from the drier eastern Northwest forests are the most affected by climate-related disturbances,[48] resulting in intermittent and unpredictable timber supplies and depressed timber prices[49] in an already difficult global market. This could affect mill investments and the long-term viability of forestry as an economic activity, particularly in the more remote areas of the region where transportation costs to mills are high.

The negative impacts on Northwest fisheries associated with ocean warming, acidification, and harmful algal blooms are expected to increase (Ch. 9: Oceans).[50] This could lead to extensive fisheries closures across all of the region's coastal fisheries, with severe economic and cultural effects on commercial and subsistence shellfish industries. The warming ocean is projected to result in range shifts, with some Northwest species shifting as far north as the Bering Sea.[51] However, these range shifts may also open up new fishing opportunities in the Northwest,[51,52] depending on interstate and international coordination between management agencies. As the marine ecosystems respond to climate change, there will likely be consequences to existing place-based fisheries resources, as well as potential benefits and new resources. How the shifting resources will be managed and how existing fishing rights and allocations will change over time is currently not known (Ch. 9: Oceans, KM 2).

Projections for increased stream temperature indicate a 22% reduction in salmon habitat in Washington by late century under a high emissions future (the A1F1 scenario).[53] This habitat loss corresponds to more than $3 billion in economic losses due to reductions in salmon populations and decreases in cold-water angling opportunities ($3.3 billion in 2015 dollars, discounting method not specified).[53] Freshwater trout are sensitive to habitat connectivity and wildfire, so land management practices will affect how trout respond to climate change.[54] Overall, commercial fishing performance and abundance are expected to decline as the climate changes.[50,55,56,57]

Decreases in low- and mid-elevation snowpack and accompanying decreases in summer streamflow are projected to impact snow- and water-based recreation, such as downhill and cross-country skiing, snowmobiling, boating, rafting, and fishing. Climate change could decrease snow-based recreation revenue by more than 70% annually in the Northwest under a higher scenario (RCP8.5).[58] Impacts to snowpack and, consequently, winter recreation will likely occur later in the colder, higher-elevation mountains in southern Idaho.[59]

Challenges, Opportunities, and Success Stories for Reducing Risk

Climate change will likely have both positive and negative effects on the natural resource sector; however, cost-effective adaptation approaches that build agro-ecosystem resilience are likely needed to maintain agricultural livelihoods (see Box 24.1). A shift in plant hardiness zones, or the ability of a given plant to thrive in a specific location, is expected, changing the suitability of growing certain crops in specific locations;[60,61] such shifts may change land uses entirely (Ch. 5: Land Changes, KM 2). For example, Northwest wine producers may see the potential for growing higher-quality and higher-value wine grape varietals,[62] but changing hydrologic regimes are projected to limit available water supplies for irrigation, requiring water storage or alternative water sources to maintain productivity. Over the longer term, changes to average growing season temperatures and the number of severe hot days are projected to reduce premium wine grape production in the Northwest, potentially shifting prime growing areas further north.[63] To take advantage of shifting opportunities, farmers would need to consider costly changes and investments in new farming practices and territories in advance of projected climate change.[37,64]

Livestock producers in the Northwest have an advantage over those in other U.S. regions where climate change impacts are likely to be more severe (Ch. 10: Ag & Rural, KM 3).[65] However, livestock production costs are still likely to increase in the Northwest due to supplemental feeding and watering requirements and the need for reducing livestock numbers in response to warmer and drier summers.[40]

The prevalence of wildfires, insect infestations, disease epidemics, and drought-induced dieback of Northwest forests have heightened forestry managers' awareness of potential climate change impacts. Over the long term, these sustained impacts are projected to fundamentally alter forest composition and land cover (Ch. 6: Forests, KM 1; Ch. 5: Land Changes). Forest management adaptation strategies are being developed,[21,66] including strategies

Supplemental Watering of Livestock During Drought

Figure 24.4: Supplemental watering of livestock in Eastern Oregon during the 2015 drought. Photo credit: Sonia A. Hall.

that address drought-related risks, improve the reliability of forest transportation infrastructure, and protect forest-related ecosystem services (Ch. 6: Forests, KM 3).[67] Vulnerability assessments and adaptation plans have been completed, or are in progress, for almost every National Forest and Park in the region.[68]

Marine and ocean environments of the Northwest are projected to continue to change gradually in response to climate change, but the full extent of the potential effects on fisheries is not well understood.[69] In the near term, the fisheries industry can use existing strategies that work within the limits of the natural environment to maintain species abundance, avoid extinction, or increase harvests, such as limited fishing seasons, developing quota systems, and expanding aquaculture (Ch. 9: Oceans, KM 2). In the longer term, particularly as large-scale range shifts occur, species-dependent management changes and alternative management systems are likely to be needed to maintain fisheries and open up new fisheries opportunities.[70]

Despite the many strategies for reducing risks, adaptive capacity is not uniform across the natural resource sector. Given the heterogeneity across climatic and natural resource industries in the region, it is not likely that productivity gains and losses will be felt equally across the broad diversity in the region.[71,72]

Emerging Issues

Climate stressors such as increased temperatures, CO_2 fertilization, and precipitation changes are projected to impact pest, disease, and weed pressures (Ch. 10: Ag & Rural).[77,78] Improved modeling of climate stressors on yields and crop quality will likely enhance the understanding of climate change effects and inform adaptation options[36] and assist in addressing farmers' concerns about future pest and pathogen impacts in the region.[79,80] Water shortfalls are also likely to continue during drought periods despite adaptation efforts focused on water efficiency and reducing water usage (Ch. 3: Water, KM 1). Western water law assigns a priority date to each right based on seniority, so junior (or more recent) water rights are more likely to be adversely affected under shortage conditions than

Box 24.1: Adaptive Agricultural Approaches in Practice

Farmers and ranchers across the Northwest are creating resilient agro-ecosystems to reduce weather- and climate-related risks while meeting economic, conservation, and adaptation goals. Below are a few examples of these efforts from the region.

- A dryland farmer in Eastern Oregon is implementing flexible cropping methods, which allows the farmer to plant additional crops, instead of leaving the field uncultivated (fallow), when soil moisture conditions allow. By intensifying production and reducing fallow periods, profits have increased while also improving weed management, reducing erosion, and improving soil quality.[73]

- A vegetable, grain, and livestock farmer in Washington is caring for the soil by using conservation tillage, direct seeding, and double cropping to reduce soil erosion, improve soil health, and increase revenues.[74]

Figure 24.5: A farmer in Oregon surveys his no-till field, a practice used to build climate resilience. Photo credit: Sylvia Kantor, Washington State University Extension.

- A cattle ranching family in Washington is using holistic management, a comprehensive approach for ranch decision-making, to reduce environmental risks and improve pasture productivity and profitability.[75]

- Farmers in Oregon's Willamette Valley are using dry farming methods to reduce reliance on irrigation water. This Dry Farming Collaborative is developing and implementing approaches that reduce drought risks during dry summer growing seasons.[76]

those with senior water rights. More studies would enhance the understanding of which watersheds are at the greatest risk and what, if any, changes could address water limitations in the future. The development of more robust water markets may facilitate adaptation to climate change in the arid and semiarid Pacific Northwest; however, considerable institutional barriers currently prevent their full implementation.[81]

Although much is being researched with respect to the effects of climate change on forests and associated ecosystem services, far less has been explored with respect to timber markets. Even then, most of the focus has been on changes in forest productivity overall (e.g., Latta et al. 2010[47]) and less on the consequences of disturbance. Research is absent on the effects of potential increases in supply volatility and the consequences for investment and ultimately on harvest and milling jobs.

Ocean acidification poses a direct threat to shellfish and other calcifying species that are at the base of the food web (Ch. 9: Oceans, KM 1). The prominence of the impact on shellfish farms in the Northwest led to the installation of an ocean monitoring system to track ocean acidity. Although calcium carbonate can be used to increase seawater pH in a hatchery setting,[82] the same approach cannot be used in the open ocean to prevent shell dissolution.[83] The broader food web consequences of decline in calcifying species is an area of active research (Ch. 9: Oceans).

There is a great deal of uncertainty regarding impacts on the economic viability of primarily rural, natural-resource-based economies in the region, particularly the degree to which individual sectors are integrated into global commodity markets, which are likely to vary immensely and be difficult to predict (Ch. 10: Ag & Rural; Ch. 16: International, KM 4).[50]

Key Message 2

Natural World and Cultural Heritage

Climate change and extreme events are already endangering the well-being of a wide range of wildlife, fish, and plants, which are intimately tied to tribal subsistence culture and popular outdoor recreation activities. Climate change is projected to continue to have adverse impacts on the regional environment, with implications for the values, identity, heritage, cultures, and quality of life of the region's diverse population. Adaptation and informed management, especially culturally appropriate strategies, will likely increase the resilience of the region's natural capital.

Linkage Between Observed Climate and Regional Risks

The intangible values and aspects of the Northwest's natural environment that support a high quality of life for its residents—wildlife, habitat, and outdoor recreation—are at risk in a changing climate. Tribes and Indigenous communities that rely heavily on the natural environment for their culture and heritage are also at risk.

The Northwest's native wildlife is impacted by climate variability and change *directly* through temperature shifts, water availability, and extreme events, and *indirectly* through loss or fragmentation of habitat.[84] Changes in climate can alter the balance among competing species or predator–prey relationships (e.g., Wenger et al. 2011[52]). Three wildlife categories are of principal concern: already sensitive or endangered species, snow-dependent species, and game species. While the first two groups of animals are generally negatively impacted by changes in climate, some game species, such as deer and elk, may thrive. Game species are

First Salmon Ceremony of the Lummi Tribe, Washington

Figure 24.6: Tribes in the Northwest typically honor the first salmon caught in the season through tribal ceremonies. Photo credit: Northwest Indian Fisheries Commission (CC BY 3.0).

of concern not because of their sensitivity to changes in climate and habitat but because of their notable value for recreational hunting and as key cultural resources for tribes. Climate change is also projected to impact First Foods, or foods that tribes have historically cultivated for subsistence, economic, and ceremonial purposes. First Foods vary among tribes but often include berries, roots, water, fish, and local wildlife.[85,86] Additionally, nearly half of all adults in the region participated in wildlife-related recreation in 2010.[87] As temperatures increase, the demand for warm-weather outdoor and water-based recreation increases, and visitation rates at local, state, and national parks increase.[88,89,90] However, boating and other water-based recreation opportunities are likely to decline in the future when summer streamflows and reservoir levels are low. Additionally, popular winter sports and snow-based recreational activities, such as downhill skiing, cross-country skiing, and snowmobiling, have been dramatically impacted by reduced snowfall (see Box 24.7). In low-snowfall years, Washington and Oregon show the highest percentage drop of skier visits, meaning that residents and visitors are losing desirable skiing opportunities.[91]

Future Climate Change Relevant to Regional Risks

Wildlife responses to a changing climate are varied and complex (Ch. 7: Ecosystems). Some species, such as cavity nesting birds, will very likely benefit from greater disturbance.[92,93] Others, particularly snow-dependent species, will likely be unable to persist under climate change.[94]

Game species are expected to have diverse responses to climate change. Longer dry seasons and more pronounced droughts are projected to reduce wetland habitat extent and duration, causing changes in waterfowl movement. Increased fire disturbance, on the other hand, will likely increase shrub cover, a preferred food for deer and elk;[95] reduced winter snowpack may increase food availability in winter; and warmer temperatures reduce winter stress, all of which would support higher deer and elk populations. The primary climate-related impact on game species will likely come from increases in disease and disease-carrying insects and pests.[96]

Temperature-sensitive bull trout, salmon, and other water-dependent species, such as amphibians, are most vulnerable to increased habitat fragmentation.[97,98,99] Increased frequency of extreme events such as flooding, debris flows, and landslides are projected to alter habitats and likely cause local extinctions of aquatic species.

Increased winter streamflow and decreased summer flow are projected to threaten salmon spawning,[100] compromising salmon hatchery and reintroduction efforts.[101] Projected increases in winter storm intensity will likely lead to higher river flows and increased sediment loading that can bury salmon eggs and reduce salmon survival.[101] Rising stream temperatures, ocean acidification, and loss of nearshore and estuarine habitat also increase salmon mortality across all phases of the salmon life cycle.[102]

Shellfish beds are threatened by sea level rise, storm surge, and ocean acidification.[85,103] Species moving out of traditional hunting, gathering, and fishing areas are projected to impact resource access for many tribes.[101,104] Increasing wildfire frequency and intensity are changing foraging patterns for elk and deer, and increased prevalence of invasive species and disease will likely diminish both wildlife and foraging for traditional plants, berries, roots, and seeds.[105]

In winter, continued decreases in lower-elevation snowpack are projected to impact snow-based recreation.[19] Less snowpack and earlier melting of snowpack will likely result in decreased water availability, reducing the quality, quantity, and availability of water-based recreational opportunities, such as boating, rafting, and fishing.[18]

Increased wildfire occurrence is projected to degrade air quality and reduce the opportunity for and enjoyment of all outdoor recreation activities, such as camping, biking, hiking, youth sports, and hunting. Degraded air quality also directly impacts human health and quality of life (see Key Message 4).

Razor Clamming in Washington State

Figure 24.7: Razor clamming draws crowds on the coast of Washington State. This popular recreation activity is expected to decline due to ocean acidification, harmful algal blooms, warmer temperatures, and habitat degradation. Photo courtesy of Vera Trainer, NOAA.

Wildfires Affect Outdoor Recreation

Figure 24.8: Wildfires impact outdoor wilderness activities and recreation. Reduced air quality and closed trails and camping grounds are projected to increase as wildfire occurrences increase. Photo credit: Charles Luce.

Recreational ocean fishing opportunities are expected to decline under future climate change scenarios,[55,56,57] and it is likely that fishery ranges will change.[51] Recreational razor clamming on the coast is also expected to decline due to cumulative effects of ocean acidification, harmful algal blooms, higher temperatures, and habitat degradation (see Figure 24.7 and Key Message 1).

Challenges, Opportunities, and Success Stories for Reducing Risk

Historical and projected changes in amenities affecting the quality of life in the Northwest, such as wildlife, recreation opportunities, and edible plants, form a key challenge for managers of these resources. Informed management, however, can reduce the consequences to those who enjoy and value these resources. Sensitive and endangered plant and animal species currently require special management considerations due to historical habitat changes and past species declines. Management of these species can substantially constrain land and water management options, and the protection of these species will likely become more difficult as suitable habitat is lost.

Game species are already managed. Further management of waterfowl habitat is projected to be important to maintain past hunting levels. If deer and elk populations increase, the pressures they place on plant ecosystems (including riparian systems) may benefit from management beyond traditional harvest levels.

The cultural practice of harvesting and consuming First Foods is integral to tribes and Indigenous health (Ch. 15: Tribes).[106] Many tribes, such as the Confederated Tribes of the Umatilla Indian Reservation are using climate change vulnerability assessments and climate change adaptation plans to alter how First Foods are managed.[107] Tribes can exercise their sovereign rights to manage their resources in a self-determined and culturally appropriate manner, thereby increasing each tribe's adaptive capacity to respond to climate change impacts on tribal lands, foods, health, and cultures (see Box 24.2).[85,108,109] Tribes can also increase their adaptive capacity through regional networks, such as the Columbia River Inter-Tribal Fish Commission, that support tribal and Indigenous planning and management (see Key Message 5).

As fisheries become stressed due to climate change, additional management strategies are likely to be needed to maintain fish populations. Strategies that focus on habitat quality and quantity are likely to be the most successful.[110]

Box 24.2: Pacific Salmon and the Identity and Culture of Northwest Tribes

For most Northwest tribes and Indigenous peoples, salmon fishing is more than a cultural, subsistence, and economic act. The tribes view salmon as an extension of life and an indicator of environmental health, and loss of salmon is equated with the loss of tribal identity and culture. As a testament of the importance of salmon, Julia Davis-Wheeler, a Nez Perce elder, stated: "We need the salmon because it is part of our lives and part of our history. The salmon is a part of us, and we are a part of it. Our children need to be able to feel what it is like to catch and eat salmon. They need to be able to experience that sense of respect that many of us have felt in past years."[111]

Figure 24.9: Pacific salmon are essential to most Northwest Tribes' identity and culture. Typically, the first salmon caught is displayed, cleaned, and cooked for the community to share. The skeleton is returned to the water to show respect to the salmon. This photo shows the First Salmon ceremony of the Puyallup Tribe. Pacific salmon—a keystone species in the Northwest—are at risk because of climate change. Economic, social, and cultural values are also at risk if salmon populations continue to decline. Recreational salmon fishing contributes to the quality of life and well-being for many Northwest residents. Photo credit: Matt Nagle, Puyallup Tribal News.

Adaptation strategies aimed at restoring and enhancing salmon fisheries can be more successful when traditional knowledge is coupled with modern science.[112,113] For example, the Nez Perce Tribe used local tribal knowledge to construct "natural" rearing ponds in the Columbia River coupled with introducing wild salmon as broodstock to enhance and restore a culturally significant salmon population.[109] Adaptation and informed management can reduce the consequences to those who enjoy and value these resources.

Emerging Issues

Some of the species likely to be affected by climate change are already imperiled by population declines, extirpations, or even extinction as a result of historical changes in habitat and other factors. Climate change adds urgency to addressing existing and emergent challenges. Research is already active in identifying resilient habitats (e.g., Morelli et al. 2016, Luce et al. 2014, Isaak et al. 2016[114,115,116]) and the means for maintaining and improving habitat resilience in the face of increasing climate and disturbance pressure.[117] Habitat modeling that includes projections of natural resource shifts, fragmentation, and identification of new wildlife corridors are projected to be beneficial in supporting land and water management decisions that benefit people, recreation, and the Northwest's varied wildlife.

An institutional network of land, wildlife, and fishery management agencies, tribes, and non-governmental conservation organizations has already successfully reversed negative trends in many fish and wildlife populations caused by other human activities.[118] These same groups are exploring methods to improve fish and wildlife resilience in a changing climate. Many habitat improvement activities, a cornerstone of conservation biology, also provide flood mitigation, climate mitigation, adaptation, and ecosystem service co-benefits (Ch. 6: Forests).[119,120] Despite proactive management and adaptation, it is likely that species not currently listed as endangered could become endangered over the next century, and eventual extinctions are likely, yet challenging to predict.[121]

First Foods are an important aspect of tribal and Indigenous health and well-being,[122] and they can be used as indicators in tribal health assessments and climate adaptation plans.[112,123] The loss or decline of First Foods is projected to have cascading physical and mental health impacts for tribes and Indigenous peoples (see Key Message 5) (see also Ch. 15: Tribes, KM 2).[124,125] However, more research to refine these indicators would better support decision-making (see Box 24.2).[123,126]

Social indicators link a decline in quality of life in the Northwest to loss of recreational opportunities due to climate change impacts,[127] but the causal links are not well understood. Additionally, future human migration and population increases may alter the relationship and nature of recreation in the Northwest.[128] As the population increases, the demand for snow-based recreation is likely to also increase. However, it is not clear how the limited availability of snow-based recreation (for example, a shorter ski season) in the Northwest over the long term can influence interest in snow sports in contrast to alternatives.

Key Message 3

Infrastructure

Existing water, transportation, and energy infrastructure already face challenges from flooding, landslides, drought, wildfire, and heat waves. Climate change is projected to increase the risks from many of these extreme events, potentially compromising the reliability of water supplies, hydropower, and transportation across the region. Isolated communities and those with systems that lack redundancy are the most vulnerable. Adaptation strategies that address more than one sector, or are coupled with social and environmental co-benefits, can increase resilience.

Linkage Between Observed Climate and Regional Risks

Infrastructure plays a critical role in keeping the Northwest's economy running smoothly. Roads, highways, railways, and ports facilitate the movement of people and goods within the region and support valuable import and export markets. Powerlines and substations maintain the reliable supply of electricity to homes, businesses, schools, and hospitals. Dams and reservoirs manage streamflow to minimize flood risks, generate electricity, and provide water supply for irrigation and human consumption. Groundwater wells act as an important water source for agriculture and drinking supplies across much of the region. Levees and seawalls prevent damage to homes and property along rivers and the coast. Culverts manage water flows to protect roadways from flooding and assist with fish passage, including for migrating salmon. Storm water and wastewater systems help minimize flooding, especially in urban areas, and are critical for maintaining water quality. However, most infrastructure is designed for a historical climate, and damage and disruptions caused by extreme events demonstrate existing infrastructure vulnerabilities that are likely to increase in a changing climate (Ch. 3: Water, KM 2; Ch. 4: Energy, KM 1; Ch. 11: Urban, KM 2; Ch. 12: Transportation, KM 1; Ch. 28: Adaptation, KM 2).

Services provided by infrastructure can be disrupted during extreme weather and climate events, illustrating the sensitivity of these systems to climate variability and change (see Box 24.3). During the 2015–2016 extreme El Niño winter, wave energy along the West Coast was about 50% above normal.[16] Several major storms hit northwestern Oregon, bringing record-breaking rainfall, high winds, and high tides. Tillamook County in Oregon experienced a state of emergency that included major highway and road closures due to flooding, failed culverts, landslides, and sinkholes. Disruptions in transportation networks affected access to food, healthcare, and social services (see Key Message 2) (see also Ch. 12: Transportation, KM 2).[130] The event highlighted the need to maintain detour routes that were valuable in reaching communities that could become isolated. Wave and storm surge energy

Box 24.3: Tribal Relocation as a Last Resort

The Quinault Indian Nation (QIN), located on the southern coast of Washington's Olympic Peninsula, has experienced repeated flood disasters, as described in the U.S. Climate Resilience Toolkit.[129] In March 2014, coastal storm surge breached the seawall protecting the town of Taholah, flooding the lower village. In January 2015, heavy rainfall washed out roads, including the Highway 109 bridge, a main access road to and from QIN, and threatened wastewater treatment facilities. With more severe impacts anticipated with climate change, combined with risks from tsunamis, QIN's leadership developed a master plan to relocate the lower village to higher ground. The master plan is considered the first step toward realizing QIN's vision for relocation based on sustainable practices and cultural values. Other Washington tribes have also relocated or begun relocation efforts, including the Hoh Tribe, Quileute Tribe, Makah Tribe, and Shoalwater Bay Tribe. Relocation of a tribe is considered a last resort.

Figure 24.10: Coastal floodwaters inundated the Quinault Indian Nation's lower village of Taholah in March 2014. This event, and continuing concerns about future climate change, prompted the village to begin relocation to higher ground. Photo credit: Michael Cardwell.

along the Pacific Northwest coast is expected to increase with climate change.[131] Continuing efforts to build resilience within the health and transportation sectors in response to flooding hazards will likely help the county weather future storms.[130]

Heavy rainfall can lead to slope instabilities and landslides, which can close roadways and railways. Along the Amtrak Cascades Corridor, more than 900 coastal bluff landslides have blocked the tracks and shut down rail service since 1914, with over 240 disruptions occurring between 2009 and 2013.[132] Each landslide results in a minimum 48-hour moratorium on commuter rail service. The Washington State Department of Transportation is implementing a Landslide Mitigation Action Plan to proactively address the climatic and other factors contributing to landslide-based rail closures.[132]

Landslides during winter storms have also closed major Interstates, such as the December 2015 closure of eastbound Interstate 90 near Snoqualmie Pass and the February 2017 closure of westbound Interstate 90 near Issaquah.

Wildfires can result in road and railway closures, reduced water quality in reservoirs, and impacts on the energy sector. The Goodell wildfire in August 2015 forced Seattle City Light to de-energize transmission lines around its Skagit River Hydroelectric Project for several days.[133] The combined impact of damages and lost power production totaled nearly $3 million (in 2015 dollars).[134] The Eagle Creek fire along the Washington–Oregon border in 2017 led to the closure of Interstate Highway 84 and an adjacent railway, likely increasing shipping costs and creating negative economic impacts on tourism and regional small businesses.[135]

Drought conditions also present challenges for infrastructure, especially water supplies. In Washington, the Department of Ecology allocated almost $7 million in drought relief funds in 2015 (in 2015 dollars). Relief grants were used to provide backup or emergency water supplies for irrigation or human consumption where wells were failing or pumping capacity was inadequate.[136] These small and typically rural systems are relatively more vulnerable to drought impacts when compared to larger urban systems (Ch. 10: Ag & Rural, KM 4).

Future Climate Change Relevant to Regional Risks

Climate change is expected to increase the frequency and/or intensity of many extreme events that affect infrastructure in the Northwest. Available vulnerability assessments for infrastructure show the prominent role that future extremes play. Since much of the existing infrastructure was designed and is managed for an unchanging climate, changes in the frequency and intensity of flooding, drought, wildfire, and heat waves affect the reliability of water, transportation, and energy services.

Hydrologic change will likely be an important driver of future climate stress on infrastructure. As higher temperatures increase the proportion of cold season precipitation falling as rain rather than snow, higher streamflow is projected to occur in many basins, raising flood risks.[137,138,139,140] An increased risk of landslides is also expected, as more mixed rain and melting snow events occur in low- to mid-elevation mountains.[141] Increases in the amount of precipitation falling in heavy rainfall events (including atmospheric rivers)[142] are anticipated to magnify these risks. Along the coast, sea level rise is projected to increase flood risks in low-lying areas and will likely magnify the potential for coastal erosion (Ch. 5: Land Changes) and infrastructure damage during extreme events with high storm surge and wave hazards. By the end of the century, the upper sea level rise projection of 4.3 feet[143] would impact significant infrastructure investments throughout the Northwest, particularly in the low-lying urban areas of the Puget Sound and Portland (Ch. 8: Coastal).

Multiple Climate Stressors Affect Vulnerable Infrastructure

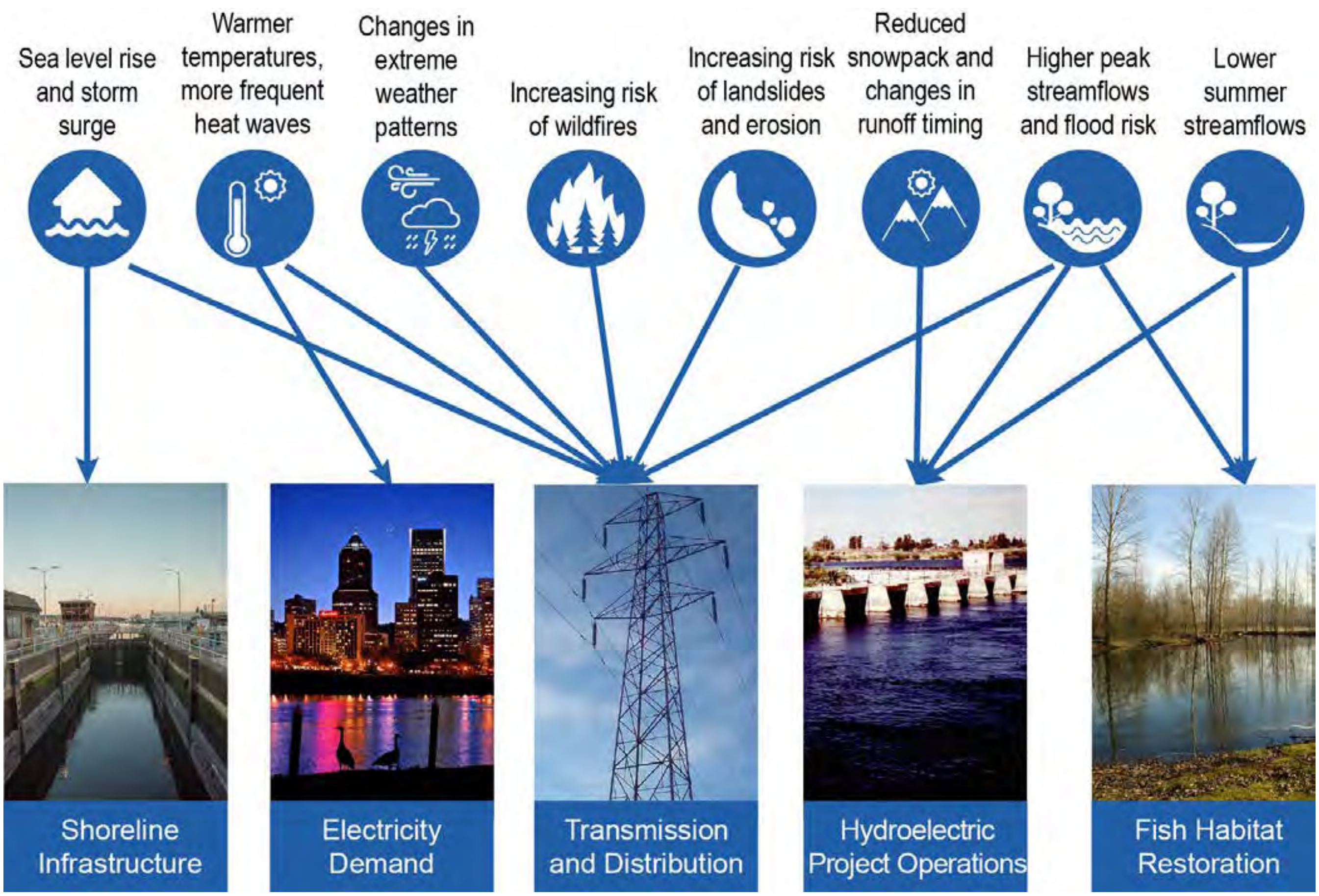


Figure 24.11: Extreme events such as floods, heat waves, wildfires, landslides, and drought play an important role in the vulnerability of infrastructure. The figure, from Seattle City Light's Vulnerability Plan,[133] illustrates how the utility's assets, operations, and management goals are affected by a broad range of climate impacts and extreme events. Adaptation strategies to increase the resilience of the energy system must focus on multiple potential risks as well as environmental considerations. Source: adapted from Raymond 2015.[133] Photo credits (from left to right): Emmet Anderson (Flickr, CC BY-NC 2.0), Justin Miller (Flickr, CC BY-NC 2.0), photojojo3 (Flickr, CC BY 2.0), U.S. Department of Energy, Rick Swart, Oregon Department of Fish & Wildlife.

Spring and summer streamflows are anticipated to decline in basins that have historically relied on snowmelt, and low flow periods are projected to be more prolonged and more severe. If observed declines in higher elevation precipitation continue,[144] this would exacerbate low streamflow conditions,[27] resulting in decreased water supply and reservoir storage. Climate change can affect water quality as well (Ch. 3: Water, KM 1). Higher air temperatures, lower streamflow, and decreases in rainfall are expected to raise summer stream temperatures, making it more difficult to meet water quality standards. In coastal areas, sea level rise will likely lead to saltwater intrusion into groundwater supplies.

Challenges, Opportunities, and Success Stories for Reducing Risk

Anticipated future impacts on infrastructure create opportunities for addressing existing environmental and social goals. For example, actions by the city of Boise, Idaho, to improve water quality are likely to minimize some of the impacts associated with a warmer climate. In Boise, a phosphorous removal facility reduces the amount of phosphorous entering rivers, thereby reducing the need for water treatment facility upgrades[145] and perhaps also preventing downstream algal blooms, which are anticipated to become more common in a warmer climate.

The Northwest has several examples of successful cross-sector collaboration between resource managers and scientists to plan and prepare for climate impacts across multiple sectors (Ch. 17: Complex Systems, KM 3). In Portland and Multnomah County, Oregon, the 2030 Climate Change Preparation Strategy and 2050 Climate Action Plan have incorporated strategies across multiple sectors including water systems, natural and built infrastructure, and human health, with specific social equity considerations woven throughout.[146,147] For many socially vulnerable populations, limited access to transportation, businesses, and other community resources can inhibit their ability to cope with climate impacts. Addressing these disparities can have the added benefit of bolstering resilience (see Key Message 5). Building and strengthening partnerships across sectors will continue to be important in addressing these complex challenges.

Infrastructure managers in larger urban areas like Seattle and Portland have invested in building climate resilience for their systems (e.g., Vogel et al. 2015, Mauger et al. 2015[139,148]) (see also Ch. 11: Urban, KM 4), often partnering with researchers to develop tailored climate risk information and adaptation strategies. However, in many parts of the Northwest, especially areas outside urban centers, the lack of redundancy within infrastructure systems will likely be an important factor in limiting adaptive capacity (Ch. 12: Transportation, KM 2; Ch. 10: Ag & Rural, KM 4). Understanding the risks associated with these systems remains a challenge, as impacts could emerge directly from climate events or from the interaction of non-climate and climate stressors (such as equipment failure making a water system more susceptible to subsequent drought). For example, in the Washington Department of Transportation's vulnerability assessment, lifeline roadways that serve as the only means to access communities often emerged as highly vulnerable.[149] Disruptions to these roadways could cut off communities, preventing supplies or first responders from arriving. The lack of redundancy in transportation networks has also been noted for several of the region's National Parks, contributing to their vulnerability.[141] In a similar vein, the Washington Department of Health is examining aspects of groundwater systems that contribute to climate vulnerability. They have found that many groundwater systems are single source and lack any back-up supplies (see Figure 24.12). If supplies are disrupted, either by climate or non-climate stressors, surrounding communities may be forced to transport water to their area or relocate to a place with a more reliable supply (Ch. 3: Water, KM 2).

An additional challenge in addressing future impacts to infrastructure is cost. Projects for replacing, retrofitting, or improving dams, reservoirs, pipelines, culverts, roadways, electrical transmission and distribution systems, and shoreline protection can have costs in the billions (e.g., Wilhere et al. 2017[150]).

Managing water in the face of a changing climate also presents an opportunity for transboundary collaboration and coordination. For the Columbia River, projections of future streamflow have been generated for use by U.S. federal agencies, in partnership with Canadian agencies.[151] The information about future hydrology can support infrastructure decisions about water supply management, flood risk management, and hydropower production (Ch. 3: Water, KM 3; Ch. 16: International, KM 4).

Emerging Issues

Infrastructure managers are beginning to consolidate planning for the combined risks of sea level rise, flooding, and seismic hazards, as well as tsunami risks that can also arise from a major earthquake event. Going forward, it could be useful to identify strategies that enhance community resilience and emergency

Single-Source Water Systems in Washington

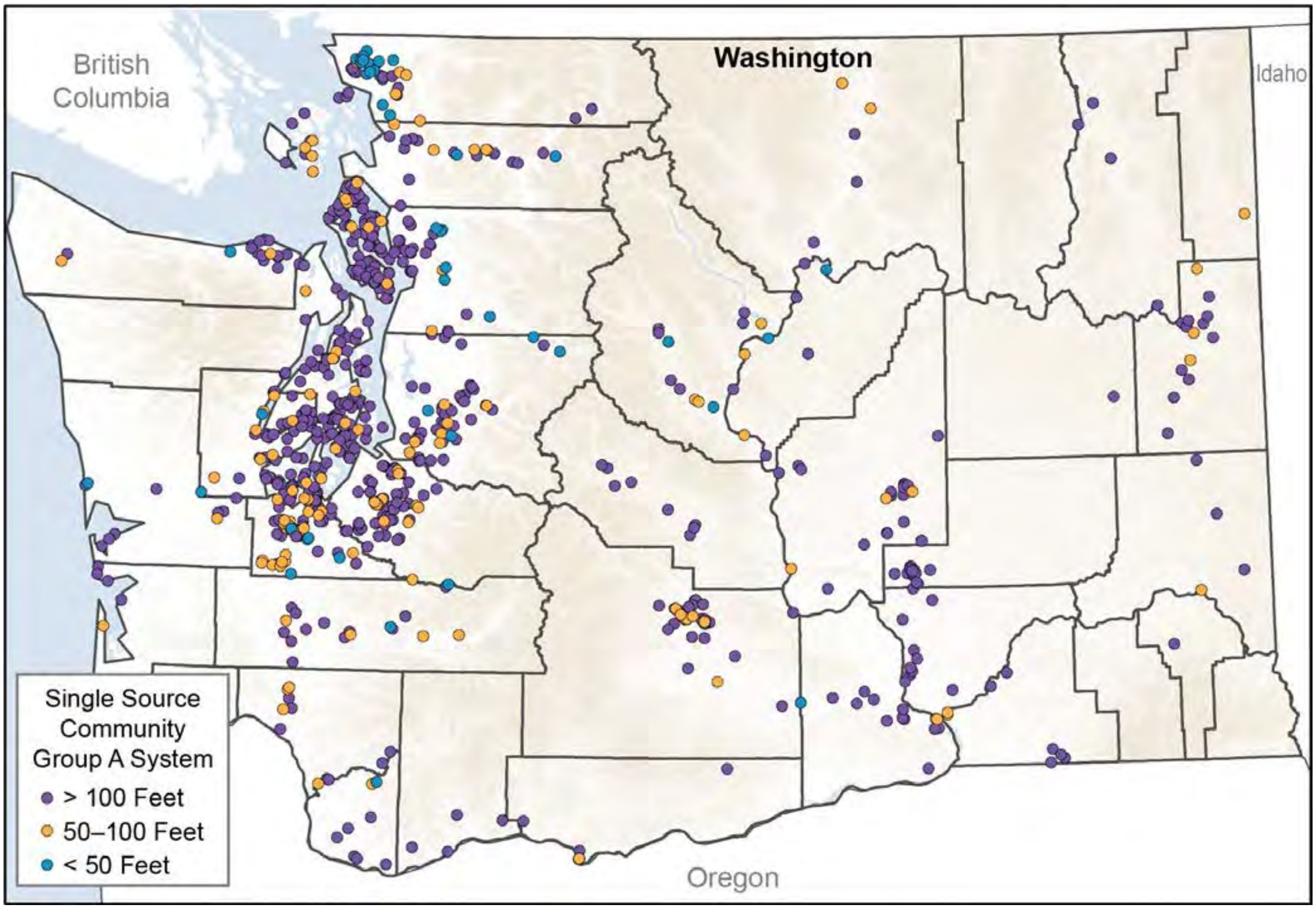


Figure 24.12: The map shows public water systems in Washington that are single source, meaning they lack a backup supply, and service at least 25 people per day or have 15 or more connections. Smaller public water systems exist but are not shown. For operators of single source systems, it will likely be particularly difficult to deal with climate-related disruptions such as flooding, drought, and saltwater intrusion. Approximate well depth is indicated by color; shallower wells (less than 100 feet in blue and orange) are projected to be more vulnerable to impacts, although aquifer type also influences vulnerability. Although similar impacts will likely occur in Oregon and Idaho, the data are not readily available to assess at a statewide level. Source: Washington Department of Health.

response capacity to many types of hazards and potential disruptions.

Infrastructure management is traditionally oriented to protecting assets and services in place. The use of "green" or hybrid "green and gray" infrastructure (e.g., Kittitas County Flood Control Zone District 2015, City of Portland 2010[152,153]) that utilizes nature-based solutions is emerging as a potential adaptation option. However, in some locations and for some impacts, it may be more efficient to remove or abandon infrastructure and find alternatives (for example, relocating communities and distributing water or energy systems). The knowledge and experience are just emerging to identify thresholds when such transformative decisions might be appropriate (Ch. 11: Urban, KM 3; Ch. 17: Complex Systems, KM 4).

Key Message 4

Health

Organizations and volunteers that make up the Northwest's social safety net are already stretched thin with current demands. Healthcare and social systems will likely be further challenged with the increasing frequency of acute events, or when cascading events occur. In addition to an increased likelihood of hazards and epidemics, disruptions in local economies and food systems are projected to result in more chronic health risks. The potential health co-benefits of future climate mitigation investments could help to counterbalance these risks.

Linkage Between Climate Change and Regional Risks

Over the last few decades, an increase in climate-related extreme events has led to an increase in the number of emergency room visits and hospital admissions. Warmer and drier conditions during summer have contributed to longer fire seasons.[140] Wildfire smoke can be severe, particularly in communities in the eastern Northwest.[154] Smoke events during 2004–2009 were associated with a 7.2% increase in respiratory hospital admissions among adults over 65 in the western United States.[155] In Boise, Idaho, 7 of the last 10 years have included smoke levels considered "unhealthy for sensitive groups" (including children) for at least a week during the fire season,[154] causing some cancellation of school-related sports activities (Ch. 13: Air Quality, KM 2).

During extreme heat events in King County, Washington, from 1990 to 2010, heat-related hospital admissions were 2% higher and deaths 10% higher than the average for that period,[156,157] with an increased demand for emergency medical services for children, outdoor laborers, and the elderly.[158] The state of Oregon has also recorded spikes in heat-related emergency room visits.[159] In particular, agricultural workers are at increased risks for heat-related injuries because they work outside during the summer harvest season.[160]

In the last several years, the region has seen an increase in some infectious diseases. An increase in Lyme disease cases is associated with rising temperatures and changing tick habitat.[161] The Washington Department of Health's vector surveillance program has observed an earlier onset of West Nile virus-carrying mosquitoes, likely associated with higher temperatures, and an increasing number of human infections, with some resulting in fatalities.[162] Before 1999, cryptococcal infections were limited to the tropics, but *Cryptococcus gatti*, the species that causes these infections, is now established in Northwest soil, with 76 cases occurring in Oregon in 2015.[163] The Oregon Health Authority recorded spikes in cases of Salmonella and *E. coli* during months with extreme heat in 2015.[163] A large outbreak of Shigellosis (a bacterial diarrheal disease) occurred in late 2015, affecting a large number of homeless people in the Portland Metro region; this outbreak was associated with unusually extreme precipitation.[164]

Changes in drought conditions and increased water temperatures have increased the potential for freshwater harmful algal blooms in recreational waters,[165] although there is little capacity among state health departments to monitor and track harmful algal blooms. Toxins from marine harmful algal blooms can accumulate in shellfish, leading to illnesses for those who eat them.[166] In 2015, during the largest harmful algal bloom ever observed off the West Coast from California to Alaska, high levels of domoic acid led to the closure of shellfish harvesting in much of the Northwest (Box 24.7).[167]

Children and youth, in general, will likely experience cumulative physical and mental health effects of climate change over their lifetimes[168] due to increased exposure to extreme weather events (such as heat stress, trauma from injury, or displacement) and increased toxic exposures (such as increased ground-level ozone pollution in urban areas or increased risk of drinking water contamination in rural areas). Beginning at the fetal development stage, environmental exposures to air or water pollution can increase the risk of impaired brain development,[169] stillbirth,[170] and preterm births.[171,172] Infants and children can be disproportionately affected by toxic exposures because they eat, drink, and breathe more in proportion to their body size.[173] Natural disasters, as well as gradual changes (like changing landscapes and livelihoods) caused by climate stressors, increase the risk of anxiety, depression, and post-traumatic stress disorder (PTSD).[174] Evidence shows that exposure to both pollution and trauma early in life is detrimental to near-term health, and an increasing body of evidence suggests that early-childhood health status influences health and socioeconomic status later in life.[175,176]

Future Climate Change Relevant to Regional Risks

More frequent wildfires and poor air quality are expected to increase respiratory illnesses in the decades to come (Ch. 13: Air Quality, KM 2). Airborne particulate levels from wildfires are projected to increase 160% by mid-century under a lower scenario (RCP4.5),[177] creating a greater risk of smoke exposure through increasing frequency, length, and intensity of smoke events.[177]

Projected increases in ground-level ozone (smog), small particulate matter ($PM_{2.5}$), and airborne allergens[178] can further complicate respiratory conditions (Ch. 13: Air Quality, KM 1). There is a well-documented link between exposure to air pollution and risk of heart attack, stroke, some types of cancer, and respiratory diseases,[179] all of which are leading causes of death in the Northwest.[180] The portion of each health condition attributed to air pollution is unknown, but the social and economic costs of these diseases are large. In Oregon, the medical costs associated with heart attacks in 2011 alone were over $1.1 billion, and those associated with stroke were $254 million ($1.2 billion and $269 million, respectively, in 2015 dollars).[181]

Increases in average and extreme temperatures are projected to increase the number of heat-related deaths.[182,183] Mid-century climate in Portland, Oregon, under a mid-high scenario (RCP6.0) may result in more than 80 additional heat-related deaths per year, although this figure does not account for future population growth or possible adaptations.[184]

Future extreme precipitation events could increase the risk of exposure to water-related illnesses as the runoff introduces contaminants and pathogens (such as *Cryptosporidium, Giardia*, and viruses) into drinking water.[185] In the Puget Sound, under a mid-high emissions scenario (SRES A1B), local atmospheric heating of surface waters is projected to result in 30 more days per year that are favorable to algal blooms and an increased rate of bloom growth.[186]

Income loss associated with climate impacts will likely increase the risk of people experiencing food insecurity (see Key Message 1).[187] As an example, in early 2016 a harmful algal bloom impacted the local economy in Long Beach, Washington, which is largely dependent on shellfish, tourism, and service industries. The local Food Bank recorded an almost 25% increase in the number of families requesting assistance in the six months that followed.[188] Climate-driven hardships can also affect mental health, resulting in outcomes ranging from stress to suicide.[189] Oregon, Washington, and Idaho all rank among the top 10 states in terms of prevalence of mental illness and lowest access to mental health care.[190] Serious mental illness costs the U.S. economy more than $193 billion in lost earnings each year ($224 billion in 2015 dollars).[191] Tribes and Indigenous peoples face multiple physical and mental health challenges related to climate change, with impacts to subsistence and cultural resources (see Key Messages 2 and 5) (see also Ch. 15: Tribes, KM 2). Some of these health concerns are described in a recent project created by members of the Confederated Tribes of Warm Springs.[192] Tracking climate stressors and training related to climate anxiety and post-disaster trauma is not widespread among the region's health workforce.[193]

Challenges, Opportunities, and Success Stories for Reducing Risk

Existing environmental health risks are expected to be exacerbated by future climate conditions,[187] yet over 95% of local health departments in Oregon reported having only partial-to-minimal ability to identify and address environmental health hazards.[194]

With funding from the Centers for Disease Control and Prevention, Oregon has been able to make some headway on assessing climate change vulnerabilities[195] and recently released a statewide climate and health resilience plan.[196] Five local health jurisdictions in Oregon are some of the first in the country to complete local climate and health adaptation plans. Interventions to address community-identified priorities range from providing water testing for domestic well users in drought-prone areas to quantifying the health co-benefits of proposed transportation investments. The Washington Department of Health has also added a climate program to begin integrating climate considerations into the state's public health system. In addition, the Drinking Water State Revolving Fund has made it possible for water system managers and utilities to apply for low interest loans that support resilience projects. Washington's Marine Biotoxin Program, also housed within the Department of Health, operates an early warning system in partnership with academics, organizations, and citizen scientists to increase the geographic breadth and frequency of sampling for harmful algal blooms that could compromise the safety of shellfish. Public health practitioners in southeastern Idaho have formed a new working group with tribes, universities, local jurisdictions, businesses, and nonprofits to develop strategies for mitigating health impacts of wildfire smoke and water insecurity.

Together, Northwest states have launched the Northwest Climate and Health Network for public health practitioners to share resources and best practices. Idaho, Oregon, and Washington all have syndromic surveillance systems that provide near-real-time data from emergency room visits. These health data have the potential to be layered with climate and environmental data (such as temperature and air quality data), but such analysis has not been carried out on a broad scale.

Incorporating more health and wellness considerations into climate decision-making can increase a community's overall resilience (Ch. 14: Human Health, KM 3). For example, preserving the ecological functions of an area can also promote tribal and Indigenous health, while investing in active transportation and green infrastructure can also improve air quality and increase physical activity.[197]

Box 24.4: Healthcare Partnerships That Increase Resilience

A new International Transformational Resilience Coalition (ITRC) has grown out of the Northwest and is engaging cross-sector partners in pilot projects to build psycho-social resilience in some communities. The initiative uses neuroscience and mindfulness to train leaders and organizations on how to cope with, and use, climate-related adversities to catalyze collective adaptation.[193] Composed of more than 250 mental health, trauma treatment, resilience, climate, and other professionals, the ITRC is working to enhance the ability of organizations and communities to heal, grow, and flourish during economic, social, and environmental stress and adversity.

Figure 24.13: Participants at the 2017 Northwest International Transformational Resilience Coalition Conference on Building Psycho-Social Resilience to Climate Change. Photo Credit: The Resource Innovation Group/International Transformational Resilience Coalition.

Emerging Issues

Communities with higher rates of illness and death often have less adaptive capacity and are more vulnerable to climate stressors.[198] Many people living in the Northwest already struggle to meet basic needs that could serve as protective factors—and these numbers could increase. For example, roughly 1 in 5 children in the region live in a food-insecure household[199,200,201] and are already at higher risk of poor health outcomes like asthma and diabetes.[202] Both the states of Washington and Idaho have had some of the largest increases in homeless populations in the United States, and in 2016, Oregon had the highest rate of unsheltered homeless families with children.[203] People lacking adequate shelter face increased climate risks (such as direct exposure to extreme heat or winter storms) while also having increased vulnerability (such as poorer health and less access to resources).

Displacement and increased migration to the Northwest could place increasing pressures on housing markets, infrastructure, and health and social service systems.[128] However, the role of climate as a driver for migration to the Northwest is speculative; current population forecasts do not yet account for climate factors.[204]

Public health leaders in the Northwest are working to modernize health systems to better respond to and prepare for complex and emerging health risks. Coordinated Care Organizations (CCOs) in Oregon, which serve as Medicaid insurance providers, are beginning to invest in certain climate protections for members. For example, some are covering the cost of air conditioning units for patients at risk of heat-related illnesses, ensuring patients can remain in their homes.[205] More studies would be needed to fully account for the cost savings associated with these kinds of health-related services.

Key Message 5

Frontline Communities

Communities on the front lines of climate change experience the first, and often the worst, effects. Frontline communities in the Northwest include tribes and Indigenous peoples, those most dependent on natural resources for their livelihoods, and the economically disadvantaged. These communities generally prioritize basic needs, such as shelter, food, and transportation; frequently lack economic and political capital; and have fewer resources to prepare for and cope with climate disruptions. The social and cultural cohesion inherent in many of these communities provides a foundation for building community capacity and increasing resilience.

Linkage Between Observed Climate and Regional Risks

Because people care about the place they live, a focus on places serves to highlight the local material and symbolic contexts in which people create their lives and through which those lives derive meaning.[206,207] This is true for communities across the Northwest whether or not they are on the frontline of dealing with climate change. While there are many types of frontline communities (those communities likely to experience climate impacts first and worst) in the region, this chapter highlights three sets of communities: tribes (Ch. 15: Tribes), farmworkers, and low-income populations in urban and rural (Ch. 10: Ag & Rural) environments.

The effects of climate variability and extreme events are not felt equally across communities in the Northwest. Frontline communities have higher exposures, are more sensitive, and are less able to adapt to climate change for a variety of reasons (Ch. 14: Human Health, KM 1),[187,208,209] including enhanced occupational exposure,[210] dependence on natural and cultural resources (Ch. 15: Tribes, KM 1),[124] fewer economic resources,[209] other demographic factors,[211,212] and gender.[213] In addition, frontline communities frequently must overcome cumulative exposures[125] and intergenerational and historical trauma.[125,214] It is the interconnected nature of legacy exposure, enhanced exposure, higher sensitivity, and less capability to adapt that intensifies a community's climate vulnerability.[187,215,216] Climate change can affect the health, well-being, and livelihoods of these communities directly by increasing the risk of acute health impacts, such as physical injury during severe weather,[189,209] and indirectly through chronic impacts, such as food insecurity or mental health conditions like PTSD (see Key Message 4) (see also Ch. 15: Tribes, KM 2; Ch. 14: Human Health, KM 1).

Future Climate Change Relevant to Regional Risks

Frontline communities generally prioritize meeting existing basic needs, such as shelter, food, and transportation. While climate-related risks vary from community to community, neighborhood to neighborhood, and even person to person, for frontline communities, climate variability, change, and extreme events can exacerbate existing risks, further limiting their ability to meet basic needs.[217]

Northwest tribes directly depend on natural resources, both on and off reservations, and are among the first to experience climate impacts. In the United States, the history of colonization, coupled with ongoing management barriers (such as land fragmentation and limited authority and control over natural resources), has led to many challenges for tribal and Indigenous climate adaptation (see Box 24.5) (see also Ch. 15: Tribes, KM 3).[124,218] The loss or reduced availability of First Foods (Key Message 2) can have broad physical, cultural, and spiritual impacts, including diabetes, heart disease, mental health impacts, and loss of cultural identity.[125,209] This is likely to be coupled with mental health impacts associated with intergenerational and historical trauma, alcohol abuse, suicide, and other impacts (see Key Message 2) (see also Ch. 15: Tribes, KM 2).[209]

Farmworkers are vital to the region, yet they often earn very low wages and face discrimination and workplace hazards. Farmworkers and their families often deal with both chronic and acute health impacts because of the high cost of healthcare and physically demanding work environments. Overall, farmworkers, who are largely immigrant laborers from Mexico, Central America, and South America, face distinct challenges and are more vulnerable due to structural causes that can lead to exploitation, discrimination, and violence.[219] Climate change is projected to exacerbate these existing stressors.

While the Northwest is not typically considered a high-risk area for heat-related illness, heat waves (defined as 5-day, 1-in-10-year events) across the country are projected to increase in frequency and intensity.[3] In the Northwest, nighttime heat waves (defined as 3-day, 1-in-100-year events) have a greater influence on human health than daytime heat waves [220] and have increased in frequency since 1901.[221] These changes are projected to make heat-related illness more common in the future. Farmworkers can be particularly vulnerable to heat-related illness due to occupational exposure (heavy exertion and working outdoors)[210] and to air quality concerns associated with wildfires, yet they often do not seek healthcare because of high costs, language barriers, and fear of deportation.[222] Working conditions, as well as cooling and hydration practices, vary across the region.[223]

In urban environments, economically disadvantaged communities and communities of color live in neighborhoods with the greatest exposure to climate and extreme weather events [224] and are, therefore, disproportionately affected by climate stressors.[225,226] Urban heat islands, worsening air quality,[227] less access to transit, increasing demands for food and energy, and proximity to pollution sites can lead to injury, illness, and loss of life for the urban poor (Key Message 4).[225,228] For instance, in the Northwest, increased risk of heat-related illnesses and deaths has been associated with socioeconomic status, age, race, and occupation (for example, outdoor labor).[156,182,229]

Challenges, Opportunities, and Success Stories for Reducing Risk

Many frontline communities are taking actions that begin to address these challenges. Indigenous peoples and Northwest tribes have demonstrated a high degree of resilience by adapting to changing environmental and social conditions for thousands of years (Ch. 15: Tribes).[124] The strong social networks and connectivity, present in many tribes and Indigenous communities, can reduce vulnerability to climate change (Ch. 15: Tribes, KM 3).[230] Efforts to enhance communication and strengthen network connections between tribes and their partners can be seen across the region.

Box 24.5: Collaborations Can Use Existing Social Cohesion to Build Resilience

Social cohesion, social networks, and other forms of social capital can help communities be more resilient to climate change.[231] The Pacific Northwest Tribal Climate Change Network is a regional collaboration aimed at supporting tribal and Indigenous climate resilience by better understanding and communicating the impacts of climate change on Indigenous peoples, tribal sovereignty, and culture. The Network does this by sharing resources such as case studies, tools, and funding opportunities through the Online Tribal Climate Change Guide (https://tribalclimateguide.uoregon.edu/); bringing together a diverse group of tribes, agencies, and nonprofit and private sector organizations; and discussing key actions and initiatives that are building resilience among tribes in the region.

Figure 24.14: Social cohesion and social networks can help communities adapt to changing climate conditions. One example is the Pacific Northwest Tribal Climate Change Network (https://tribalclimate.uoregon.edu/). The Network provides a forum for tribes to work together and with universities, federal agencies, and private and nonprofit organizations to share information, strengthen connections, and build resilience through events such as the 2017 Tribes and First Nations Climate Summit (http://atnitribes.org/climatechange/events/) hosted by the Tulalip Tribes and co-sponsored by the Affiliated Tribes of Northwest Indians, the North Pacific Landscape Conservation Cooperative, and the Pacific Northwest Tribal Climate Change Project. Photo credit: Peggy Harris, Affiliated Tribes of Northwest Indians.

Acknowledging the risk of heat-related illness for outdoor workers, the state of Washington issued rules requiring employers to make specific changes to job sites during the summer season (from May 1 through September 30). For temperatures above certain thresholds, the employer is required to provide at least one quart of water per employee per hour, relieve employees from duty if they are showing signs of heat-related illness, and provide training for employees and supervisors about heat-related illness.[232]

Economically disadvantaged populations and communities of color often face multiple barriers to participating in public processes where decisions about future climate-related investments are made. Organizations representing these frontline communities have found some success prioritizing leadership development through workshops and training that enable new and emerging voices to be heard in more formal policy settings. Engagement has partly been made possible by providing transportation, childcare, meals, and accessibility and by using a relational worldview and trauma-informed approach to community capacity-building. Cities and counties have also made concerted efforts at the policy level to explicitly acknowledge and address race and social inequities alongside environmental concerns.[147,228,233,234,235] Example actions include targeting investments in frontline communities and providing job training and employment opportunities that help limit displacement and enhance resilience.[147]

Box 24.6: Community Organizations Empower Frontline Communities

Community-based organizations in the Northwest's two most urban centers, Seattle and Portland, have engaged communities of color to assess priorities for building climate resilience. Our People, Our Planet, Our Power[236] and Tyee Khunamokwst: Leading Together[237] both emphasize that any efforts to build climate resilience will be undermined if low-income people and people of color continue to be displaced. Both community-driven efforts indicate strong support for strategies that reduce emissions and simultaneously build community resilience, such as increasing access to active transportation options and installing green infrastructure within under-resourced communities. The cities of Seattle and Portland have made progress in placing equity more centrally in municipal climate planning. The Portland-Multnomah Climate Action through Equity report[147] documents how these efforts led to a more inclusive and accountable climate action plan, and the Seattle Equity & Environment Agenda[228] articulates current disparities and a commitment to ensuring that people most affected by environmental injustices have a strong voice in finding solutions moving forward.

Emerging Issues

There is an emerging understanding of the importance of not only prioritizing climate change preparedness efforts in frontline communities but also involving and empowering these groups in the decision-making and implementation of climate change plans and actions.

The physical and psychological connections people have with natural resources are complex, and additional research would aid understanding of how changing climate conditions are likely to affect not only those natural resources but also the people who depend on them. How intersecting vulnerabilities, driven by a confluence of climatic, social, and economic factors, will compound and accelerate risks in frontline communities is not yet fully understood (Ch. 17: Complex Systems, KM 1). Additional research would help to measure and evaluate how supporting frontline communities in the implementation of community-identified strategies might improve outcomes and increase not only climate resilience but also equity and economic vitality in the Northwest and across the country.

Box 24.7: 2015—A Prelude of What's to Come?

In 2015, the Northwest experienced its warmest year on record.[238] Severe drought, large wildfires, heat waves (on land and in the ocean), and record harmful algal blooms occurred. An exceptionally warm winter led to record-low mountain snowpack across the region as precipitation fell largely as rain instead of snow.[9] The lack of snowpack and a dry spring led to dry fuel conditions that primed the largest wildfire season recorded in the region.[239]

Extreme climate variability provides a preview of what may be commonplace in the future.

In the Northwest, 2015 temperatures were 3.4°F above normal (as compared to the 1970–1999 average),[238] with winter temperatures 6.2°F above normal.[240] The warm 2015 winter temperatures are illustrative of conditions that may be considered "normal" by mid-century (higher scenario, RCP8.5) or late century (lower scenario, RCP4.5).[11]

Winter, spring, and summer precipitation during 2015 for the Northwest were below normal (as compared to the 1970–1999 average) by 25%, 35%, 14%, respectively (NOAA 2017).[241,242,243] Precipitation from January to June 2015 was the 7th driest on record for the region (4.6 inches below the 20th century average).[244] In general, most climate models project increases in future Northwest winter and spring precipitation with decreases in the summer, although some models project increases and others decreases in each season.[11] The 2015 spring precipitation deficits are similar to the largest decreases (−34%) in summer precipitation projected for the end of the century (2070–2099) under a higher scenario (RCP8.5).[11]

Snowpacks in Oregon and Washington in 2015 were the lowest on record at 89% and 70% below average, respectively.[9] These levels are more extreme than projected under the higher scenario (RCP8.5) by end of century (65% below average).[245] However, with continued warming, this type of low snowpack drought is expected more often. For example, the 2015 extreme low snowpack conditions in the McKenzie River Basin (which sits largely in the middle elevation of the Oregon Cascades) could occur on average about once every 12 years under 3.6°F (2.0°C) of warming.[246] For each 1.8°F (1°C) of warming, peak snow-water equivalent in the Cascades is expected to decline 22%–30%.[247]

What happened? How were systems tested? What vulnerabilities were highlighted?

Impacts from the 2015 "snow drought" were widespread, including irrigation shortages, agricultural losses, limited snow- and water-based recreation, drinking water quality concerns, hydropower shortages, and fish die-offs from impaired stream water quality. Many farmers received a reduced allocation of water, and irrigation water rights holders had their water shut off early; senior water rights holders had their water shut off early for the first time ever.[248] For example, Treasure Valley farmers in eastern Oregon received only a third of their normal irrigation water because the Owyhee Reservoir received inadequate river inflows to fill the reservoir for the third year in a row.[249]

Box 24.7: 2015—A Prelude of What's to Come? *continued*

Agricultural-related impacts of the drought were numerous, including damaged crops, reduced yields, altered livestock management, fewer planted crops, and land left idle (for example, 20% of farm acres in Treasure Valley, Oregon, were left idle).[248] Estimated agricultural economic losses were between $633 million and $773 million in Washington, including losses of over $7.7 million in blueberries, nearly $14 million in red raspberries, $500 million in a selection of 15 crops that make up more than three-quarters of Washington's cultivated acreage, and more than $33 million in the dairy industry (losses reported in 2015 dollars).[250]

Low-elevation ski areas struggled to stay open during the 2014–2015 season. Hoodoo Ski Area in the Oregon Cascades had its shortest season in 77 years of operations after closing for the season in mid-January;[246] Stevens Pass Mountain Resort in Washington's North Cascades only opened for 87 days, down from an average of 150;[251] and Silver Mountain Resort in Idaho closed its ski lifts by the end of March, a month earlier than usual.[252] Summer water recreation also suffered. Visitation at Detroit Lake, a reservoir in the Cascade foothills, decreased by 26% due to historically low water levels—70 feet (21 meters) below reservoir capacity in July—and unusable boat ramps.[246,253]

Low summer stream levels and warm waters, which amplified a naturally occurring fish disease, resulted in widespread fish die-offs across the region, including hundreds of thousands of sockeye salmon in the Columbia and Snake River Basins.[136,248,254] And for the first time ever, Oregon implemented a statewide daily fishing curtailment beginning in July 2015 to limit added stress on the fish from fishing.[248]

The lack of snowpack in 2015 in concert with extreme spring and summer precipitation deficits led to the most severe wildfire season in the Northwest's recorded history with more than 1.6 million acres burned across Oregon and Washington, incurring more than $560 million in fire suppression costs (in 2015 dollars).[239] In Oregon, the cost of large fires in 2015 was 344% of the 10-year average of large-fire costs.[248] The wildfire season resulted in transmission shutdowns for Seattle City Light during the Goodell Fire (see Key Message 3) and infrastructure damage for Idaho Power Company following the Soda Fire.[255] Smoke from the wildfires caused significant air quality and health concerns from late July through September, particularly in eastern Oregon and Washington, Idaho, Colorado, and Canada.[256,257]

The ocean heat wave referred to as "the Blob" was first detected off the Pacific coast in 2013, and by 2014 it spanned the coast from Alaska to California.[10] In 2015, the largest harmful algal bloom recorded on the West Coast was associated with the Blob. High levels of multiple toxins, including domoic acid and paralytic shellfish toxins, closed a wide range of commercial, recreational, and tribal fisheries, including salmon, shellfish, and Dungeness crab along the entire Northwest coast.[172,258,259,260]

Box 24.7: 2015—A Prelude of What's to Come? *continued*

Who is doing what to increase resilience? What success stories are there?

The conditions in 2015 tested the capacity of existing systems and provided insights into potential future adaptation priorities. Several actions to increase resilience have already begun across multiple levels of governance. For example, the Oregon Drought Task Force was created to "review the State's existing drought response tools, identify potential gaps, and make recommendations on tools and information needed to ensure that the State is prepared to respond during a drought in the future."[261] Washington assessed the economic impact on agriculture and recommended developing a plan "to assist growers and plan for a future that will include increased incidence of severe weather events such as the 2015 drought."[250]

At the onset of the drought, anticipated agricultural losses were much higher than what occurred because of actions at the federal and state levels, and actions implemented by the farmers themselves (Box 24.1).[250] This highlights the adaptive capacity of some producers in the agricultural sector (Key Message 1). However, as conditions experienced in 2015 become more regular as a result of climate change, some farms will likely struggle to stay solvent despite adaptation interventions (Ch. 10: Ag & Rural, KM 1).[250]

After the lack of snow during the previous winter season prevented Mount Ashland Ski Area in southwest Oregon from opening at all, the ski area instituted several adaptation strategies that helped it open and stay open during the 2015 busy winter holidays. Strategies included snow-harvesting and thinning vegetation, among others. Future plans include diversifying the business by creating more summer recreation opportunities, so that the ski area's revenue depends less on snow-related recreation.[249]

In the Yakima Basin, irrigators, conservation groups, and state and federal agencies worked together to replenish the diminished tributary flows to bolster the salmon runs and riparian habitat during the drought. Water from the Yakima River was redirected through farm irrigation canals to seven tributaries. Although this further reduced the farmers' irrigation water, they agreed to continue rerouting water to sustain the fish.[262]

Acknowledgments

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Opening Image Credit
Sawtooth National Forest, Idaho. Photo credit: Mark Lisk/USDA Forest Service.

Traceable Accounts

Process Description

This assessment focuses on different aspects of the interaction between humans, the natural environment, and climate change, including reliance on natural resources for livelihoods, the less tangible values of nature, the built environment, health, and frontline communities. Therefore, the author team required a depth and breadth of expertise that went beyond climate change science and included social science, economics, health, tribes and Indigenous people, frontline communities, and climate adaptation, as well as expertise in agriculture, forestry, hydrology, coastal and ocean dynamics, and ecology. Prospective authors were nominated by their respective agencies, universities, organizations, or peers. All prospective authors were interviewed with respect to the qualifications, and selected authors committed to remain part of the team for the duration of chapter development.

The chapter was developed through technical discussions of relevant evidence and expert deliberation by the report authors at workshops, weekly teleconferences, and email exchanges. The author team, along with the U.S. Global Change Research Program (USGCRP), also held stakeholder meetings in Portland and Boise to solicit input and receive feedback on the outline and draft content under consideration. A series of breakout groups during the stakeholder meetings provided invaluable feedback that is directly reflected in how the Key Messages were shaped with respect to Northwest values and the intersection between humans, the natural environment, and climate change. The authors also considered inputs and comments submitted by the public, interested stakeholders, the National Academies of Sciences, Engineering, and Medicine, and federal agencies. For additional information on the overall report process, see Appendix 1: Process. The author team also engaged in targeted consultations during multiple exchanges with contributing authors for other chapters, who provided additional expertise on subsets of the Traceable Accounts associated with each Key Message.

The climate change projections and scenarios used in this assessment have been widely examined and presented elsewhere[11,50,263,264] and are not included in this chapter. Instead, this chapter focuses on the impact of those projections on the natural resources sector that supports livelihoods (agriculture, forestry, fisheries, and outdoor recreation industry), the intangible values provided by the natural environment (wildlife, habitat, tribal cultures and well-being, and outdoor recreation experiences), human support systems (built infrastructure and health), and frontline communities (farmworkers, tribes, and economically disadvantaged urban communities). The literature cited in this chapter is largely specific to the Northwest states: Washington, Oregon, and Idaho. In addition, the authors selected a series of case studies that highlight specific impacts, challenges, adaptation strategies and successes, and collaborations that are bringing communities together to build climate resilience. The most significant case study is the 2015 case study (Box 24.7), which cuts across all five Key Messages and highlights how extreme climate variability that is happening now may become more normal in the future, providing important insights that can help inform and prioritize adaptation efforts.

Key Message 1

Natural Resource Economy

Climate change is already affecting the Northwest's diverse natural resources (*high confidence*), which support sustainable livelihoods; provide a robust foundation for rural, tribal, and Indigenous communities; and strengthen local economies (*high confidence*). Climate change is expected to continue affecting the natural resource sector (*likely*, *high confidence*), but the economic consequences will depend on future market dynamics, management actions, and adaptation efforts (*very likely*, *medium confidence*). Proactive management can increase the resilience of many natural resources and their associated economies (*very likely*, *medium confidence*).

Description of evidence base

Multiple studies suggest that Northwest natural resource sectors will likely be directly affected by climate change, including increased temperatures, changes in precipitation patterns, and reduced snowpack (see NOAA State Climate Summaries for Oregon, Washington, and Idaho).[265,266,267] The direct and indirect consequences of these climate drivers are projected to impact regional natural resource sectors in varied ways. In many cases, the secondary and tertiary effects of climatic changes have larger consequences on the natural resource sector, such as increased insect and pest damage to forests,[41] increased wildfire activity,[8] changes to forage quality and availability for livestock,[38,39,40] reductions in water availability for irrigation and subsequent impacts to water rights,[268,269] and increasing temperatures and ocean acidity limiting the viability of existing commercial and recreational fisheries;[30,55,56,57] lower snowfall is also expected to reduce the economic benefits associated with the recreational skiing industry.[19,58]

There is good evidence that natural resource managers are attempting to build more resilient production systems in the face of climate change through the adoption of adaptation practices (see Box 24.1), particularly those that build soil resources to increase resilience in the face of more extreme and variable weather; however, in some cases not all adaptation strategies will necessarily lead to broader soil benefits.[270,271] There is also evidence that adaptive strategies coupled with increased warming will likely shorten the growing season in some parts of the Northwest due to earlier crop maturation, coupled with earlier plantings, leading to lower irrigation demand during low flow periods.[34] Forest managers are also incorporating adaptation strategies focused on addressing drought and fire risks as well as broader efforts to protect and maintain key forest ecosystem services.[67] While adapting to changing ocean conditions is challenging,[83] some in the industry are improving monitoring and hatchery practices to reduce risks.[82] And some in the outdoor recreation industry are looking for ways to benefit from increased temperatures;[88] for instance, many ski resorts are diversifying their recreational opportunities to take advantage of warmer weather and earlier snowmelt.[272,273]

Yet, how individual actors respond to changes in climate is a source of uncertainty, particularly if these actions do not reduce climate risks or capitalize on potential benefits as expected.[64] Additionally, many adaptive actions, at least in the short term, will likely be costly for individual producers to implement.[37,274]

Major uncertainties

Climate impacts, such as increased temperatures, reduced snowpack, and more variable precipitation and subsequent impacts on pests, disease, fire incidence, and other secondary impacts will very likely indirectly affect livelihoods and the economic viability of natural resource sectors, with more severe impacts to rural, tribal, and Indigenous communities (Ch. 10: Ag & Rural). There is, however, greater uncertainty as to how precisely these impacts are projected to affect natural resource managers' financial security and their subsequent land-use decisions (Ch. 5: Land Changes), as well as other factors important to sustainable livelihoods and community well-being.

This is particularly relevant for key commodities that are integrated with national and international markets that are influenced by multiple factors and are difficult to predict (Ch. 10: Ag & Rural; Ch. 16: International). National and global market dynamics will likely be influenced by broader climate change effects on other natural resource sectors in the United States and across the globe,[50] while also being impacted by a broad array of factors that include technological developments, laws, regulations and policies affecting trade and subsidies, and security issues. There are instances where the economic consequences will likely be positive, particularly in comparison to other regions in the United States, such as found in the dairy production sector.[65] The economic impacts to regional fisheries are much less certain as iconic species and industries in the Northwest struggle to maintain viability.[51,52,53] Although much is being researched with respect to the effects of climate change on forests and associated ecosystem services (e.g., Vose et al. 2016[275]), far less has been explored with respect to timber markets and attendant infrastructure and processing.

Description of confidence and likelihood

There is *high confidence* that climate change, through reductions in snowpack, increased temperatures, and more variable precipitation, is already affecting the Northwest's diverse natural resource base. There is *high confidence* that these natural resource sectors provide critical economic benefits, particularly for rural, tribal, and Indigenous communities who are more dependent on economic activities associated with natural resource management. There is *high confidence* that climate change will have a large impact on the natural resource sector throughout this century; however, there is *medium confidence* that these impacts will negatively impact rural, tribal, and Indigenous livelihoods, particularly about how projected changes will economically impact specific natural resource sectors due to large uncertainties surrounding global market dynamics that are influenced by climatic and non-climatic factors. It is *very likely* that proactive management efforts will be required to reduce climate risks, yet there is *medium confidence* that these adaptation efforts will adequately reduce negative impacts and promote sector-specific economic benefits.

Key Message 2

Natural World and Cultural Heritage

Climate change and extreme events are already endangering the well-being of a wide range of wildlife, fish, and plants (*high confidence*), which are intimately tied to tribal subsistence culture (*very high confidence*) and popular outdoor recreation activities (*high confidence*). Climate change is projected to continue to have adverse impacts on the regional environment (*very likely*), with implications for the values, identity, heritage, cultures, and quality of life of the region's diverse population (*high confidence*). Adaptation and informed management, especially culturally appropriate strategies, will likely increase the resilience of the region's natural capital (*medium confidence*).

Description of evidence base

Since the Third National Climate Assessment, there have been significant contributions within the literature in relation to climate impacts to Northwest communities, with specific focus on how values and activities, such as recreation, iconic wildlife, management, and tribal and Indigenous cultures, will likely be impacted.

Wildlife are projected to have diverse responses to climate change.[94,96,121] Droughts, wildfires, reduced snowpack and persistence, shifted flood timing, and heat stress can cause habitat loss or fragmentation[84] and increase mortality of waterfowl; trout, salmon, and other coldwater fish;[52,98,276,277,278] amphibians; wolverines; lynxes; and snowshoe hares.[94] Other species, such as elk and deer, may benefit from future climate conditions.[96]

Multiple studies also demonstrate that climate change impacts will likely affect other iconic, Northwest species. Wildfires will affect berries, roots, and plants;[85,105] ocean acidification is increasing shellfish mortality, and ocean acidification and warmer ocean temperatures are altering marine food webs;[279,280,281] and aquatic acidification is affecting salmon physiology and behavior.[282] These impacts are project to have direct negative impacts on traditional Sacred First Foods.[85,86] Droughts and reduced snowpack will also reduce tribal water supplies.[101,283] The loss of these First Foods is projected to have cascading physical health impacts, such as diabetes,[125] and mental health impacts.[124,125,189,209,214]

Salmon is one of the most iconic Northwest species and important First Foods for Tribes. Salmon are at high risk to climate change because of decreasing summer flows due to changes in seasonal precipitation and reduced snowpack,[284,285,286,287,288] habitat loss through increasing storm intensity and flooding,[100,287] physiological and behavioral sensitivity and increasing mortality due to warmer stream and ocean temperatures, and cascading food web effects due to ocean acidification.[29,281,289,290] These impacts can be amplified due to human-placed impediments (culverts, dams), contaminants, and diseases.[291,292,293]

There are multiple lines of evidence verifying that reduced snowfall and snowpack in the future will adversely impact winter and snow-based recreation, including a reduction in ski visitation rates.[19,58,91] This will also adversely affect summer water-based recreation such as boating and rafting,[277] although warmer temperatures in the future can increase demand for water-based recreation and visitations rates to parks.[88,89,90] Future habitat shifts in marine species[51] and warmer ocean temperatures are projected to lead to declines in opportunities for ocean fishing recreation.[55,56,57,294] Ocean acidification and harmful algal blooms are also projected to reduce recreational shellfish gathering.[55] Increased wildfire frequency[8] will reduce air quality, and some evidence suggests that this can reduce outdoor recreation opportunities and enjoyment. Regional case studies highlight climate impacts to snow-based recreation, ocean fishing, water-based recreation, and decreased air quality.[28,53,276]

Adaptation and management strategies in response to climate impacts on the natural capital and Northwest heritage are extremely varied across the region. Many tribes have begun managing First Foods and other important cultural resources through climate change vulnerability assessments and adaptation plans that incorporate both traditional knowledge and western science.[85,107,109,112,113,123] Efforts to manage wildlife, habitats, and species are variable in their approaches to increasing climate resilience, with limited uncertainty in how these strategies can collectively result in increased climate resilience of the region's natural capital.[54,110,114,117,118,119,120]

Major uncertainties

There is strong evidence to suggest that recreational opportunities are an important quality of the Northwest,[87] but there is uncertainty around the perceived importance of future recreation opportunities' prioritization in people's quality of life despite the direct reduction of many recreational opportunities.[127]

The effects of climate change on game species are uncertain, with large potential forcing in both directions and a lack of information on which processes will dominate consequences for game species and how managers might be able to effectively adapt to changing climate.

Description of confidence and likelihood

There is *high confidence* that climate change and extreme events have already endangered the well-being of a wide range of wildlife, fish, and plants. There is *very high confidence* that these impacts will directly threaten tribal subsistence and culture and *high confidence* that these impacts will threaten popular recreation activities. Future climate change will *very likely* continue to have adverse impacts on the regional environment. There is *high confidence* that future climate change will have negative impacts on the values, identity, heritage, cultures, and quality of life of the diverse population of Northwest residents. There is *medium confidence* that adaptation and informed management, especially culturally appropriate strategies, will increase the resilience of the region's natural capital.

Key Message 3

Infrastructure

Existing water, transportation, and energy infrastructure already face challenges from flooding, landslides, drought, wildfire, and heat waves (*very high confidence*). Climate change is projected to increase the risks from many of these extreme events, potentially compromising the reliability of water supplies, hydropower, and transportation across the region (*likely*, *high confidence*). Isolated communities and those with systems that lack redundancy are the most vulnerable (*likely*, *medium confidence*). Adaptation strategies that address more than one sector, or are coupled with social and environmental co-benefits, can increase resilience (*high confidence*).

Description of evidence base

There is a growing body of evidence suggesting that climate change will likely increase the frequency and/or intensity of extreme events such as flooding, landslides, drought, wildfire, and heat waves.[27,139,142,295,296,297,298,299,300,301,302] Several investigations have highlighted the vulnerability of water supply, hydropower, and transportation to such changes.[33,139,303,304,305,306,307]

Infrastructure redundancy is widely accepted as a means to enhance system reliability. Multiple investigations cite the importance of system redundancy for transportation, energy, and water supply.[136,146,308] Several studies describe the ways that agencies tasked with water, energy, and transportation management are exploring climate change impacts and potential adaptation options.[133,146,148,151,309,310,311,312,313,314]

Major uncertainties

Many analyses and anecdotal evidence link the risk of infrastructure disruption or failure to extreme events. However, the attribution of specific infrastructure impacts to climate variability or climate change remains a challenge. In many cases, infrastructure is subject to multiple climate and non-climate stressors. Non-climate stressors common to many parts of the region include increases in demand or usage from growing populations and changes in land use or development. In addition, much infrastructure across the region is beyond its useful lifetime or may not be in a state of good repair. These factors typically enhance sensitivity to many types of stressors but add uncertainty when trying to draw a direct connection between climate and infrastructure impacts.

Demographic shifts remain an important uncertainty when assessing future infrastructure impacts as well as the relative importance of certain types of infrastructure. Migration to and within the region can fluctuate on timescales shorter than those of climate change. As people move, the relative importance of different types of infrastructure are likely to change, as are the consequences of impacts.

Lastly, there is considerable uncertainty in quantitatively assessing the role of redundancy in minimizing or managing impacts. Metrics for determining the extent to which networking or emergency/backup systems yield adaptive capacity are not currently available at the regional scale.

Description of confidence and likelihood

There is *very high confidence* in the link between extreme events and infrastructure impacts. Most of the existing vulnerability assessments in this region, as well as those at larger spatial scales, emphasize extreme events as a key driver of past impacts. Most infrastructure is planned and designed to withstand events of a specified frequency and magnitude (for example, the 100-year flood, design storms), underscoring the importance of extreme events to our assumptions about infrastructure reliability and function. There is *high confidence* that rising temperatures, increases in heavy rainfall, and hydrologic changes are projected for the region.[5,71,139] These changes are anticipated to raise the risk of flooding, landslides, drought, wildfire, and heat waves. There is *medium confidence* about the role of redundancy in determining vulnerability. Although this link has been exhibited in many case studies, quantitative evidence at the local and regional scale has yet to be developed.

Impacts discussed in this chapter (e.g., WSDOT 2014, ODOT and OHA 2016, Withycomb 2017, US Climate Resilience Toolkit 2017[129,130,132,135]), within other chapters (see Ch. 11: Urban; Ch. 12: Transportation; Ch. 17: Complex Systems; Ch. 28: Adaptation), and elsewhere[139] highlight the connections among infrastructure systems, or between infrastructure reliability, and access to critical services. In addition, infrastructure systems are faced with a host of non-climate stressors (for example, increased demands from growing population, land-use change). As a result, there is *high confidence* that adaptation efforts designed to address climate impacts across multiple sectors (e.g., Portland-Multnomah County 2014, 2016[146,147]), as well as those that will yield social environmental co-benefits, will build resilience.

Key Message 4

Health

Organizations and volunteers that make up the Northwest’s social safety net are already stretched thin with current demands (*very likely*, *high confidence*). Healthcare and social systems will likely be further challenged with the increasing frequency of acute events, or when cascading events occur (*very likely*, *high confidence*). In addition to an increased likelihood of hazards and epidemics, disruptions in local economies and food systems are projected to result in more chronic health risks (*very likely*, *medium confidence*). The potential health co-benefits of future climate mitigation investments could help to counterbalance these risks (*likely*, *medium confidence*).

Description of evidence base

Cascading hazards could occur in any season; however, the summer months pose the biggest health challenges. For example, wildfire could occur at the same time as extreme heat and could damage electrical distribution systems, thereby simultaneously exposing people to smoke and high temperatures without the ability to pump water, filter air, or control indoor temperatures. Although some work is being done to prepare, responses to emergency incidents continue to show that there are considerable gaps in our medical and public health systems.[315] Public health departments are in place to track, monitor, predict, and develop response tactics to disease outbreaks or other health threats. In the case of cascading hazards, the public health system has a role in communicating risks to the public as well as strategies for self-care and sheltering-in-place during a crisis. Unfortunately, local health departments report inadequate capacity to respond to local climate change-related health threats, mainly due to budget constraints.[316] Hospitals in the United States routinely operate at or above capacity. Large numbers of emergency rooms are crowded with admitted patients awaiting placement in inpatient beds, and hospitals are diverting more than half a million ambulances per year due to emergency room overcrowding.[317]

Existing environmental health risks are expected to be exacerbated by future climate conditions,[187] yet over 95% of local health departments in Oregon reported having only partial-to-minimal ability to identify and address environmental health hazards.[194] The capacity of our public health systems is largely inadequate and unable to meet basic responsibilities to protect the health and safety of people in the Northwest.[162,194] Public health leaders from state and local health authorities, state advisory boards, and public health associations have been working together for over five years to develop a plan for rebuilding, modernizing, and funding the region's public health systems.

Socioeconomic income levels can be a predictor of environmental health outcomes in the future.[187,195] Food systems face continued increases in environmental pressures, with climate change influencing both the quality of food and the ability to distribute it equitably. The capacity to ensure food security in the face of rapidly changing climate conditions will likely be a major determinant of disease burden.[318]

Climate mitigation strategies can in some cases have substantial health co-benefits, with evidence pointing toward active transportation[319] and green infrastructure improvements.[320] This evidence of health co-benefits provides an additional and immediate rationale for reductions in greenhouse gas emissions beyond that of climate change mitigation alone. Recognition that mitigation strategies can have substantial benefits for both health and climate protection offers the possibility of strategies that are potentially both more cost effective and socially attractive than are those that address these priorities independently.[321] The Oregon Health Authority's Climate Smart Strategy Health Impact Assessment found that almost all climate mitigation policies under consideration by the Metro Regional Government could improve health, and that certain policy combinations were more beneficial, namely those that reduced vehicle miles traveled.[322] For example, according to 2009 data available on the National Environmental Public Health Tracking Network, a 10% reduction in $PM_{2.5}$ could prevent more than 400 deaths per year in a highly populated county and about 1,500 deaths every year in the state of California alone. Working across sectors to incorporate a health promotion approach in the design and development of built environment components could mitigate climate change, promote adaptation, and improve public health.[323]

Major uncertainties

Preparing and responding to cascading hazards is complex and involves many organizations outside of the medical and public health systems. There is not a common set of metrics or standards for measuring surge capacity and emergency preparedness across the region.

There is uncertainty in whether domestic migration will place further stress on social safety net systems.

Description of confidence and likelihood

There is *high confidence* that there will be increased hazards and epidemics, which will *very likely* disrupt local economies, food systems, and exacerbate chronic health risks, especially among populations most at risk. There is *high confidence* that these acute hazards will increase due to future climate conditions and will *very likely* increase the demand on organizations and volunteers that respond and form the region's social safety net. There is *medium confidence* that mitigation investments can help counterbalance these risks and *likely* result in health co-benefits for the region.

Key Message 5

Frontline Communities

Communities on the front lines of climate change experience the first, and often the worst, effects. Frontline communities in the Northwest include tribes and Indigenous peoples, those most dependent on natural resources for their livelihoods, and the economically disadvantaged (*very high confidence*). These communities generally prioritize basic needs, such as shelter, food, and transportation (*high confidence*); frequently lack economic and political capital; and have fewer resources to prepare for and cope with climate disruptions (*very likely*, *very high confidence*). The social and cultural cohesion inherent in many of these communities provides a foundation for building community capacity and increasing resilience (*likely*, *medium confidence*).

Description of evidence base

Multiple lines of research have shown that the impacts of extreme weather events and climate change depend not only on the climate exposures but also on the sensitivity and adaptive capacity of the communities being exposed to those changes.[187,230,324,325] For frontline communities in the Northwest, it is the interconnected nature of legacy exposure, enhanced exposure, higher sensitivity, and less capability to adapt that intensifies a community's climate vulnerability.[187,216]

There are multiple lines of evidence that demonstrate that tribes and Indigenous peoples are particularly vulnerable to climate change. Climate stressors, such as sea level rise, ocean acidification, warmer ocean and stream temperatures, wildfires, or droughts, are projected to disproportionately affect tribal and Indigenous well-being and health,[106,187,326,327] economies,[85,124] and cultures.[105,106] These losses can affect mental health and, in some cases, trigger multigenerational trauma.[125,189,209,214]

There is limited research on how climate change is projected to impact farmworkers, yet evidence suggests that occupational health concerns, including heat-related concerns[210,223] and pesticide exposure,[328] could increase, thus exacerbating health and safety concerns among economically and politically marginalized farmworker communities.

Particularly relevant to economically disadvantaged urban populations, extensive work has been done evaluating and analyzing social vulnerability[211] and applying that work to the Northwest.[195] There has also been work completed considering both relative social vulnerability and environmental health data (see WSDOH 2018[162]).

Strong evidence through reports and case studies demonstrates that tribes are active in increasing their resilience through climate change vulnerability assessments and adaptation plans (see https://

www.indianaffairs.gov/WhoWeAre/BIA/climatechange/Resources/Tribes/index.htm and http://tribalclimateguide.uoregon.edu/adaptation-plans for a list of tribal and Indigenous climate resilience programs, reports, and actions) and through regional networks (for example, Pacific Northwest Tribal Climate Change Network, Affiliated Tribes of Northwest Indians, Northwest Indian Fisheries Commission, Columbia River Inter-Tribal Fish Commission, Point No Point Treaty Council, Upper Snake River Tribes Foundation).

There are also many community organizations across the region focusing on engaging, involving, and empowering frontline communities, including communities of color, immigrants, tribes and Indigenous peoples, and others to design plans and policies that are meaningful (for example, Front and Centered, Got Green, Puget Sound Sage, Coalition of Communities of Color).

Major uncertainties

Actual climate change related vulnerabilities will vary by community and neighborhood.[187,208] Therefore, the scale of any vulnerability assessment or adaptation plan will matter greatly in assessing the uncertainties.

The secondary and tertiary impacts of changing climate conditions are less well understood. For example, climate change may increase the amount and frequency of pesticides used, and the variety of products used to manage crop diseases, pests, and competing weeds.[328] This is likely to increase farmworker exposure to pesticides and ultimately affect their health and well-being. Further, it is unclear how the altered timing of agricultural management of key crops across the United States (for example, the timing of cherry picking) due to increased temperatures and altered growing seasons may influence the demand for farmworker labor, particularly migrant labor, and how this might impact their livelihoods and occupational health.

There is emerging evidence that there are overlaps between environmental justice concerns and climate change impacts on these communities,[233,237] and that solutions designed to address one issue can provide effective solutions for the other issue if done well.[147]

No systematic catalogue of the actions and efforts of frontline communities in the region to address their climate-related challenges exists. Thus, at this point, most examples of adaptation and climate preparedness are anecdotal, but these examples suggest an increasing trend to link adaptation efforts that simultaneously address both climate and equity concerns. However, this approach is still used sporadically based on the interests, needs, and resources of the communities.

Description of confidence and likelihood

There is *very high confidence* that frontline communities are the first to be affected by the impacts of climate change. Due to their enhanced sensitivity to changing conditions, direct reliance on natural resources, place-based limits, and lack of financial and political capital, it is *very likely* that they will face the biggest climate challenges in the region. However, there is a significant amount of uncertainty in how individuals and individual communities will respond to these changing conditions, and responses will likely differ between states, communities, and even neighborhoods. Thus, it is the complex interaction between the climate exposures and the integrated social-ecological systems as well as the surrounding policy and response environment that will ultimately determine the challenges these communities face.

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25 Southwest

Low water levels in Lake Mead

Key Message 1

Water Resources

Water for people and nature in the Southwest has declined during droughts, due in part to human-caused climate change. Intensifying droughts and occasional large floods, combined with critical water demands from a growing population, deteriorating infrastructure, and groundwater depletion, suggest the need for flexible water management techniques that address changing risks over time, balancing declining supplies with greater demands.

Key Message 2

Ecosystems and Ecosystem Services

The integrity of Southwest forests and other ecosystems and their ability to provide natural habitat, clean water, and economic livelihoods have declined as a result of recent droughts and wildfire due in part to human-caused climate change. Greenhouse gas emissions reductions, fire management, and other actions can help reduce future vulnerabilities of ecosystems and human well-being.

Key Message 3

The Coast

Many coastal resources in the Southwest have been affected by sea level rise, ocean warming, and reduced ocean oxygen—all impacts of human-caused climate change—and ocean acidification resulting from human emissions of carbon dioxide. Homes and other coastal infrastructure, marine flora and fauna, and people who depend on coastal resources face increased risks under continued climate change.

Key Message 4

Indigenous Peoples

Traditional foods, natural resource-based livelihoods, cultural resources, and spiritual well-being of Indigenous peoples in the Southwest are increasingly affected by drought, wildfire, and changing ocean conditions. Because future changes would further disrupt the ecosystems on which Indigenous peoples depend, tribes are implementing adaptation measures and emissions reduction actions.

Key Message 5

Energy

The ability of hydropower and fossil fuel electricity generation to meet growing energy use in the Southwest is decreasing as a result of drought and rising temperatures. Many renewable energy sources offer increased electricity reliability, lower water intensity of energy generation, reduced greenhouse gas emissions, and new economic opportunities.

Key Message 6

Food

Food production in the Southwest is vulnerable to water shortages. Increased drought, heat waves, and reduction of winter chill hours can harm crops and livestock; exacerbate competition for water among agriculture, energy generation, and municipal uses; and increase future food insecurity.

Key Message 7

Human Health

Heat-associated deaths and illnesses, vulnerabilities to chronic disease, and other health risks to people in the Southwest result from increases in extreme heat, poor air quality, and conditions that foster pathogen growth and spread. Improving public health systems, community infrastructure, and personal health can reduce serious health risks under future climate change.

Executive Summary

The Southwest region encompasses diverse ecosystems, cultures, and economies, reflecting a broad range of climate conditions, including the hottest and driest climate in the United States. Water for people and nature in the Southwest region has declined during droughts, due in part to human-caused climate change. Higher temperatures intensified the recent severe drought in California and are amplifying drought in the Colorado River Basin. Since 2000, Lake Mead on the Colorado River has fallen 130 feet (40 m) and lost 60% of its volume, a result of the ongoing Colorado River Basin drought and continued water withdrawals by cities and agriculture.

The reduction of water volume in both Lake Powell and Lake Mead increases the risk of water shortages across much of the Southwest. Local water utilities, the governments of seven U.S. states, and the federal governments of the United States and Mexico have voluntarily developed and implemented solutions to minimize the possibility of water shortages for cities, farms, and ecosystems. In response to the recent California drought, the state implemented a water conservation plan in 2014 that set allocations for water utilities and major users and banned wasteful practices. As a result, the people of the state reduced water use 25% from 2014 to 2017.

Exposure to hotter temperatures and heat waves already leads to heat-associated deaths in Arizona and California. Mortality risk during a heat wave is amplified on days with high levels of ground-level ozone or particulate air pollution. Given the proportion of the U.S. population in the Southwest region, a disproportionate number of West Nile virus, plague, hantavirus pulmonary syndrome, and Valley fever cases occur in the region.

Analyses estimated that the area burned by wildfire across the western United States from 1984 to 2015 was twice what would have burned had climate change not occurred. Wildfires around Los Angeles from 1990 to 2009 caused $3.1 billion in damages (unadjusted for inflation). Tree death in mid-elevation conifer forests doubled from 1955 to 2007 due, in part, to climate change. Allowing naturally ignited fires to burn in wilderness areas and preemptively setting low-severity prescribed burns in areas of unnatural fuel accumulations can reduce the risk of high-severity fires under climate change. Reducing greenhouse gas emissions globally can also reduce ecological vulnerabilities.

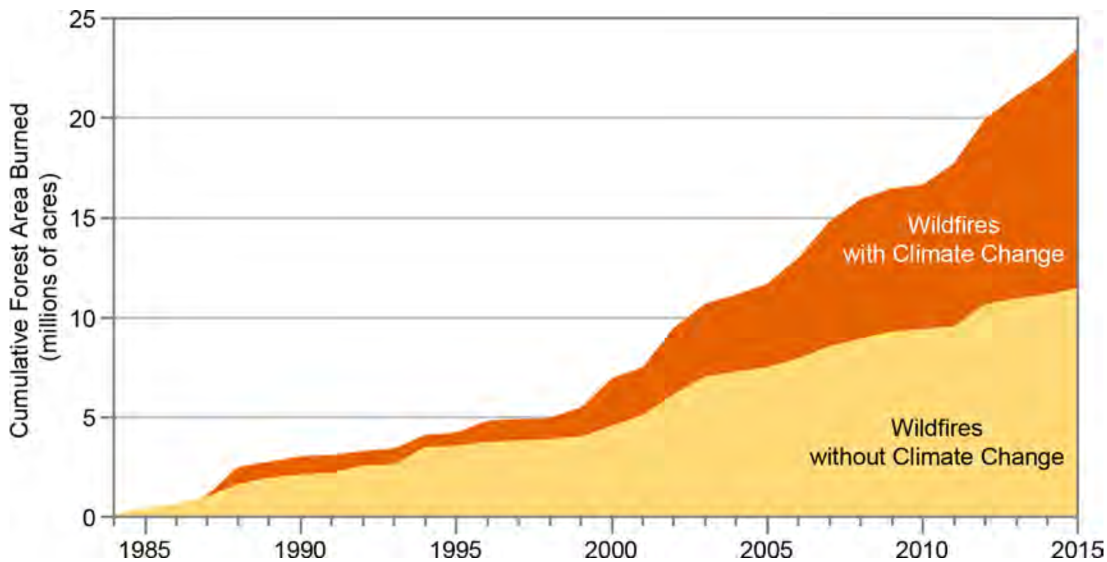
At the Golden Gate Bridge in San Francisco, sea level rose 9 inches (22 cm) between 1854 and 2016. Climate change caused most of this rise by melting of land ice and thermal expansion of ocean water. Local governments on the California coast are using projections of sea level rise to develop plans to reduce future risks. Ocean water acidity off the coast of California increased 25% to 40% (decreases of 0.10 to 0.15 pH units) from the preindustrial era (circa 1750) to 2014 due to increasing concentrations of atmospheric carbon dioxide from human activities. The marine heat wave along the Pacific Coast from 2014 to 2016 occurred due to a combination of natural factors and climate change. The event led to the mass stranding of sick and starving birds and sea lions, and shifts of red crabs and tuna into the region. The ecosystem disruptions contributed to closures of commercially important fisheries.

Agricultural irrigation accounts for approximately three-quarters of water use in the Southwest region, which grows half of the fruits, vegetables, and nuts and most of the wine grapes, strawberries, and lettuce for the United States. Increasing heat stress during specific phases of the plant life cycle can increase crop failures.

Drought and increasing heat intensify the arid conditions of reservations where the United States restricted some tribal nations in the Southwest region to the driest portions of their traditional homelands. In response to climate change, Indigenous peoples in the region are developing new adaptation and mitigation actions.

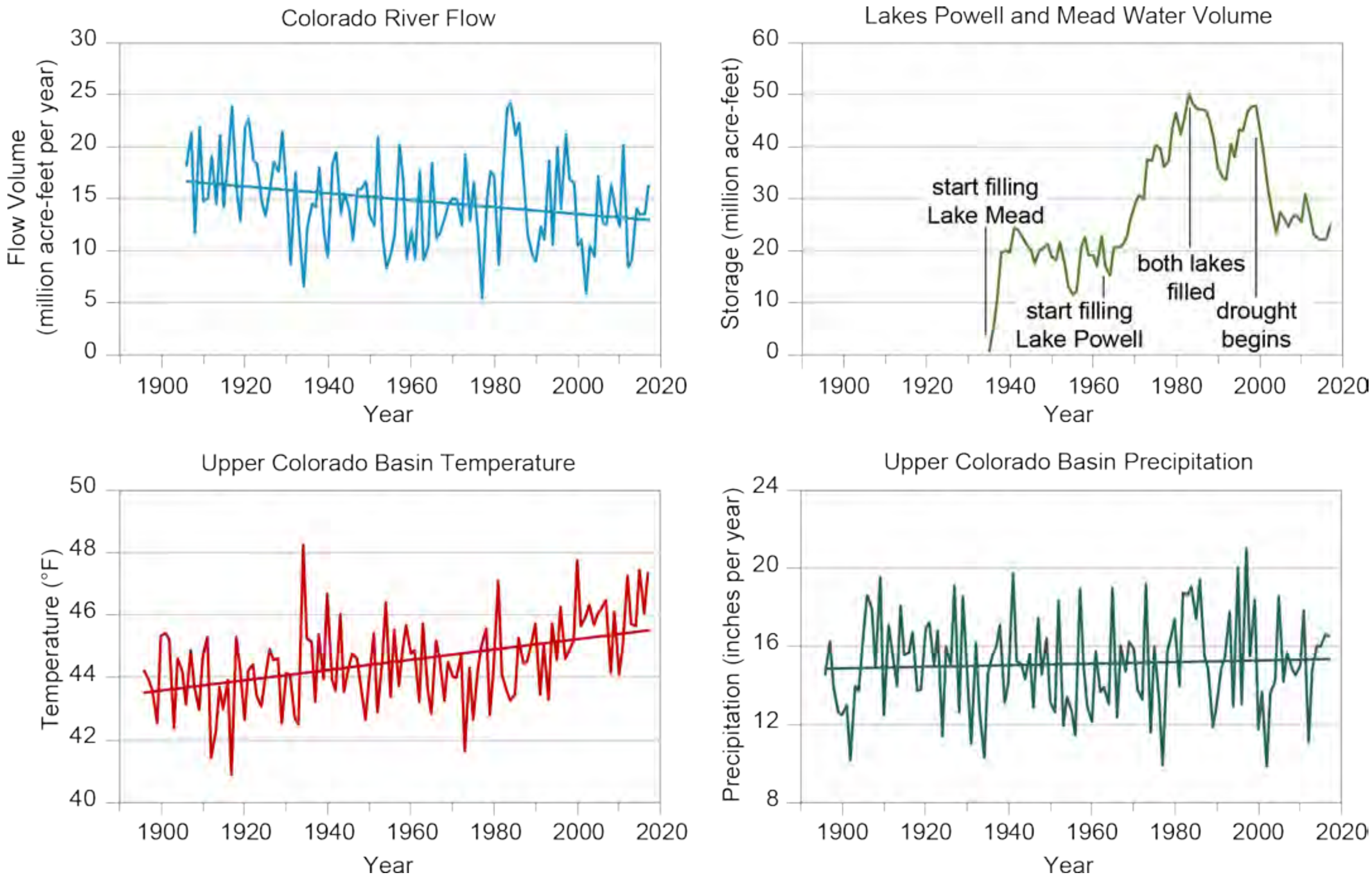
The severe drought in California, intensified by climate change, reduced hydroelectric generation two-thirds from 2011 to 2015. The efficiency of all water-cooled electric power plants that burn fuel depends on the temperature of the external cooling water, so climate change could reduce energy efficiency up to 15% across the Southwest by 2050. Solar, wind, and other renewable energy sources, except biofuels, emit less carbon and require less water than fossil fuel energy. Economic conditions and technological innovations have lowered renewable energy costs and increased renewable energy generation in the Southwest.

Climate Change Has Increased Wildfire



The cumulative forest area burned by wildfires has greatly increased between 1984 and 2015, with analyses estimating that the area burned by wildfire across the western United States over that period was twice what would have burned had climate change not occurred. *From Figure 25.4 (Source: adapted from Abatzoglou and Williams 2016).*

Severe Drought Reduces Water Supplies in the Southwest



Since 2000, drought that was intensified by long-term trends of higher temperatures due to climate change has reduced the flow in the Colorado River (top left), which in turn has reduced the combined contents of Lakes Powell and Mead to the lowest level since both lakes were first filled (top right). In the Upper Colorado River Basin that feeds the reservoirs, temperatures have increased (bottom left), which increases plant water use and evaporation, reducing lake inflows and contents. Although annual precipitation (bottom right) has been variable without a long-term trend, there has been a recent decline in precipitation that exacerbates the drought. Combined with increased Lower Basin water consumption that began in the 1990s, these trends explain the recently reduced reservoir contents. Straight lines indicate trends for temperature, precipitation, and river flow. The trends for temperature and river flow are statistically significant. *From Figure 25.3 (Sources: Colorado State University and CICS-NC. Temperature and precipitation data from: PRISM Climate Group, Oregon State University,* http://prism.oregonstate.edu, *accessed 20 June 2018).*

Background

The Southwest region encompasses diverse ecosystems, cultures, and economies, reflecting a broad range of climate conditions, including the hottest and driest climate in the United States. Arizona, California, Colorado, New Mexico, Nevada, and Utah occupy one-fifth of U.S. land area, extending across globally unique ecosystems from the Sonoran Desert to the Sierra Nevada to the Pacific Coast. The region is home to 60 million people, with 9 out of 10 living in urban areas and the total population growing 30% faster than the national average.[1] The Nation depends on the region for more than half of its specialty crops such as fruits, nuts, and vegetables.[2] The Southwest also drives the U.S. technology sector, with more than 80% of the country's technology capitalization located in California.[3]

Ecosystems in the Southwest gradually transform from deserts and grasslands in hotter and lower elevations in the south to forests and alpine meadows in cooler, higher elevations in the north. Natural and human-caused wildfire shapes the forests and shrublands that cover one-quarter and one-half of the region, respectively.[4] To conserve habitat for plants and wildlife and supply clean water, timber, recreation, and other services for people, the U.S. Government manages national parks and other public lands covering half of the Southwest region.[5] Climate change is altering ecosystems and their services through major vegetation shifts[213] and increases in the area burned by wildfire.[7]

The California coast extends 3,400 miles (5,500 km),[8] with 200,000 people living 3 feet (0.9 m) or less above sea level.[9] The seaports of Long Beach and Oakland, several international airports, many homes, and high-value infrastructure lie along the coast. In addition, much of the Sacramento–San Joaquin River Delta is near sea level. California has the most valuable ocean-based economy in the country, employing over half a million people and generating $20 billion in wages and $42 billion in economic production in 2014.[10] Coastal wetlands buffer against storms, protect water quality, provide habitat for plants and wildlife, and supply nutrients to fisheries. Sea level rise, storm surges, ocean warming, and ocean acidification are altering the coastal shoreline and ecosystems.

Water resources can be scarce because of the arid conditions of much of the Southwest and the large water demands of agriculture, energy, and cities. Winter snowpack in the Rocky Mountains, Sierra Nevada, and other mountain ranges provides a major portion of the surface water on which the region depends. Spring snowmelt flows into the Colorado, Rio Grande, Sacramento, and other major rivers, where dams capture the flow in reservoirs and canals and pipelines transport the water long distances. Complex water laws govern allocation among states, tribes, cities, ecosystems, energy generators, farms, and fisheries, and between the United States and Mexico. Water supplies change with year-to-year variability in precipitation and water use, but increased evapotranspiration due to higher temperatures reduces the effectiveness of precipitation in replenishing soil moisture and surface water.[11,12,13,14]

Agricultural irrigation accounts for nearly three-quarters of water use in the Southwest region,[15,16] which grows half of the fruits, vegetables, and nuts[2] and most of the wine grapes, strawberries, and lettuce[17] for the United States. Consequently, drought and competing water demands in this region pose a major risk for agriculture and food security in the country. Through production and trade networks, impacts to regional crop production can propagate nationally and internationally (see Ch. 16: International, KM 1)[18]

Parts of the Southwest reach the hottest temperatures on Earth, with the world record high of 134°F (57°C) recorded in Death Valley National Park, California[19] and daily maximum temperatures across much of the region regularly exceeding 98°F (35°C) during summer.[20] Greenhouse gases emitted from human activities have increased global average temperature since 1880[21] and caused detectable warming in the western United States since 1901.[22] The average annual temperature of the Southwest increased 1.6°F (0.9ºC) between 1901 and 2016 (Figure 25.1).[23] Moreover, the region recorded more warm nights and fewer cold nights between 1990 and 2016),[24] including an increase of 4.1°F (2.3°C) for the coldest day of the year. Parts of the Southwest recorded the highest temperatures since 1895, in 2012,[25] 2014,[26] 2015,[27] 2016,[28] and 2017.[29]

Extreme heat episodes in much of the region disproportionately threaten the health and well-being of individuals and populations who are especially vulnerable (Ch. 14: Human Health, KM 1).[30] Vulnerability arises from numerous factors individually or in combination, including physical susceptibility (for example, young children and older adults), excessive exposure to heat (such as during heat waves), and socioeconomic factors that influence susceptibility and exposure (for example, hot and poorly ventilated homes or lack of access to public emergency cooling centers).[31,32,33] Communicable diseases, ground-level ozone air pollution, dust storms, and allergens can combine with temperature and precipitation extremes to generate multiple disease burdens (an indicator of the impact of a health problem).

Episodes of extreme heat can affect transportation by reducing the ability of commercial airlines to gain sufficient lift for takeoff at major regional airports (Ch. 12: Transportation, KM 1).[34]

Temperature Has Increased Across the Southwest

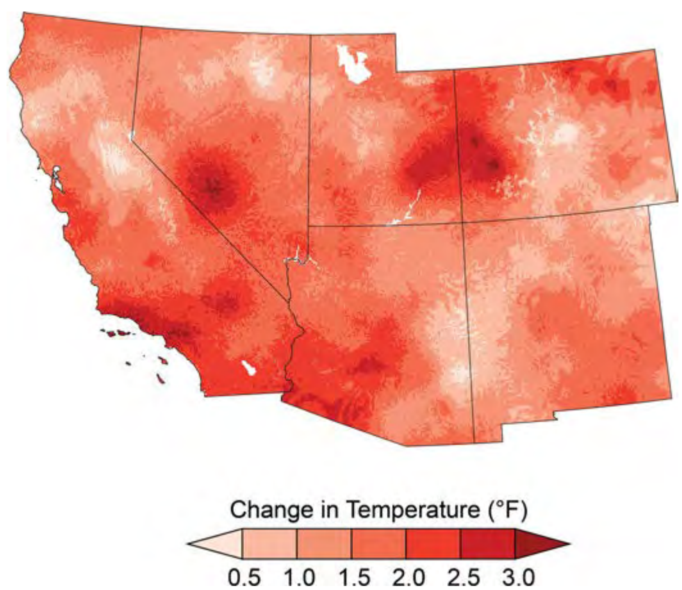


Figure 25.1: Temperatures increased across almost all of the Southwest region from 1901 to 2016, with the greatest increases in southern California and western Colorado.[23] This map shows the difference between 1986–2016 average temperature and 1901–1960 average temperature.[23] Source: adapted from Vose et al. 2017.[23]

Native Americans are among the most at risk from climate change, often experiencing the worst effects because of higher exposure, higher sensitivity, and lower adaptive capacity for historical, socioeconomic, and ecological reasons. With one and a half million Native Americans,[35] 182 federally recognized tribes,[36] and many state-recognized and other non-federally recognized tribes, the Southwest has the largest population of Indigenous peoples in the country. Over the last five centuries, many Indigenous peoples in the Southwest have either been forcibly restricted to lands with limited water and resources[37,38,39] or struggled to get their federally reserved water rights recognized by other users.[40] Climate change exacerbates this historical legacy because the sovereign lands on which many Indigenous peoples live are becoming increasingly dry.

Further, climate change affects traditional plant and animal species, sacred places, traditional building materials, and other material cultural heritage. The physical, mental, emotional, and spiritual health and overall well-being of Indigenous peoples rely on these vulnerable species and materials for their livelihoods, subsistence, cultural practices, ceremonies, and traditions.[41,42,43,44]

In parts of the region, hotter temperatures have already contributed to reductions of seasonal maximum snowpack and its water content over the past 30–65 years,[45,46,47,48,49] partially attributed to human-caused climate change.[45,46,48,49] Increased temperatures most strongly affect snowpack water content, snowmelt timing, and the fraction of precipitation falling as snow.[48,50,51,52,53,54]

The increase in heat and reduction of snow under climate change have amplified recent hydrological droughts (severe shortages of water) in California,[14,55,56,57,58] the Colorado River Basin,[12,13,59] and the Rio Grande.[45,60] Snow droughts can arise from a lack of precipitation (dry snow drought), temperatures that are too warm for snow (warm snow drought), or a combination of the two.[48,51]

Periods of low precipitation from natural variations in the climate system are the primary cause of major hydrological droughts in the Southwest region,[61,62,63,64,65,66,67,68] with increasing temperatures from climate change amplifying recent hydrological droughts, particularly in California and the upper Colorado River Basin.[12,13,14,56,57,59]

Under the higher scenario (RCP8.5), climate models project an 8.6°F (4.8°C) increase in Southwest regional annual average temperature by 2100.[23] Southern parts of the region could get up to 45 more days each year with maximum temperatures of 90°F (32°C) or higher.[23] Projected hotter temperatures increase probabilities of decadal to multi-decadal megadroughts,[61,62,69,70] which are persistent droughts lasting longer than a decade,[69] even when precipitation increases. Under the higher scenario (RCP8.5), much of the mountain area in California with winters currently dominated by snow would begin to receive more precipitation as rain and then only rain by 2050.[71] Colder and higher areas in the intermountain West would also receive more rain in the fall and spring but continue to receive snow in the winter at the highest elevations.[71]

Increases in temperature would also contribute to aridification (a potentially permanent change to a drier environment) in much of the Southwest, through increased evapotranspiration,[69,70,72,73] lower soil moisture,[74] reduced snow cover,[71,75,76,77] earlier and slower snowmelt,[75] and changes in the timing and efficiency of snowmelt and runoff.[50,54,75,76,78,79] Some research indicates increasing frequency of dry high-pressure weather systems associated with changes in Northern Hemisphere atmospheric circulation.[80,81] These changes would tend to increase the duration and severity of droughts[67,74] and generate an overall drier regional climate.[69,70,72]

Climate models project an increase in the frequency of heavy downpours, especially through atmospheric rivers,[74,82] which are narrow bands of highly concentrated storms that move in from the Pacific Ocean. A series of strong atmospheric rivers caused extreme flooding in California in 2016 and 2017. Under the higher scenario (RCP8.5), models project increases in the frequency and intensity of atmospheric rivers.[83,84,85,86] Climate models also project an increase in daily extreme summer precipitation in the Southwest region, based on projected increases in water vapor resulting from higher temperatures.[20,87,88] Projections of summer total precipitation are uncertain, with average projected totals not differing substantially from what would be expected due to natural variations in climate.[88]

The Southwest generates one-eighth of U.S. energy, with hydropower, solar, wind, and other renewable sources supplying one-fifth of regional energy generation.[89] By installing so much renewable energy, the Southwest has lowered its per capita and per dollar greenhouse gas emissions below the U.S. average.[90] Climate change can, however, decrease hydropower and fossil fuel energy generation.[91] California has enacted mandatory greenhouse gas emissions reductions,[92] and Arizona, California, Colorado, Nevada, and New Mexico have passed renewable portfolio standards to reduce fossil fuel dependence and greenhouse gas emissions.[93]

What Is New in the Fourth National Climate Assessment

This chapter builds on assessments of climate change in the Southwest region from the three previous U.S. National Climate Assessments.[94,95,96] Each assessment has consistently identified drought, water shortages, and loss of ecosystem integrity as major challenges that the Southwest confronts under climate change. This chapter further examines interconnections among water, ecosystems, the coast, food, and human health and adds new Key Messages concerning energy and Indigenous peoples.

Since the last assessment, published field research has provided even stronger detection of hydrological drought, tree death, wildfire increases, sea level rise, and warming, oxygen loss, and acidification of the ocean that have been statistically different from natural variation, with much of the attribution pointing to human-caused climate change. In addition, new research has provided published information on future vulnerabilities and risks from climate change, including floods, food insecurity, effects on the natural and cultural resources that sustain Indigenous peoples, illnesses due to the combination of heat with air pollution, harm to mental health, post-wildfire effects on ecosystems and infrastructure, and reductions of hydropower and fossil fuel electricity generation.

This chapter highlights many of the increasing number of actions that local governments and organizations have been taking in response to historical impacts of climate change and to reduce future risks (Figure 25.2). Some examples include voluntary water conservation and management in California and the Colorado River Basin, restoring cultural fire management in California, and rooftop solar policies in California, Colorado, and Nevada. Many state and local governments have issued climate change assessments and action plans.

Actions Responding to Climate Change Impacts and Vulnerabilities

Figure 25.2: These examples illustrate actions that people, communities, and governments are taking in response to past impacts of climate change and future vulnerabilities. **Coastal protection**: In response to sea level rise and storm surge in San Francisco Bay, federal, state, and local agencies, supported by voter-approved funds, are restoring coastal habitats and levees to protect cities from flooding. **Crop water savings**: The risk of reduced food production increases as climate change intensifies drought. In the Gila River Basin, local government agencies have lined 15 miles (24 km) of irrigation canals to reduce seepage from the canals, saving enough water to irrigate approximately 8,500 acres (3,400 hectares) of alfalfa and other crops each year. **Cultural fire restoration**: Reintroduction of cultural burning by the Yurok Tribe in northern California reduces wildfire risks and protects public and tribal trust resources. **Desert soil restoration**: In Utah, transplanting native and drought-resistant microbial communities improves soil fertility and guards against erosion. **Health protection**: To reduce heat-associated injury and deaths on Arizona trails, the City of Phoenix and Arizona tourism organizations developed a campaign "Take a Hike. Do it Right." Signs at trailheads and on websites remind hikers to bring water, stay hydrated, and stay aware of environmental conditions. **Ranching and habitat**: The Malpai Borderlands Group in Arizona and New Mexico integrates native plant and wildlife conservation into private ranching. **Rooftop solar**: The state governments of California, Colorado, and Nevada have enacted policies that support rooftop solar on homes, which reduces greenhouse gas emissions, improves reliability of the electricity generation system, and creates local small businesses and new jobs. **Water conservation**: Drought in the Colorado River Basin has reduced the volume of water in both Lake Mead and Lake Powell by over half. The United States, Mexico, and state governments have mobilized users to conserve water, keeping the lake above a critical level. **Wildfire fuel reduction**: In response to severe wildfires, the City of Flagstaff, Arizona, enacted a bond to fund reduction of fire fuels in forests around the town. Source: National Park Service.

Key Message 1

Water Resources

Water for people and nature in the Southwest has declined during droughts, due in part to human-caused climate change. Intensifying droughts and occasional large floods, combined with critical water demands from a growing population, deteriorating infrastructure, and groundwater depletion suggest the need for flexible water management techniques that address changing risks over time, balancing declining supplies with greater demands.

Higher temperatures intensified the recent severe drought in California and are amplifying drought in the Colorado River Basin. In California, the higher temperatures intensified the 2011–2016 drought,[14,56,97,98,99] which had been initiated by years of low precipitation,[57,58] causing water shortages to ecosystems, cities, farms, and energy generators. In addition, above-freezing temperatures through the winter of 2014–2015 led to the lowest snowpack in California (referred to as a warm snow drought) on record.[47,55,98,100] Through increased temperature, climate change may have accounted for one-tenth to one-fifth of the reduced soil moisture from 2012 to 2014 during the recent California drought.[14] In the ongoing Colorado River Basin drought, high temperatures due mainly to climate change have contributed to lower runoff[12,59] and to 17%–50% of the record-setting streamflow reductions between 2000 and 2014 (Figure 25.3).[13] In the Rio Grande, higher temperatures have been linked to declining runoff efficiency[60] and reductions in snowpack.[45]

Increased temperatures, especially the earlier occurrence of spring warmth,[101] have significantly altered the water cycle in the Southwest region. These changes include decreases in snowpack and its water content,[46,47,48,49,102] earlier peak of snow-fed streamflow,[103] and increases in the proportion of rain to snow.[49,103] These changes, attributed mainly to climate change,[49,103] exacerbate hydrological drought.

With continued greenhouse gas emissions, higher temperatures would cause more frequent and severe droughts in the Southwest.[11,56,62,65,80] This would also lead to drier future conditions for the region.[70,74] Higher temperatures sharply increase the risk of megadroughts—dry periods lasting 10 years or more.[61,62,65] Under the higher scenario (RCP8.5), models project annual declines of river flow in southern basins (the Rio Grande and the lower Colorado River) and either no change or modest increases in northern basins (northern California and the upper Colorado River).[78,104,105,106,107] Snowpack supplies a major portion of water in the Southwest, but with continued emissions, models project substantial reductions in snowpack, less snow and more rain, shorter snowfall seasons, earlier runoff,[55,71,78,79,108,109] and warmer late-season stream temperatures.[110] Fewer days with precipitation would lead to increased year-to-year variability.[111,112,113] Substantial increases in precipitation would be needed to overcome temperature-induced decreases in river flow.[13] The combination of reduced river flows in California and the Colorado River Basin and increasing population in southern California, which imports most of its water, would increase the probability of future water shortages.[114]

In response to the recent California drought, the state government implemented a water conservation plan in 2014 that set allocations for water utilities and major users and banned wasteful practices such as watering during or after a rainfall, hosing off sidewalks, and irrigating ornamental turf on public street medians.[115] As a result, the people of the state reduced water use 25% from 2014 to 2017, when abundant rains allowed the state to lift many restrictions while continuing to promote water conservation as a way of life.[116]

The Southern Nevada Water Authority used similar measures to reduce water use per person 38% from 2002 to 2016.[117] Water utilities in the Colorado Front Range also used similar conservation practices to reduce water use more than 20% in the early 2000s.[118] While many southwestern cities have reduced total and per-person water use since the 1990s despite growing populations,[119] ongoing drought has increased competition for reliable water supplies in many locations. In parts of Colorado, Nevada, and Utah, population growth has prompted proposals for new water diversions and transfers from agriculture. While desalination of seawater and brackish water has been proposed as a partial solution to water scarcity, its high energy requirement creates greenhouse gas emissions and its capital costs are high.[15]

Atmospheric rivers, which have caused many large floods in California,[120] may increase in severity and frequency under climate change.[82,83,107,121,122,123,124] In the winter of 2016–2017, a series of strong atmospheric rivers generated high runoff in northern California and filled reservoirs. At Oroville

Dam, high flows eroded the structurally flawed emergency spillway, caused costly damage, and led to the preventive evacuation of people living downstream. In addition to the immediate threat to human life and property, this incident revealed two water supply risks. First, summer water supplies are reduced when protective flood control releases of water from reservoirs are necessary in the spring.[108] Second, several studies have concluded that deteriorating dams, spillways, and other infrastructure require substantial maintenance and repair.[125,126] In U.S.–Mexico border cities with chronic urban storm water and pollutant runoff problems[127] and populations vulnerable to flooding,[127,128] projected increases in heavy precipitation[88] would increase risks of floods.

Wet periods present a water resource opportunity because increased infiltration from the surface into the ground recharges groundwater aquifers. Groundwater was critical for farmers during the California drought, especially for fruit and nut trees and grapevines.[129,130,131] Overdraft of groundwater, however, caused land subsidence (sinking), which can permanently reduce groundwater storage capacity and damage infrastructure as the ground deforms.[132]

In light of projected future changes in the hydrologic cycle, water resource planners and scientists are testing new techniques to combine results from multiple climate and hydrology models, downscale climate model output to finer geographic scales, calculate changing water demands, and use forecasts for flood control.[133,134,135,136] Integrating data from satellites, climate and hydrology models, and field observations remains difficult with existing water management tools, methods, and legal requirements.

Box 25.1: Collaborative Management of Colorado River Water

Since 2000, Lake Mead on the Colorado River has fallen 130 feet (40 m) and lost 60% of its volume,[137,138,139] a result of the ongoing Colorado River Basin drought and continued water withdrawals by cities and agriculture (Figure 25.3). This is the lowest level since the filling of the reservoir in 1936.[139] The reduction of Lake Mead increases the risk of water shortages across much of the Southwest and reduces energy generation at the Hoover Dam hydroelectric plant at the reservoir outlet. Local water utilities, the governments of seven U.S. states, and the federal governments of the United States and Mexico have voluntarily developed and implemented solutions to minimize the possibility of water shortages for cities, farms, and ecosystems. The parties have taken four key actions:

Hydrological drought in Lake Mead, Nevada, on March 10, 2014. Photo credit: U.S. Bureau of Reclamation.

1. Arizona, California, and Nevada agreed in 2007, with Mexico joining in 2012, to allow users to store water in Lake Mead for later years, rather than being forced to use it immediately or lose their rights.[140]

2. The United States and Mexico agreed in 2014 to release water for eight weeks to re-water the Colorado River Delta in Mexico in order to improve wildlife habitat and to conduct research on environmental restoration.[141]

Box 25.1: Collaborative Management of Colorado River Water, *continued*

3. The water agencies of Denver, Las Vegas, Los Angeles, and Phoenix and the U.S. Bureau of Reclamation in 2015 set up the Colorado River System Conservation Pilot Program, a fund for local water conservation projects. A second phase extended conservation projects to all of the Colorado River Basin.

4. Mexico agreed in 2017 to absorb a share of water shortages if Lake Mead fell below a specific elevation. The agreement continues Mexico's right to bank unused water in Lake Mead for future use. With financial and other U.S. assistance, Mexico will pursue water conservation projects and environmental restoration within the Colorado River Delta.

Currently, stakeholders are engaged in drought contingency planning for multiple climate futures, implementing management strategies that make sense for the range of climate futures, and preserving options when possible.[142]

Severe Drought Reduces Water Supplies in the Southwest

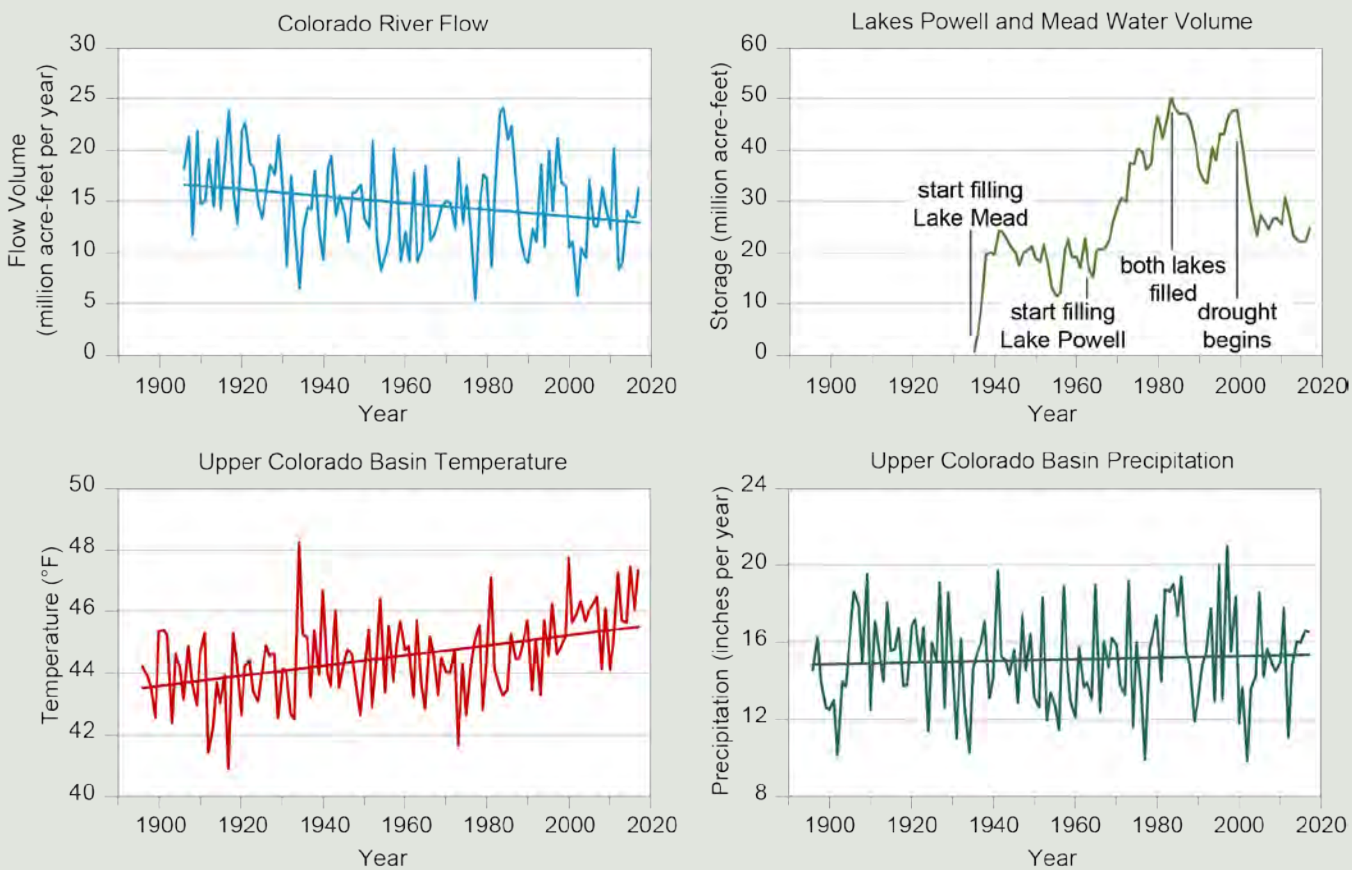


Figure 25.3: Since 2000, drought that was intensified by long-term trends of higher temperatures due to climate change has reduced the flow in the Colorado River (top left), which in turn has reduced the combined contents of Lakes Powell and Mead to the lowest level since both lakes were first filled (top right). In the Upper Colorado River Basin that feeds the reservoirs, temperatures have increased (bottom left), which increases plant water use and evaporation, reducing lake inflows and contents. Although annual precipitation (bottom right) has been variable without a long-term trend, there has been a recent decline in precipitation that exacerbates the drought. Combined with increased Lower Basin water consumption that began in the 1990s, these trends explain the recently reduced reservoir contents. Straight lines indicate trends for temperature, precipitation, and river flow. The trends for temperature and river flow are statistically significant. Sources: Colorado State University and CICS-NC. Temperature and precipitation data from: PRISM Climate Group, Oregon State University, http://prism.oregonstate.edu, accessed 20 June 2018.

Key Message 2

Ecosystems and Ecosystem Services

The integrity of Southwest forests and other ecosystems and their ability to provide natural habitat, clean water, and economic livelihoods have declined as a result of recent droughts and wildfire due in part to human-caused climate change. Greenhouse gas emissions reductions, fire management, and other actions can help reduce future vulnerabilities of ecosystems and human well-being.

The forests and other ecosystems of the Southwest region that provide natural habitat and essential resources for people have declined in fundamental ways due in part to climate change. Vast numbers of trees have died across Southwest forests and woodlands,[143,144,145,146] disproportionately affecting larger trees.[147] Tree death in mid-elevation conifer forests doubled from 1955 to 2007 due in part to climate change.[146] Field measurements showed that changes attributable, in part, to climate change, including increases in temperature, wildfire,[7] and bark beetle infestations,[148,149] outweighed non-climate factors such as fire exclusion or competition for light.[146]

Wildfire is a natural part of many ecosystems in the Southwest, facilitating germination of new seedlings and killing pests. Although many ecosystems require fire, excessive wildfire can permanently alter ecosystem integrity.[150,151] Climate change has led to an increase in the area burned by wildfire in the western United States.[7,152] Analyses estimate that the area burned by wildfire from 1984 to 2015 was twice what would have burned had climate change not occurred (Figure 25.4).[7] Furthermore, the area burned from 1916 to 2003 was more closely related to climate factors than to fire suppression, local fire management, or other non-climate factors.[152]

Climate change has driven the wildfire increase,[7,153] particularly by drying forests and making them more susceptible to burning.[154,155] Specifically, increased temperatures have intensified drought in California,[14] contributed to drought in the Colorado River Basin,[12,13]

Climate Change Has Increased Wildfire

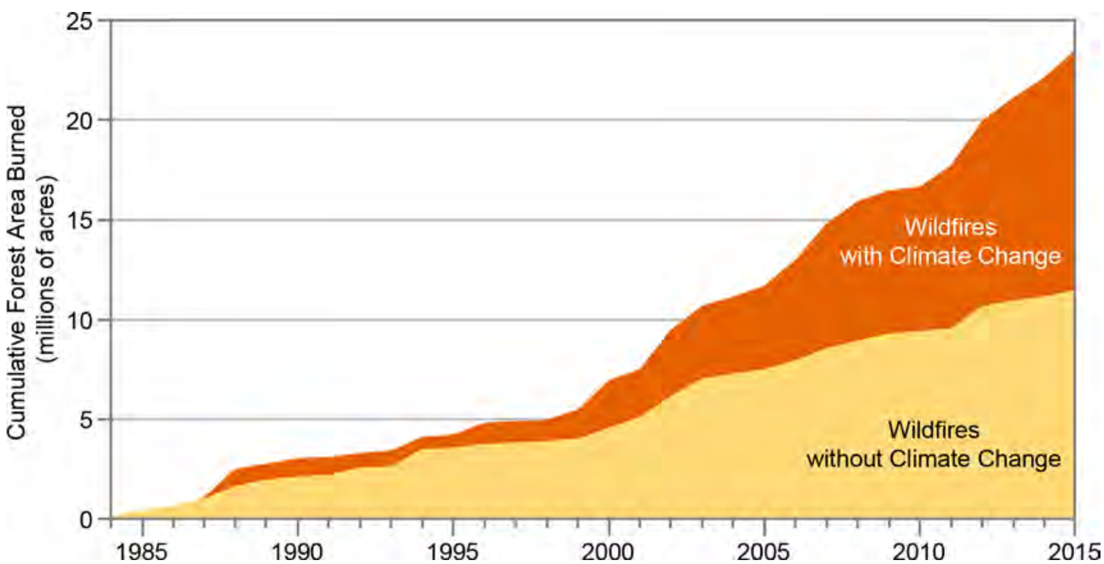


Figure 25.4: The cumulative forest area burned by wildfires has greatly increased between 1984 and 2015, with analyses estimating that the area burned by wildfire across the western United States over that period was twice what would have burned had climate change not occurred. Source: adapted from Abatzoglou and Williams 2016.[7]

reduced snowpack,[46,49,156] and caused spring-like temperatures to occur earlier in the year.[101] In addition, historical fire suppression policies have caused unnatural accumulations of understory trees and coarse woody debris in many lower-elevation forest types, fueling more intense and extensive wildfires.[150,157]

Wildfire can threaten people and homes,[159] particularly as building expands in fire-prone areas. Wildfires around Los Angeles from 1990 to 2009 caused $3.1 billion in damages (unadjusted for inflation).[159] Respiratory illnesses and life disruptions from the Station Fire north of Los Angeles in 2009 cost an estimated $84 per person per day (in 2009 dollars).[160] In addition, wildfires degraded drinking water upstream of Albuquerque with sediment, acidity, and nitrates[161,162] and in Fort Collins, Colorado, with sediment and precursors of cancer-causing trihalomethane, necessitating a multi-month switch to alternative municipal water supplies.[163,164]

Ecosystems can naturally slow climate change by storing carbon, but recent wildfires have made California ecosystems and Southwest forests net carbon emitters (they are releasing more carbon to the atmosphere than they are storing).[6,144,165] Wildfire has also exacerbated the spread of invasive plant species and damaged habitat. For example, repeated wildfire in sagebrush in Nevada and Utah has caused extensive invasions of cheatgrass, reducing habitat for the endangered sage-grouse.[64,166]

Post-wildfire erosion damages ecosystems by denuding hillsides, such as occurred in Valles Caldera National Preserve in New Mexico when the 2011 Las Conchas Fire generated the biggest local erosion event in 1,000 years.[167] In New Mexico, consecutive large wildfires degraded habitat and reduced abundance of six out of seven native coldwater fishes and some native insects, although nonnative fishes were less affected.[168]

With continued greenhouse gas emissions, models project more wildfire across the Southwest region.[169,170,171,172,173] Under higher emissions (SRES A2)[174] (see the Scenario Products section of App. 3), fire frequency could increase 25%,[172] and the frequency of very large fires (greater than 5,000 hectares) could triple.[169] The Santa Ana winds and other very dry seasonal winds increase fire risk in California[175] and Mexico.[176] Under higher emissions (SRES A2), sediment flows after fires would double in one-third of western U.S. watersheds modeled,[177] with the sediment potentially damaging ecosystems, homes, roads, and rail lines (Ch. 12: Transportation; Ch. 17: Complex Systems). Under the higher scenario (RCP8.5), cumulative firefighting costs for the Southwest could total $13 billion from 2006 to 2099 (in 2015 dollars, discounted at 3%).[178]

Reducing greenhouse gas emissions can reduce ecological vulnerabilities to wildfire.[179] For example, under a higher emissions scenario (SRES A2), climate change could triple burned area (in a 30-year period) in the Sierra Nevada by 2100, while under a lower emissions scenario (SRES B1[174]), fire would only slightly increase.[173]

Allowing naturally ignited fires to burn in wilderness and preemptively setting low-severity prescribed burns in areas of unnatural fuel accumulations can reduce the risk of high-severity fires under climate change.[180,181,182,183,184] These actions can naturally reduce or slow climate change because long-term storage of carbon in large trees can outweigh short-term emissions.[185,186] Proactive use of fire in Yosemite, Sequoia, and Kings Canyon National Parks has improved the resilience of giant sequoias and other trees to severe fires and protected their stores of carbon.[187,188,190,191]

Climate change has also contributed to increased forest pest infestations, another major cause of tree death in Southwest forests and woodlands (Ch. 17: Complex Systems, Box 17.4). Bark beetle infestations killed 7% of western U.S. forest area from 1979 to 2012,[148,149] driven by winter warming due to climate change[103,192] and by drought.[193] Tree death from bark beetles in Colorado increased organic matter in local streams, elevating precursors of cancer-causing trihalomethane in local water treatment plants[194] to levels that exceed the maximum contaminant levels for drinking water specified by the U.S. Environmental Protection Agency.[195] Without greenhouse gas emissions reductions, further increases in heat and drought could kill many more trees,[143,196,197] especially affecting piñon pine,[198] whitebark pine,[199] and tall old-growth trees.[200] Drought hastens tree mortality over a wide range of temperatures.[201] On the Colorado Plateau in Utah, five years of hotter temperatures in experiments killed microbial biocrusts, which conserve soil fertility and protect soils from erosion.[202,203,204] In addition, grasslands[205,206] and desert plants[207,208] are vulnerable to increased plant death.

Field research in Southwest ecosystems has detected geographic shifts (Ch. 7: Ecosystems) of both plant and animal species, partly attributable to climate change. In Yosemite National Park, forest shifted into subalpine meadows from 1880 to 2002,[209] and small mammals shifted 1,600 feet (500 m) upslope from 1914 to 2006,[210] with climate change outweighing other factors as the cause.[209,210] Across the United States, including the Southwest, birds shifted northward between 0.1 and 0.5 miles (0.2 to 0.8 km) per year from 1975 to 2004, and analyses attribute the shift to climate change.[211,212]

Continued climate change would cause north–south or upslope shifts of biomes (major vegetation types) in the Southwest as vegetation follows cooler temperatures.[213] Areas highly vulnerable to such biome shifts include the Arizona Sky Islands[214] and the Sierra Nevada.[215] Potential shifts of suitable habitat for individual species include the shifting of Joshua tree habitat out of much of Joshua Tree National Park,[207,216] American pika habitat shifting off of mountain tops,[217,218] and upslope or northward shifts of numerous birds and reptiles across the Southwest.[219,220,221] Climate change may also cause shifts in the timing of plant and animal life events (phenology), including flower blooming, plant leafing, and breeding time of birds and other animals.[222,223,224] The arrival of migrating broad-tailed hummingbirds in Colorado advanced five days between 1975 and 2011.[225] Plant species that provide essential food (nectar) for the hummingbirds also shifted in phenology (Ch. 7: Ecosystems), but much more than the birds, potentially jeopardizing breeding success.

To prepare for potential future ecological changes, U.S. federal agencies have begun to integrate climate change science into resource management planning in the Southwest. For example, the U.S. National Park Service has developed park plans with specific actions for managing resources under climate change.[226] On private lands, planning that integrates native plants and wildlife into working landscapes such as farms, orchards, and ranches can promote conservation outside of protected areas and provide valued ecosystem services,

The 2013 Rim Fire in California burned more than 257,000 acres, the second largest wildfire in the Sierra Nevada and the third largest fire in California since 1932. Photo credit: Mike McMillan, U.S. Forest Service.

as demonstrated for rangelands by the Malpai Borderlands Group in Arizona and New Mexico.[227,228] In response to severe wildfires, the City of Flagstaff, Arizona, enacted a bond to provide funds to thin forest around the town perimeter.[229,230] Ecosystem restoration provides an opportunity to integrate climate change considerations into natural resource management.[231] Desert research scientists have developed the ability to grow microbial biocrusts and are testing whether translocating biocrusts that are adapted to thrive at higher temperatures can restore the soil-stabilizing, nutrient-fixing, and other services that these organisms provide in many Southwest desert ecosystems.[232,233,234] Finally, conservation of forests, especially coast redwoods, which have the highest carbon densities of any ecosystem in the world,[235] can slow or reduce climate change by naturally removing carbon from the atmosphere.[6]

Key Message 3

The Coast

Many coastal resources in the Southwest have been affected by sea level rise, ocean warming, and reduced ocean oxygen—all impacts of human-caused climate change—and ocean acidification resulting from human emissions of carbon dioxide. Homes and other coastal infrastructure, marine flora and fauna, and people who depend on coastal resources face increased risks under continued climate change.

At the Golden Gate Bridge in San Francisco, sea level rose 9 inches (22 cm) between 1854 and 2016 (Figure 25.5),[236] and in San Diego, sea level rose 9.5 inches (24 cm) from 1906 to 2016.[237] Tidal gauges around the world show increases in sea level,[238,239] and analyses show that climate change caused most of this rise by melting of land ice and thermal expansion of ocean water.[21,240,241] Non-climate-related land level changes influence relative sea level change. For example, between Cape Mendocino, California, and the Oregon border, lifting of the land at the San Andreas Fault has caused a drop in relative sea level between 1933 and 2016. Past earthquakes in the northern California coastal zone have abruptly lowered the shoreline and raised relative sea level.[242]

Under the higher scenario (RCP8.5), continued climate change could raise sea level near San Francisco by 30 inches (76 cm) by 2100, with a range of 19–41 inches (49–104 cm).[242] Currently, 200,000 people in California live in areas 3 feet (0.9 m) or less above sea level.[9] Projections of sea level rise show that this population lives in areas at risk of inundation by 2100.[9] Storm surges and high tides on top of sea level rise would exacerbate flooding.[242] In Redwood City, one-fifth of houses and one-quarter of roads are at risk of flooding under the higher scenario (RCP8.5) by 2100.[243] Sea level rise and storm surge could completely erode two-thirds of southern California beaches by 2100[244] and cause saltwater infiltration that would spoil groundwater at Stinson Beach in Marin County, California.[245] Major seaports in Long Beach and Oakland and the international airports of San Francisco, Oakland, and San Diego are vulnerable. Projected sea level rise and storm surges could cause as much as $5 billion (2015 dollars, undiscounted) in damage to property along the California coast from 2000 to 2100 under the higher scenario (RCP8.5).[178] In Point Reyes National Seashore, sea level rise threatens to inundate habitat for the endangered western snowy plover, harbor seals,[246] and northern elephant seals,[247] as well as archaeological Indigenous sites.

Governments and private landowners along the California coast have built seawalls, revetments, and other structures to protect against sea level rise and storm surge, armoring 10% of the coastline.[248] Because hard structures often alter natural water flows and increase coastal erosion, many parties are now exploring how to restore dunes, reefs, wetlands, and other natural features to protect the coast by breaking wave energy, to increase wildlife habitat, and to preserve public access to the coast.[249]

Local governments on the California coast are using projections of sea level rise to develop plans to reduce future risks. The City of San Francisco[250] is implementing a plan that limits building in low-lying areas, constructs terraced wetlands at India Basin to facilitate upland migration of marsh habitat, and protects San Francisco International Airport with berms and seawalls along the 8-mile (13 km) shoreline. Golden Gate National Recreation Area has produced a detailed spatial analysis of the vulnerability of the marsh, paths, and buildings at Crissy Field to sea level rise and storm surges and has developed adaptation options, including moving infrastructure and establishing protective wetlands on inundated land.[251] In 2016, residents of the nine counties of the San Francisco Bay passed Measure AA, which provides funding for wetlands restoration to naturally reduce risks of flooding and inundation due to sea level rise and storm surge.

Ocean waters off the California coast and around the world warmed 0.6° to 0.8ºF (0.3° to 0.5ºC) from 1971 to 2010,[252] mainly due to human-caused climate change.[21] Over the past century, sea surface temperatures in the northeast Pacific Ocean (including those off the coast of California) also experienced large year-to-year and decade-to-decade variations in response to changes in wind and weather patterns that altered the exchange of heat between the ocean and atmosphere and within the upper ocean,[253] but showed overall warming from 1920 to 2016 (Figure. 25.6).

Sea Level Rise

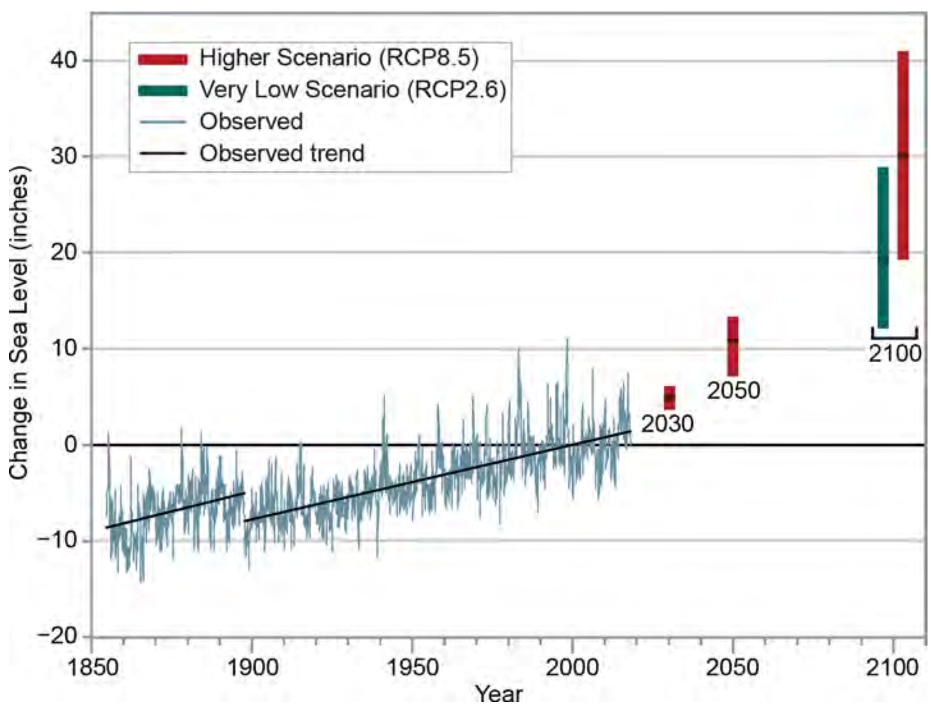


Figure 25.5: Sea level rise increases risks to infrastructure. At the Golden Gate Bridge in San Francisco, California, the tidal gauge with the longest time series in the Western Hemisphere shows that sea level has risen nearly 9 inches (22 cm) since 1854 (blue line).[236,295] In 1897, the tidal gauge was moved, which caused a slight shift downward of the numerical level but no change in the long-term trend (trends indicated by the black lines). The bars show models projections of sea levels under a higher scenario (RCP8.5; red) and a very low scenario (RCP2.6; green).[242] The change in sea level is shown relative to the 1991–2009 average. Source: National Park Service.

Ocean Temperature Increase

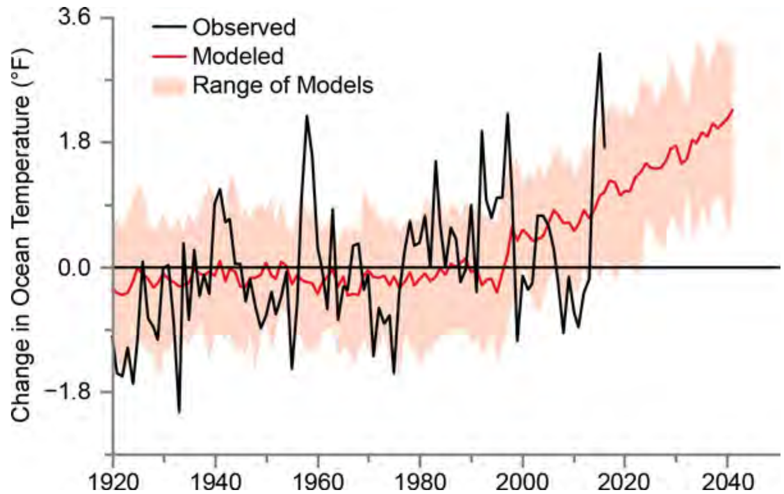


Figure 25.6 Ocean warming increases risks to fisheries and shellfish. The graph shows observed ocean temperatures of the California Current from measurements (black line); modeled temperatures, extended into the future under the higher scenario (RCP8.5; red line); and the range of 10% to 90% of the 28 models used (pink).[254,296,297] Sources: National Park Service and NOAA.

The marine heat wave along the Pacific Coast from 2014 to 2016 occurred due to a combination of natural factors and climate change.[254] The event led to the mass stranding of sick or starving birds and sea lions and shifts in pelagic (open water) red crabs and tuna into the region.[255] The ecosystem disruptions contributed to closures of commercially important fisheries and substantial reductions in California salmon catches in 2016 and 2017.[256,257,258] Ocean warming also contributed to an increase in harmful blooms of algae along the Pacific Coast.[259,260,261,262] These harmful algal blooms have produced domoic acid, which can kill people who eat tainted shellfish[261,263] and kill California sea lions.[261,264,265] Harmful algal blooms and shellfish contamination in the record warm year of 2015 delayed the commercially important Dungeness crab fishery, which contributed to a substantially reduced catch. Shifts in the timing of Dungeness and rock crab fisheries into whale migration season in 2016 contributed to increases in whale entanglements in fishing gear.[266]

Continued climate change could warm California Current waters 4°–7°F (2°–4°C) above the 1980–2005 average by 2100 (Figure 25.6).[267] This could contribute to more harmful algal blooms,[259,261] deaths of birds and sea lions, closures of fisheries, and economic loss to sectors dependent upon coastal marine resources. Under higher emissions (SRES A2), 28 fish species, including coho salmon and steelhead, could shift northward more than 180 miles (300 km) by 2050 due to higher sea surface temperatures.[268] Marine heat waves may also increase in frequency, possibly causing local disappearance of some fish and economic losses.[269]

Observed ocean water acidity off the coast of California increased 25% to 40% (decreases of about 0.10 to 0.15 pH units) from the preindustrial era (circa 1750) to the early 2000s[270,271] due to increasing emissions of carbon dioxide from human activities.[21,272] Modeling studies show that human-caused changes in ocean acidity have increased beyond what would be expected from natural variations in the early-to-mid-20th century.[273] Along the California coast, during some episodes of naturally acidic spring/summer upwelling of deeper ocean water, ocean acidity has quadrupled (a decrease of 0.7 pH units) to some of the most acidic values in the world.[274] Increased ocean acidity along California's coast has dissolved shells of some small planktonic sea snails (pteropods), exceeding their adaptive capacity, which was developed from evolution in natural acidic upwellings.[275,276,277] In contrast, nearshore kelp forests in the northern Channel Islands off the California coast experienced few acidic events compared to local mainland sites in one three-year study.[278]

Higher carbon emissions (SRES A2) could increase the acidity of California coastal waters 40% (a decrease of 0.15 pH units) above 1995 levels by 2050.[270] In addition to damaging marine ecosystems, ocean acidification increases risks of economic losses in the shellfish industry. One ecosystem modeling study suggests negative effects of projected ocean acidification on California's state-managed crab, shrimp, mussel, clam, and oyster fisheries, but an increase in the urchin fishery.[279] Warming of ocean waters has reduced oxygen concentrations in the California Current System by 20% from 1980 to 2012.[280,281] Dissolved oxygen variations in waters far offshore affect oxygen concentrations in the California Current System nearshore.[280,282] This deoxygenation contributed to an expansion of Humboldt squid, a species that thrives in deoxygenated water, in the northeastern Pacific Ocean in the late 1990s.[283,284] Invading Humboldt squid prey on hake and other fish that are commercially important to coastal fishing communities.[283]

Climate change may reduce ocean oxygen in Pacific Ocean waters to levels lower than any naturally occurring levels as early as 2030[285] or 2050.[273] Reduced oxygen could decrease rockfish habitat off southern California by 20% to 50%.[286] Further deoxygenation may harm bottom-dwelling marine life, shrink open-water habitat for hake and other economically important species,[287] and increase the number of invasions by squid. Tracking the variability of ocean waters and fish populations and adjusting catch quotas accordingly can reduce pressures on fisheries stressed by climate change,[288] actions that have been identified as parts of the National Oceanic and Atmospheric Administration's (NOAA) Fisheries Climate Science Strategy.[289]

With continued climate change, risks would cascade from one area to another. For example, projected warmer winter temperatures in the Sierra Nevada would increase winter runoff, reduce spring and summer freshwater inflows into San Francisco Bay, and increase salinity in the Bay 3 to 5 grams per kilogram of water by 2100.[290,291,292] Also, sea level rise and storm surge would compound effects inland of river and stream flooding, putting houses and roads at risk of inundation and damage.[293,294]

Key Message 4

Indigenous Peoples

Traditional foods, natural resource-based livelihoods, cultural resources, and spiritual well-being of Indigenous peoples in the Southwest are increasingly affected by drought, wildfire, and changing ocean conditions. Because future changes would further disrupt the ecosystems on which Indigenous peoples depend, tribes are implementing adaptation measures and emissions reduction actions.

Droughts in the Southwest have contributed to declines in traditional Indigenous staple foods, including acorns, corn, and pine nuts.[298,299,300] Drought and increasing heat intensify the arid conditions of reservations where the United States restricted some tribal nations in the Southwest region to the driest portions of their traditional homelands.[301] Navajo elders tell of the increasingly arid conditions over the last half of the 20th century that contributed to declines in culturally significant crops, the flow of specific water springs and seeps, and wildlife populations, such as eagles.[44,302] Projected reductions in water supply reliability,[13,114] coupled with water agreements that involve selling or leasing tribal water to neighboring communities, could place tribal water supplies at risk during severe shortages. As water supplies decrease and water demand increases, tribes are at risk of finding themselves committed to providing purchased water to other entities, resulting in situations in which, in the words of one elder, "water sold must be delivered, regardless of the condition of the selling reservation. In this worst-case scenario, the Community will have to breach its contracts for the survival of its people."[303]

In addition to drought, wildfires affect traditional resources, including fish, wildlife, and plants, such as tanoaks and beargrass, upon which some Southwest tribes rely for food and cultural uses.[304,305,306] Continued climate change would reduce populations of some fish, wildlife, and plants that serve as traditional foods, medicines, and livelihood and cultural resources.[298,307,308] Reduced availability of traditional foods often contributes to poorer nutrition and an increase in diabetes and heart disease.[298,309] Reductions in runoff would, for example, increase the salinity of Pyramid Lake in Nevada, reducing fish biodiversity and affecting the cui-ui fish, the primary cultural resource of the Pyramid Lake Paiute Tribe.[310] Tribes in the Southwest that depend on livestock are at risk of climate-related degradation of rangelands.[44,311,312] Many California tribes, including the Miwok, Paiute, Western Mono, and Yurok, among others, are concerned about the loss of acorns—a nutritious traditional food, medicine, and basketry component[313,314]—due to sudden oak death, which can increase with changes in humidity and temperature.[44,312,315] Changes in plant and animal ranges (Ch. 7: Ecosystems, KM 1) can also affect mental and spiritual health, disrupting cultural connections to disappearing plant and animal relatives and to place-based identity and practices.[42,316]

Changes in marine ecosystems affect resources for Indigenous peoples (Ch. 15: Tribes). Ocean warming affects salmon and other fish on which Pacific Coast tribes rely for subsistence, livelihoods, and cultural identity.[307,317,318,319,320] Ocean warming and acidification, as well as sea level rise, increase risks to shellfish beds (which reduces access for traditional harvesting),[298] pathogens that cause shellfish poisoning,[307,311] and damage to shellfish populations, which can cause cascading effects in food and ecological systems upon which some tribes depend.[298,321]

Although Indigenous peoples have adapted to climate variations in the past, historical intergenerational trauma, extractive infrastructure, and socioeconomic and political pressures[322,323] reduce their adaptive capacity to current and future climate change (Ch 15: Tribes, KM 1 and 3).[324] Still, in response to climate change, Indigenous peoples in the Southwest are developing new adaptation and mitigation actions based on a cultural model focused on relationships between humans and nonhumans.[313,325,326] Traditional ecological knowledge of specific plants and habitats can enable Indigenous peoples to provide early detection of invasive species and support to ecological restoration.[327] Some tribes, such as the Tesuque Pueblo of New Mexico, use their knowledge to reintegrate traditional foods into their diets. Other tribes, such as the Karuk Tribe,[304] North Fork Mono,[313] and Mountain Maidu[328] use traditional ecological knowledge to guide natural resource management. The Yurok Tribe, Gila River Indian Community, and Tohono O'odham Nation, among others, are developing climate adaptation plans, often in partnership with universities and other research institutions (Ch. 15: Tribes, KM 3 and Figure 15.1).

Many Indigenous peoples in the Southwest region have traditionally used fire as a tool central to cultural and spiritual practices. They use fire to protect and enhance species used for basket weaving, medicines, and traditional foods.[306,313,328,329,330,331,332] This cultural use of fire offers an important tool for adaptation and mitigation, as traditional burning reduces fuel accumulations that can lead to high-severity wildfires (see Case Study "Cultural Fire and Climate Resilience" and Figure 25.7).[331,333]

Case Study: Cultural Fire and Climate Resilience

Indigenous peoples in the Southwest have traditionally used fire as a tool central to social, cultural, and spiritual practices. They use fire to increase ecosystem resilience, reduce fuel loads, manage crops, and protect species used for basket weaving, medicines, and traditional foods.[306,313,328,329,330,331,332] Tribal entities are restoring cultural burning practices and management principles that guide the use of fire on the landscape to reduce wildfire risks and protect public and tribal trust resources.[331,333] For example, Yurok tribal members have formed the Cultural Fire Management Council (CFMC), in partnership with the Nature Conservancy Fire Learning Network, Firestorm Inc., Yurok Forestry/Wildland Fire, Northern California Indian Development Council, and the U.S. Department of Agriculture (USDA) Forest Service, to bring fire back to the landscape for ecosystem restoration.[334] The collaboration builds capacity and trains Yurok and local fire crews through the Prescribed Fire Training Exchange. "Restoration of the land means restoration of the people," said CFMC President Margo Robbins, "Returning fire to the land enables us to continue the traditions of our ancestors."[334]

Cultural Fire on Yurok Reservation

Figure 25.7: Andy Lamebear, a Yurok Wildland Fire Department firefighter and Yurok tribal member, ignites a cultural burn on the Yurok Reservation. The tribe uses low- to medium- intensity fires to enhance the production of plant-based medicines, traditional basket materials, native fruits, and forage for wildlife. Cultural burning also reduces risks of catastrophic wildfire. Photo courtesy of the Yurok Tribe.

Key Message 5

Energy

The ability of hydropower and fossil fuel electricity generation to meet growing energy use in the Southwest is decreasing as a result of drought and rising temperatures. Many renewable energy sources offer increased electricity reliability, lower water intensity of energy generation, reduced greenhouse gas emissions, and new economic opportunities.

Hydroelectric generation depends on sufficient water supplies. The severe drought in California, intensified by climate change,[14,56] reduced hydroelectric generation by two-thirds from 2011 to 2015.[335] Drought in the Colorado River Basin[13,59] caused river runoff, on which hydroelectric generation depends,[12,336,337] to decline. By 2016, Lake Mead, which stores water for drinking, agriculture, and the Hoover Dam hydroelectric plant, had fallen by half (Box 25.1 and Figure 25.3). Although the Bureau of Reclamation maintained constant electricity generation at Hoover Dam throughout the drought, this decline potentially reduces maximum generation capacity.

In California, utilities increased fossil fuel generation of electricity to compensate for the drought-driven decline in hydroelectricity, increasing state carbon dioxide emissions in the first year of the drought (2011 to 2012) by 1.8 million tons of carbon, the equivalent of emissions from roughly 1 million cars.[338,339] A drop in the price of natural gas also contributed to the increase, although the shift from hydroelectric to fossil fuels cost California an estimated $2.0 billion (in 2015 dollars).[340] Other southwestern states also shifted some generation from hydropower to fossil fuels.[89]

Under a higher scenario (RCP8.5), declines in snowpack and runoff in the Colorado River and Rio Grande Basins and a shift of spring runoff to earlier in the year[105] would reduce hydroelectric power potential in the region by up to 15% by 2050.[91] Under a very low scenario (RCP2.6), hydroelectric generation may remain unchanged, demonstrating the positive benefits of emissions reductions.[91] With increased precipitation, hydroelectric potential could increase,[342] except in cases of reservoir spillage to protect dams in extreme storms.[343]

The efficiency of water-cooled electric power plants that burn fuel depends on the temperature of the external cooling water, so climate change could reduce energy efficiency up to 15% across the Southwest region by 2050.[91] Since higher temperatures also increase electric resistance in transmission lines, electricity losses in many transmission lines across the Southwest could reach 5% by 2080 under a lower scenario (RCP4.5) and 7% under a higher scenario (RCP8.5).[344] Under the higher scenario (RCP8.5), water demand by thermoelectric plants in the Southwest is projected to increase 8% by 2100.[345] In a 10-year drought, summer electric generating potential in the Southwest could fall 3% to 9% under higher emissions (SRES A2) or 1% to 7% under lower emissions (SRES B1; Figure 25.8).[346]

Any increase in water requirements for energy generation from fossil fuels would coincide with reduced water supply reliability from projected decreases in snowpack[46,77] and earlier snowmelt.[75,347] Increased agricultural water demands under higher temperatures could affect the seasonal demand for hydropower electricity.[105] The water consumption, pollution, and greenhouse gas emissions of hydraulic fracturing (fracking) make that source of fuel even less adaptive under climate change.[348] Substantial energy and carbon emissions are embedded in the pumping, treatment, and transport of water, so renewable-powered water systems are less energy and carbon intense than ones powered by fossil fuels.[349]

Economic conditions and technological innovations have lowered renewable energy costs and increased renewable energy generation in the Southwest. For example, wind energy generation in California rose by half from 2011 to 2015, and solar energy generation increased by 15 times.[335]

Solar, wind, and other renewable energy sources, except biofuels, emit less carbon and require less water than fossil fuel energy. By cutting carbon emissions, renewable energy can reduce future impacts of climate change on nature and human well-being.[30,350,351,352] After the first year of the drought, when natural gas burning increased to compensate for a loss of hydroelectric energy, solar and wind energy sources in California increased enough to displace 15% of fossil fuel burning for electricity from 2012 to 2017, thereby reducing state greenhouse gas emissions by 6%.[335] Increased electricity generation by renewable sources can cut water needs up to 90% in the Southwest, depending on the fraction of production derived from fossil fuels.[353,354] Under a higher scenario (RCP8.5), conversion of two-thirds of fossil fuel plants to renewables would reduce water demand by half.[345]

State energy policies are facilitating the switch to renewable energy. Arizona, California, Colorado, Nevada, and New Mexico have enacted renewable energy portfolio standards.[93] California has set the highest standard: 50% of energy generation from renewable sources by 2030. In 2017, renewable energy sources supplied 32% of California energy generation.[355] By 2013, these standards had averted 26 trillion watt-hours of fossil fuel generation in the Southwest and 3% of carbon emissions nationally and had produced $5 billion in health benefits from reduced air pollution (in 2013 dollars; $5.2 billion in 2015 dollars).[356] Potential future benefits of existing renewable portfolio standards include carbon emission reductions of 6% nationally and health benefits of $560 billion (in 2013 dollars; $577 billion in 2015 dollars) from 2015 to 2050.[357]

Electricity Generation Capacity at Risk Under Continued Climate Change

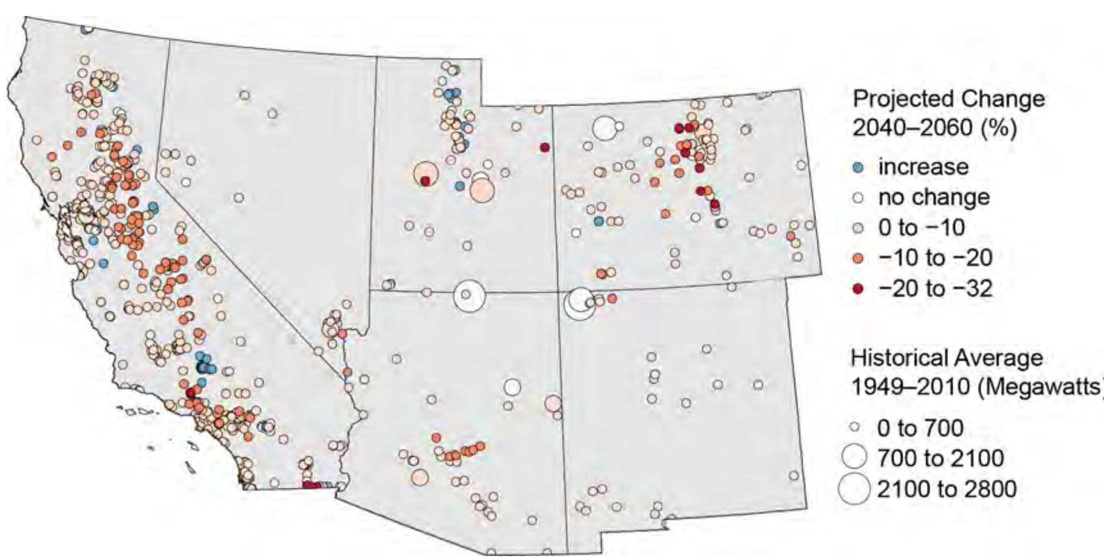


Figure 25.8: Under a higher emissions scenario (SRES A2[174]), heat-induced reduction of energy efficiency and reduced water flows would reduce summer energy generation capacity across the Southwest region. These projected reductions would increase risks of electricity shortages. The map shows projected changes for the period 2040–2060 compared to the period 1949–2010. Source: adapted from Bartos and Chester 2015.[346] Reprinted by permission from Macmillan Publishers Ltd.

Distributed solar energy systems place individual solar panels on roofs, on parking lot canopies, and other built places. The high number of sunny days in the Southwest and the great extent of existing rooftops and parking lots create a high potential for distributed solar generation, which could provide two-thirds of electricity use in California.[358] Distributed solar uses land that has already been urbanized and is close to energy users, reducing the need for transmission lines and transmission line electricity losses. Compared to industrial centralized solar power systems, distributed solar causes less death and disruption to wildlife that are already vulnerable to climate change, such as birds and endangered desert tortoises.[359] California, Colorado, and Nevada have enacted policies that support rooftop solar on homes, in particular net metering, in which customers sell their excess solar electricity to the grid.[360] Distributed wind energy systems can provide similar benefits.

Arizona, California, Colorado, Nevada, and New Mexico have enacted energy efficiency standards for utilities. California and New Mexico have also enacted policies that decouple utility profits from electricity sales.[361] White or reflective roofs, known as cool roofs, increase energy efficiency of buildings. Under a higher scenario (RCP8.5), cool roofs would reduce urban heat islands in Los Angeles and San Diego 2°–4°F (1°–2°C) by 2050 and decrease energy use and the use of air conditioning.[362] Urban tree planting in Phoenix that would increase tree cover from 10% to 25% would provide daytime cooling of up to 2°C in local neighborhoods.[363]

Newer technologies now allow generating plants to use nontraditional water sources, including saline groundwater, recycled water from landscaping, and municipal and industrial wastewater. For example, the Palo Verde Nuclear Generating Station in Arizona uses municipal wastewater.[361] Other plants in the region use extremely water-efficient hybrid wet–dry cooling technology. For instance, the Afton Generating Station in New Mexico is a natural gas combined-cycle plant that uses hybrid cooling to reduce water intensity by 60% compared to conventionally cooled plants.[361]

Electric cars can reduce fossil fuel use and greenhouse gas emissions compared to gasoline-powered vehicles. The relative greenhouse gas emissions from electric and gasoline vehicles depend on how the electricity is generated.[364,365] If the electricity is produced from renewable sources, then the operating emissions for electric vehicles are near zero, although the manufacturing of the vehicle emitted greenhouse gases. Conversely, if the electricity is produced completely from fossil fuel, the emissions from the electric vehicle are higher because of the limit of energy efficiency of large power plants and transmission line losses. Because sunlight, wind, and other renewable resources are intermittent and sometimes not available at times of demand, charging at night and improvements in battery technology would facilitate renewable energy generation.

Key Message 6

Food

Food production in the Southwest is vulnerable to water shortages. Increased drought, heat waves, and reduction of winter chill hours can harm crops and livestock; exacerbate competition for water among agriculture, energy generation, and municipal uses; and increase future food insecurity.

Climate change has altered factors fundamental to food production and rural livelihoods in the Southwest, particularly the shortage of water caused by droughts in California[14,56] and the Colorado River Basin.[13] The California drought led to losses of more than 10,000 jobs and the fallowing of 540,000 acres (220,000 hectares), at a cost of $900 million in gross crop revenue in 2015.[130] Increased temperatures in the Southwest also affected agricultural productivity from 1981 to 2010.[366]

Food production depends on reliable surface and groundwater supplies, which decline from droughts and reductions in snowpack and soil moisture.[67] Irrigated agriculture and livestock water use accounted for approximately three-quarters of total water use in the Southwest in 2010, excluding Colorado, which has wide-ranging dryland wheat production.[16,367,368] In the recent California drought, domestic wells dried out in some rural communities, but increased groundwater pumping from deeper wells prevented some agricultural revenue losses.[369] Falling groundwater tables increase pumping costs and require drilling to deepen wells.[130] Drought-related agricultural changes, stricter drilling regulations, and rapid aquifer depletion have already led to a decline in irrigation in parts of the region. According to climate projections for lower and higher emissions scenarios (RCP4.5 and RCP8.5), future changes in climate would reduce aquifer recharge in the southern part of the region by 10%–20%,[370] removing some of the secondary water source responsible for buffering effects of severe drought. In the Gila River Basin of New Mexico, farmers shift to groundwater pumping when surface water supplies are reduced, despite associated increases in production costs.[371] Under continued climate change, increased drought risk[13] and higher aridity[70] could expose some agricultural operations in the Southwest to less reliable surface and groundwater supplies (Ch. 10: Ag & Rural, KM 1).

Under continued climate change, higher temperatures would shift plant hardiness zones northward and upslope (Figure 25.9). These changes would affect individual crops differently depending on optimal crop temperature thresholds. Some crops, including corn[372] and rice,[373] are already near optimal thresholds in the Southwest. Increasing heat stress during specific phases of the plant life cycle can increase crop failures, with elevated temperatures associated with failure of warm-season vegetable crops and reduced yields or quality in other crops.[374] While crops grown in some areas might not be viable under hotter conditions, crops such as olives, cotton, kiwi, and oranges may replace them.[375] In parts of the Southwest region, increasing temperatures would prompt geographic shifts in crop production, potentially displacing existing growers and affecting rural communities.[376] Wine grape quality can be particularly influenced by elevated temperatures.[377] Increased levels of ozone and carbon dioxide near the surface, combined with increases in temperature, can decrease food quality and nutritive values of fruit and vegetable crops.[378,379]

Because many fruit and nut trees require a certain period of cold temperatures in the winter, decreased winter chill hours under continued climate change would reduce crop yields, though the magnitude may vary considerably.[380] In Yolo County, California, reduced winter chill may make conditions too hot for walnut cultivation by 2100.[381] California almond acreage has nearly doubled over the last two decades due to high foreign demand and the favorable Mediterranean climate. California now produces over 80% of world almond supply.[382] Since almonds also have a relatively high water requirement, both water and adequate cool winter temperatures will be important factors to maintain California tree nut production under climate change.

Projected Shift in Agricultural Zones

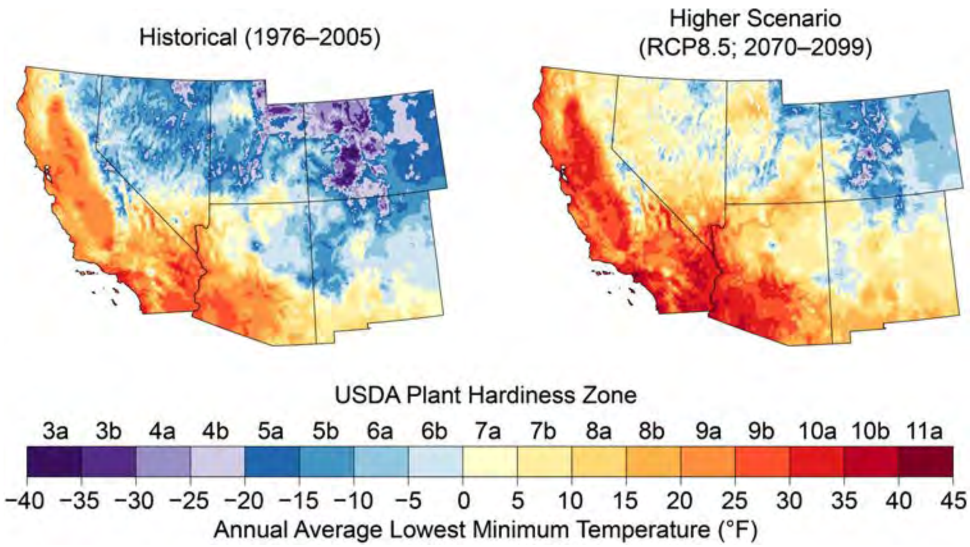


Figure 25.9: The U.S. Department of Agriculture plant hardiness zones indicate the cold temperature requirements of crops. Increases in temperature under the higher scenario (RCP8.5), would shift these zones northward and upslope, from the period 1976—2005 (left, modeled historical) compared to projections for 2070—2099 (right, average of 32 general circulation models). Sources: NOAA NCEI and CICS-NC.

Climate-related vulnerabilities of the Southwest region's livestock industry include reduced long-term livestock grazing capacity, reduced feed supply, increased heat stress (Ch. 10: Ag & Rural, KM 3), and reduced forage quality.[383] Water-intensive forage crops are especially vulnerable to water shortages.[15] Although livestock production systems persist in highly variable conditions, projected high temperatures may decrease production of rangeland vegetation and livestock forage.[384] In response to drought (1999–2004), 75% of Utah ranch operations reported major reductions in water supply, forage, and cattle productivity.[385] Only 14% felt they were adequately prepared for the drought, which may be reflected in the high use of federal relief programs.

One potential adaptation of agriculture to drought is water banking, the storage of excess surface water in groundwater aquifers.[386,387] For example, streamflows from the Sierra Nevada in high-precipitation years could provide substantial groundwater recharge in the California Central Valley.[388] Additional options include expanding surface reservoir storage or relying upon groundwater pumping, although this further depletes limited groundwater stores.[389]

Flexible livestock management strategies, such as stocking rates, grazing management practices, employing livestock bred for arid environments, erosion control, and identification of alternate forage supplies can help reduce vulnerability in an increasingly arid and variable climate.[390,391] Criollo cattle appear well-suited for the arid Southwest because they are more heat tolerant and adaptive than traditional breeds.[392]

In urban areas across the Southwest, such as Tucson, Arizona, and Sacramento, California, community food banks that grow food in community gardens can help maintain food security in a drier and more variable climate. Urban gardens and local food organizations provide fresh produce, foster community education, and support networks of local growers. These organizations build food systems capacity, which helps to mitigate impacts of urban heat, reduces food transportation costs and emissions, and supports provision of fresh local food to low-income urban dwellers.

Additional emerging issues that increase risks to food production include invasive nonnative or alien insect pests (introduced into the region intentionally or unintentionally) that are more adapted to hotter temperatures.[393] Global trade and efficient transportation also increase risks of invasion by alien insect pests. A mismatch in timing between plant flowering and the arrival of insect pollinators would reduce crop production and pollinator survival.[393] In addition, some subsistence foods, such as fish, upon which some Indigenous and other subsistence and urban communities depend,[309,394,395,396,397] and spiritually, socially, and culturally important tribal traditional foods[298] would be vulnerable in a drier and more variable climate (Key Message 4).

Key Message 7

Human Health

Heat-associated deaths and illnesses, vulnerabilities to chronic disease, and other health risks to people in the Southwest result from increases in extreme heat, poor air quality, and conditions that foster pathogen growth and spread. Improving public health systems, community infrastructure, and personal health can reduce serious health risks under future climate change.

Exposure to hotter temperatures and heat waves has led to heat-associated deaths and illnesses in Arizona and California.[398,399,400,401,402,403] In the unprecedented 2006 California heat wave, which affected much of the state and part of Nevada, extremely high temperatures occurred day and night for more than two weeks.[404] Compared to non-heat wave summer days, it is estimated that the event led to an additional 600 deaths, 16,000 emergency room visits, 1,100 hospitalizations in California,[399,405,406] and economic costs of $5.4 billion (in 2008 dollars).[405] Parts of the Southwest region experienced record-breaking heat in five of the six years from 2012 to 2017.[25,26,27,28,29] Assessments of the health impacts associated with record high temperatures in parts of the Southwest since 2010 are not yet available in the scientific literature.

Under continued climate change, projected increases in hot days and extreme heat events in the Southwest (Figure 25.10)[23,24,404,407] will increase the risk of heat-associated deaths.[30] Under the higher scenario (RCP8.5), the Southwest would experience the highest increase in annual premature deaths due to extreme heat in the country, with an estimated 850 additional deaths per year and an economic loss of $11 billion (in 2015 dollars) by 2050.[178] Under a lower scenario (RCP4.5), deaths and costs would be reduced by half compared to the higher scenario (RCP8.5).[178] By 2090, deaths and economic losses would more than double from 2050 under all emissions scenarios.[178] Heat and other environmental exposures particularly affect outdoor workers.[178] Under the higher scenario (RCP8.5), extreme heat in the Southwest (Figure 25.10) would also lead to high labor losses, including losses of high-risk labor hours of up to 6.5% for some counties by 2090 and of $23 billion per year in regionwide wages (in 2015 dollars).[178] It is projected that the lower scenario (RCP4.5) would reduce those wage losses by half.[178]

The risk of illness or death associated with extreme temperatures can be reduced through targeted public health and clinical interventions.[30,32] The main factors that put individuals and populations at increased risk in a heat wave are age (children and older adults are most at risk), hydration status, and presence of a chronic disease such as obesity, cardiovascular or respiratory disease, or psychiatric illness.[400,408,409,410,411,412,413,414,415] Psychosocial stresses and socioeconomic conditions, such as hot and poorly ventilated homes or lack of access to public emergency cooling centers can elevate these risks.[31,33,416]

Without adoption and implementation of strategies to minimize exposures to extended periods of extreme heat, the public health impacts of future heat waves may be as serious as those observed in California in 2006. The technological and behavioral adaptations to heat developed by populations in the Southwest are based on the observed historical range of nighttime minimum temperatures.[404] Projected increases in minimum temperatures and decreases in the number of cool nights[23] may diminish the efficacy of these adaptations.

Climate change and variability can also increase communicable and chronic disease burdens.[417,418,419] While infectious diseases like plague and hantavirus pulmonary syndrome disproportionately affect the Southwest region,[158] new research to support estimating future climate-associated risk for these diseases is sparse.[420] Therefore, this assessment focuses on recent developments in the understanding of heat, air quality, mosquito-borne diseases, and Valley fever and vulnerabilities that influence them.

In addition to extreme heat, the environmental conditions of greatest concern for human health are ground-level ozone air pollution, dust storms, particulate air pollution (such as from wildfires and dust storms), aeroallergens (airborne substances that trigger allergic reactions), and low water quality and availability.[30,178] In addition, alternating episodes of drought and extreme precipitation coupled with increasing temperatures promote the growth and transmission of pathogens.[30,421] The risk of onset or exacerbation of respiratory and cardiovascular disease is associated with a single or a combined exposure to ground-level ozone pollution, particulate air pollution, respiratory allergens, and extreme heat. Ground-level ozone is produced by chemical reactions of combustion-related chemicals (for example, from vehicles or wildfires) in a reaction that is dependent on ultraviolet radiation (that is, from the sun) and amplified by higher temperatures. Once formed, ozone can travel great distances and persist in high concentrations overnight in rural areas. Among many health impacts, ozone can promote or aggravate asthma and respiratory allergies.[422,423,424,425]

Projected Increases in Extreme Heat

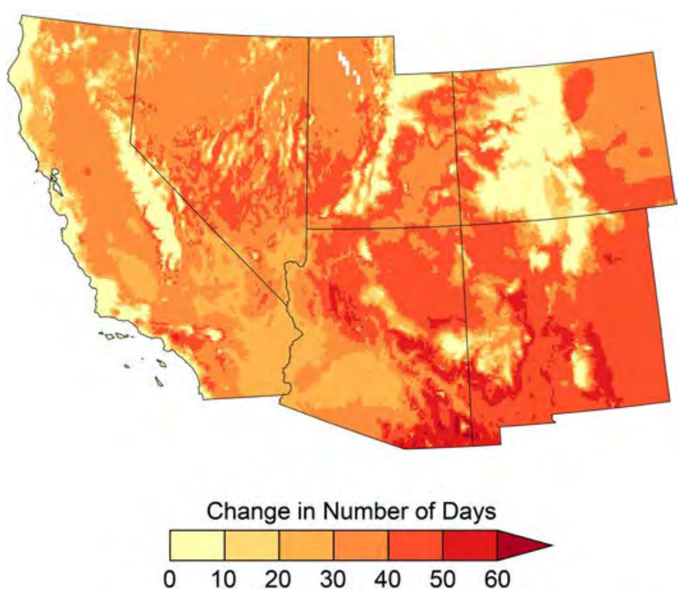


Figure 25.10: Under the higher scenario (RCP8.5), extreme heat would increase across the Southwest, shown here as the increase in the average number of days per year when the temperature exceeds 90°F (32°C) by the period 2036–2065, compared to the period 1976–2005.[23] Heat waves increase the exposure of people to heat stroke and other illnesses that could cause death.[30] Source: adapted from Vose et al. 2017.[23]

Elevated levels of CO_2 in conjunction with higher temperatures can increase the amount and potency of aeroallergens (Ch. 14: Human Health, KM 1). These conditions may also lead to new cases or exacerbation of allergy and asthma.[426,427,428,429] Mortality risk during a heat wave is amplified on days with high levels of ground-level ozone or particulate air pollution, with the greatest mortality due to cardiovascular causes.[430]

Severe dust storms in the Southwest contribute to respiratory and cardiovascular disease.[431,432] The association between Valley fever, a soilborne fungal respiratory infection of the Southwest, and warmer temperatures and soil dryness varies across the region and by time of year.[189,433,434] The connection between climate change, dust storm frequency and severity, and future public health effects in the region is complex and remains an emerging area of research.[435,436,437,438,439] Heat extremes, warming, and changes in precipitation will also influence the distribution and occurrence of vector-borne diseases like West Nile virus[440,441,442,443] and may lead to the emergence of new disease (Ch. 14: Human Health, KM 1).[30] Without proactive interventions and policies that address the biological, exposure, and socioeconomic factors that influence individual and population vulnerability, adverse health impacts may increase (Ch. 14: Human Health, KM 2). Those increases may disproportionately affect people with the lowest incomes, which hinders adaptive capacity (Ch. 14: Human Health, KM 1).[416,444]

Climate-related hazards such as heat waves, flooding, wildfires, or large disease outbreaks require emergency responses. Prolonged droughts can affect drinking water availability, reduce water quality,[445] and send more people seeking medical treatment.[446,447] The increased burden of disease can outpace the resources and adaptive capacity of public health and clinical infrastructures. The region may not be prepared to absorb the additional patient load that could accompany climate change,[448] but integrating risk reduction strategies into emergency response plans and recognizing and addressing vulnerability factors can appreciably reduce risks of future adverse health consequences (Ch. 14: Human Health, KM 3). This approach is embodied in the Centers for Disease Control and Prevention's (CDC) Building Resilience Against Climate Effects framework for adaptation planning.[449] Adaptation planning is already yielding health protection benefits.[450]

Local government agencies are preparing for extreme events by developing and updating emergency response plans and improving public warning and response systems. In 2014, California updated its Contingency Plan for Excessive Heat Emergencies,[451] Arizona released its Heat Emergency Response Plan,[452] and Salt Lake City, San Francisco, and Sonoma County were recognized in the first cohort of U.S. Department of Energy Climate Action Champions. Integrated and participatory planning for extreme heat,[453] such as the Capital Region Climate Readiness Collaborative in Sacramento, California, can help overcome institutional and governance barriers to implementing adaptation actions (Ch. 28: Adaptation).[454]

Policies and interventions related to one health factor can positively affect other factors and yield co-benefits[455,456,457,458,459] For example, research shows that heat-associated deaths and illnesses are preventable[460] and that healthier individuals are less susceptible to adverse effects of extreme heat exposure. Obesity, which affects about 30% of adults and 15% of school-age children and teens nationwide, increases the risk for many chronic diseases, such as asthma and diabetes, and increases the risk for serious heat-related adverse health outcomes.[32,461,462,463] Access to healthcare, social isolation, housing quality, and neighborhood poverty are also key risk factors for heat-related health impacts.[31,33,412]

Urban design strategies to address these risk factors include increasing walkability and bicycle safety and maintaining and planting trees and green space.[464] These strategies can achieve multiple health benefits, including increasing physical activity, thereby helping residents maintain a healthy weight,[465,466] reducing the urban heat island effect,[467] and reducing exposure to harmful air pollutants from vehicles. Reducing the urban heat island effect also reduces energy demand and risks of power outages, which can contribute to health risks, such as patients losing access to electricity-dependent medical devices.

Climate change may weigh heavily on mental health in the general population and those already struggling with mental health disorders.[468,469,470,471,472] One impact of rising temperatures, especially in combination with environmental and socioeconomic stresses, is violence towards others and towards self.[473,474,475] Slow-moving disasters, such as drought, may affect mental health over many years.[470] Studies of chronic stress indicate a potentially diminished ability to cope with subsequent exposures to stress.[476,477,478]

Populations under chronic social and economic stresses in urban and rural areas possess lower psychological, physical, and economic resilience (Ch. 10: Ag & Rural, KM 3). Communities that rely especially on well-functioning natural and agricultural systems in specific locations may be especially vulnerable to mental health effects when those systems fail. In the Southwest, the loss of stability and certainty in natural systems may affect physical, mental, and spiritual health of Indigenous peoples with close ties to the land.[42,316] For example, extended drought raises concerns about maintaining Navajo Nation water-based ceremonies essential for spiritual health, livelihoods, cultural values, and overall well-being.[301]

Acknowledgments

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Opening Image Credit

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Traceable Accounts

Process Description

The authors examined the scientific literature in their areas of expertise. The team placed the highest weight on scientific articles published in refereed peer-reviewed journals. Other sources included published books, government technical reports, and, for data, government websites. The U.S. Global Change Research Program issued a public call for technical input and provided the authors with the submissions. The University of Arizona Center for Climate Adaptation Science and Solutions organized the Southwest Regional Stakeholder Engagement Workshop on January 28, 2017, with over 70 participants at the main location in Tucson, AZ, and dozens of participants in Albuquerque, NM, Boulder, CO, Davis, CA, Los Angeles, CA, Reno, NV, and Salt Lake City, UT, all connected by video. Participants included scientists and managers. The author team met the following day for their only meeting in person. Subsequently, authors held discussions in regular teleconferences. Many chapter authors met at the all-author meeting March 26–28, 2018, in Bethesda, MD.

Key Message 1

Water Resources

Water for people and nature in the Southwest has declined during droughts, due in part to human-caused climate change (*very high confidence*). Intensifying droughts (*very high confidence*) and occasional large floods (*medium confidence*), combined with critical water demands from a growing population, deteriorating infrastructure, and groundwater depletion, suggest the need for flexible water management techniques that address changing risks over time (*high confidence*), balancing declining supplies with greater demands.

Description of evidence base

Research has found that hotter temperatures can make hydrologic droughts more severe. The unprecedented droughts in the Colorado River Basin and California showed that increased temperatures from climate change intensified the severity of the drought.[13,14,56,59] Climate change, more than natural cycles, has reduced snowpack.[46,49] Models project more drought under climate change,[13,56,62] snowpack and streamflow decline in parts of the Southwest, and decreasing surface water supply reliability for cities, agriculture, and ecosystems.[479]

Major uncertainties

Projecting future streamflow and hydrologic characteristics in a basin contains many uncertainties. These differences arise because of uncertainty in temperature and precipitation projections due to differences among global climate models (GCMs), uncertainty in regional downscaling, uncertainty in hydrological modeling, and differences in emissions, aerosols, and other forcing factors. Another important uncertainty is differences in the hemispheric and regional-scale atmospheric circulation patterns produced by different GCMs, which generate different levels of snow loss in different model simulations. A key uncertainty is the wide range in projections of future precipitation across the Southwest;[105] some projections of higher-than-average precipitation in the northern parts of the Southwest could roughly offset declines in warm-season runoff associated with warming.[105]

Detection is the finding of statistically significant changes different from natural cycles. Attribution is the analysis of the relative contribution of different causes and whether greenhouse gas emissions from human sources outweigh other factors. Attribution of extreme events, such as the recent California drought to climate change, is an area of emerging science. On the one hand, Seager et al. (2015)[58] concluded that the California drought was primarily driven by natural precipitation variability. Sea surface temperature anomalies helped set up the high-pressure ridge over California that blocked moisture from moving inland. On the other hand, Diffenbaugh et al. (2015),[56] Williams et al. (2015),[14] and Berg and Hall (2017)[55] concluded that high temperatures from climate change drove record-setting surface soil moisture deficits that made the drought more severe than it would have been without climate change. Storage of increased precipitation in soils may partially offset increased evaporation, possibly making drought less likely.[480]

In addition to the uncertainties in regional climate and hydrology projections and attribution studies, other uncertainties include potential changes in water management strategies and responses to accommodate the new changing baseline. Additionally, external uncertainties can impact water use in the region via legal, economic, and institutional options for augmenting existing supplies, adding underground storage and recovery infrastructure, and fostering further water conservation, changes in unresolved water rights, and changes to local, state, tribal, regional and national policies related to the balance of agricultural, ecosystem, and urban water use.

Description of confidence and likelihood

The *very high confidence* in historical droughts derives from the detection and attribution analyses of temperature increases, snow decreases, and soil moisture decreases that have documented hydrologic droughts in California and the Colorado River Basin due to anthropogenic climate change and the conclusions of the *Climate Science Special Report* (CSSR), Volume I of the Fourth National Climate Assessment.[74] The *very high confidence* in drought projections derives from the multitude of analyses projecting drought in the Southwest under a range of emissions scenarios and the conclusions of the CSSR.[74] Only *medium confidence* is found for flood projections due to lack of consensus in the model projections of precipitation. Increasingly arid conditions and the potential for increased water use by people lead to an assessment of *high confidence* in the need for new ways to address increasing risks of water scarcity. The actual frequency and duration of water supply disruptions will depend on the preparation of water resource managers with drought and flood plans, the flexibility of water resource managers to implement or change those plans in response to altered circumstances,[481] the availability of funding to make infrastructure more resilient, and the magnitude and frequency of climate extremes.

Key Message 2

Ecosystems and Ecosystem Services

The integrity of Southwest forests and other ecosystems and their ability to provide natural habitat, clean water, and economic livelihoods have declined as a result of recent droughts and wildfire due in part to human-caused climate change (*high confidence*). Greenhouse gas emissions reductions, fire management, and other actions can help reduce future vulnerabilities of ecosystems and human well-being (*high confidence*).

Description of evidence base

Scientific research in the Southwest has provided many cases of detection and attribution of historical climate change impacts. Detection is the finding of statistically significant changes different from natural cycles. Attribution is the analysis of the relative contribution of different causes and whether greenhouse gas emissions from human sources outweigh other factors. Published field research has detected ecological changes in the Southwest and attributed much of the causes of the changes to climate change. Wildfire across the western United States doubled from 1984 to 2015, compared to what would have burned without climate change, based on analyses of eight fuel aridity metrics calculated from observed data, historical observed temperature, and historical modeled temperature from global climate models.[7] The increased heat has intensified droughts in the Southwest,[13,14] reduced snowpack,[49,156] and advanced spring warmth.[101] These changes have dried forests,[154,155] driving the wildfire increase.[7,153] Tree death across the western United States doubled from 1955 to 2007[146] likely due to increased heat,[21] wildfire,[7] and bark beetle infestations,[148,149] all of which are mainly attributable to climate change[7,148,149] more than to other factors such as fire exclusion or competition for light and water.[146] In the Yosemite National Park biome shift,[209] the research analyzed the relative contributions of temperature, precipitation, and the Pacific Decadal Oscillation. The researchers found that "Minimum temperature was the main effect related to accelerating annual branch growth in krummholz whitebark pine and initiation of pine invasion into formerly persistent snowfield openings." In the Yosemite National Park small mammal range shift,[210] the locations of the monitoring sites allowed relative isolation of climate change factors. Moritz et al. (2008)[210] state, "The transect spans YNP [Yosemite National Park], a protected landscape since 1890, and allowed us to examine long-term responses to climate change without confounding effects of land-use change, although at low to mid-elevations there has been localized vegetation change relating to seral dynamics, climate change, or both."

Cutting emissions through energy conservation and renewable energy can reduce ecological vulnerabilities. Under high emissions, projected climate change could triple burned area in the Sierra Nevada, but under low emissions, fire could increase just slightly.[173] Projections of biome shifts[213,215] and wildlife range shifts[217,218,219,220,221] consistently show lower vulnerabilities with lower emissions. Extensive research on, and practice of, fire management show that allowing naturally ignited fires to burn in wilderness and using low-severity prescribed burns can reduce fuels and the risk of high-severity fires under climate change.[181,182,183] Proactive use of fire in Yosemite, Sequoia, and Kings Canyon National Parks has improved the resilience of giant sequoias and other trees to severe fires.[187,188,190,191] Numerous research results have identified climate change refugia for plants and animals.[207,482,483]

Major uncertainties

Because climate model projections often diverge on whether precipitation may increase or decrease, two broad types of fire futures[152] could be 1) dry-fire future—hotter and drier climate, increased fire frequency, fire limited by vegetation, potential biome change of forest to grassland after a fire due to low natural regeneration, and high carbon emissions; or 2) intense-fire future—hotter and wetter climate, more vegetation, increased fire frequency and intensity, fire limited by climate, and higher carbon emissions. These two broad categories each encompass a range of fire conditions. On the ground, gradients of temperature, precipitation, and climate water deficit (difference between precipitation and actual evapotranspiration) generate gradients of fire regimes. Because climate change, vegetation, and ignitions vary across the landscape, potential fire frequency shows high spatial variability. Therefore, future fire types could appear in patches across the landscape, with different fire future types manifesting themselves in adjacent forest patches. Changes in aridity may shift some plant and animal species ranges downslope to favorable combinations of available moisture and suitable temperature, rather than upslope.[484] Plants and animals may respond to changing climate, and have been shown to do so, through range shifts, phenology shifts, biological evolution, or local extirpation. Thus, no single expected response pattern exists.[224]

Description of confidence and likelihood

Field evidence provides *high confidence* that human-caused climate change has increased wildfire, tree death, and species range shifts. Projections consistently indicate that continued climate change under higher emissions could increase the future vulnerability of ecosystems, but that reducing emissions and increasing fire management would reduce the vulnerability, providing *high confidence* in positive benefits of these actions.

Key Message 3

The Coast

Many coastal resources in the Southwest have been affected by sea level rise, ocean warming, and reduced ocean oxygen—all impacts of human-caused climate change (*high confidence*)— and ocean acidification resulting from human emissions of carbon dioxide (*high confidence*). Homes and other coastal infrastructure, marine flora and fauna, and people who depend on coastal resources face increased risks under continued climate change (*high confidence*).

Description of evidence base

At the Golden Gate Bridge, San Francisco, sea level rose 9 ± 0.4 inches (22 ± 1 cm) from 1854 to 2016,[236] and at San Diego, 9 ± 0.8 inches (24 ± 2 cm) from 1906 to 2016.[237] Analyses of these gauges and hundreds around the world show a statistically significant increase in global mean sea level[238,239] due to melting of land ice and expansion of warming water caused by climate change.[21,240] Measurements of sea surface temperatures from buoys off the California coast and around the world, combined with remote sensing data, have found warming of the top 75 m of ocean water at a rate of 2 ± 0.4°F (1.1 ± 0.2°C) per century from 1971 to 2010,[252] caused by climate change.[21] Measurements and modeling of ocean acidity found an increase of acidity in the Pacific Ocean off San Diego of 25% to 40% (0.1 to 0.15 pH units) since 1750,[485] caused by the increase of carbon dioxide in the atmosphere from cars, power plants, deforestation, and other human activities.[21] Measurements along the California coast have found ocean acidity during the core upwelling season (April to October) increasing by as much as four times (0.7 pH units) to some of the most acidic values in the world.[274] Griggs et al. (2017)[242] project a median sea level rise of 19 inches (49 cm) and a range of 12–29 inches (30–73 cm; 67% probability) for the very low scenario (RCP2.6) and a median of 30 inches (76 cm) and a range of 19–41 inches (49–104 cm; 67% probability) for the higher scenario (RCP8.5) by the end of the century. On a similar timescale, Sweet et al. (2017)[241] provide one map showing sea level rise projections for San Francisco, which shows a 39–47 inch (1–1.2 m) rise for the Intermediate scenario (approximately RCP8.5); the range for all of their scenarios is 0.3–2.5 m. Jevrejeva et al. (2016)[486] project a sea level rise of 73 cm and a range of 12–74 inches (37–187 cm; 5% probability) for the higher scenario (RCP8.5) by 2100.

Major uncertainties

Catastrophic rapid loss of Antarctic and Greenland ice sheets could increase sea level more rapidly. Sea level rise at individual locations depends on the form of the seafloor (bathymetry) and other local conditions. Climate change impacts compound overfishing and make fish populations more vulnerable. Potential economic changes in California's coastal and marine-based economies are subject to many different environmental and socioeconomic factors.

The full complexity of ecological responses to ocean acidification in combination with other stresses in California marine waters is currently unknown. Food supply for marine species,[487] natural variation in resilience,[488,489] and other environmental factors can affect the sensitivity of organisms to acidic conditions.

Description of confidence and likelihood

Field measurements at numerous locations have detected sea level rise, ocean warming, ocean acidification, and ocean hypoxia. Multiple model-based analyses have attributed these changes to human-caused climate change, giving *high confidence* to these impacts of climate change.

Key Message 4

Indigenous Peoples

Traditional foods, natural resource-based livelihoods, cultural resources, and spiritual well-being of Indigenous peoples in the Southwest are increasingly affected by drought, wildfire, and changing ocean conditions (*very likely*, *high confidence*). Because future changes would further disrupt the ecosystems on which Indigenous peoples depend (*likely*, *high confidence*), tribes are implementing adaptation measures and emissions reduction actions (*very likely*, *very high confidence*).

Description of evidence base

Abundant evidence and strong agreement among sources exist regarding current impacts of climate change in the region. Impacts of climate change on the food sources, natural resources-based livelihoods, cultural resources and practices, and spiritual health and well-being of Southwest Indigenous peoples are supported, in part, by evidence of regional temperature increases,[23,24] drought,[14,56,58,480] declines in snow,[46,49,156] and streamflow,[11,13,60,110] which have affected ecological processes, such as tree death,[146] fire occurrence,[7,152] and species ranges.[211]

Impacts specific to Indigenous peoples include: 1) declining surface soil moisture, higher temperatures, and evaporation converge with oak trees' decreased resilience,[285] diminished acorn production, and fire and pest threat to reduce the availability and quality of acorns for tribal food consumption and cultural purposes;[306] and 2) declining vegetation, higher temperatures, diminished snow, and soil desiccation have caused dust storms and more mobile dunes on some Navajo and Hopi lands, resulting in damaged infrastructure and grazing lands and loss of valued native plant habitat.[44,301,490] Evidence and agreement among evidence exist on the effects of climate-related environmental changes on culturally important foods,[318,319] practices, and mental and spiritual health.[42]

Multiple projections of climate and hydrological changes show potential future change and disruption to the ecosystems on which Indigenous peoples depend for their natural resources-based livelihoods, health, cultural practices, and traditions. These include projections of increased temperatures and heat extremes;[24] longer, more severe, and more frequent drought;[13,65] expanded forest mortality;[197,198] increased wildfire;[172] and ocean temperature increases, ocean acidification, and inundation of coastal areas.[242,273]

Evidence of specific future disruptions to traditional food sources from forests and oceans mostly relies upon inferences, based on projections of changing seasonality and associated phenological or ecosystem responses[298,307] or potential changes to biophysical factors, such as salinity of freshwater lakes, and associated impacts to culturally important fish species.[310]

Abundant evidence exists of autonomous adaptation strategies, projects, and actions, rooted in traditional environmental knowledge and practices or integration of diverse knowledge systems to inform ecological management to support adaptation and ecosystem resilience.[490,491,492,493]

In response to the current and future projected climate changes and ecosystem disruptions, a number of tribes in the Southwest are planning and implementing energy efficient and renewable energy projects.[327,361,494,495] These include installation of or planning for photovoltaic systems,[361] solar arrays, biofuels, microgrids, utility-scale wind, biogas, geothermal heating and cooling systems,[327] increased building insulation,[495] and carbon offsets.[334] Several Southwest tribes, such as the Ramona Band of Cahuilla and the Santa Ynez Band of Chumash Indians, have established or are in the process of establishing energy independence.[495] A well-recognized example is that of the Blue Lake Rancheria Tribe, in California, which was named a Climate Action Champion in 2015–2016 for implementing innovative climate actions, such as an all-of-the-above renewable strategy of transportation, residential, and municipal renewable energy projects, which includes a biogas project. A number of these projects (Ch. 15: Tribes, Figure 15.1) aim to simultaneously meet mitigation and adaptation objectives, such as the Yurok Tribe and the Round Valley Indian Tribe, which have developed carbon offset projects under California's cap-and-trade program to support tribally led restoration and stewardship.[496]

Several tribes in the Southwest are developing climate change adaptation plans to address the current climate-related impacts and prepare for future projected climate changes. The Santa Ynez Band of Chumash Indians, which is working towards an integrated energy and climate action plan,