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10 Agriculture and Rural Communities

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10 Agriculture and Rural Communities

Tyringham, Massachusetts

Key Message 1

Reduced Agricultural Productivity

Food and forage production will decline in regions experiencing increased frequency and duration of drought. Shifting precipitation patterns, when associated with high temperatures, will intensify wildfires that reduce forage on rangelands, accelerate the depletion of water supplies for irrigation, and expand the distribution and incidence of pests and diseases for crops and livestock. Modern breeding approaches and the use of novel genes from crop wild relatives are being employed to develop higher-yielding, stress-tolerant crops.

Key Message 2

Degradation of Soil and Water Resources

The degradation of critical soil and water resources will expand as extreme precipitation events increase across our agricultural landscape. Sustainable crop production is threatened by excessive runoff, leaching, and flooding, which results in soil erosion, degraded water quality in lakes and streams, and damage to rural community infrastructure. Management practices to restore soil structure and the hydrologic function of landscapes are essential for improving resilience to these challenges.

Key Message 3

Health Challenges to Rural Populations and Livestock

Challenges to human and livestock health are growing due to the increased frequency and intensity of high temperature extremes. Extreme heat conditions contribute to heat exhaustion, heatstroke, and heart attacks in humans. Heat stress in livestock results in large economic losses for producers. Expanded health services in rural areas, heat-tolerant livestock, and improved design of confined animal housing are all important advances to minimize these challenges.

Key Message 4

Vulnerability and Adaptive Capacity of Rural Communities

Residents in rural communities often have limited capacity to respond to climate change impacts, due to poverty and limitations in community resources. Communication, transportation, water, and sanitary infrastructure are vulnerable to disruption from climate stressors. Achieving social resilience to these challenges would require increases in local capacity to make adaptive improvements in shared community resources.

Executive Summary

In 2015, U.S. agricultural producers contributed $136.7 billion to the economy and accounted for 2.6 million jobs. About half of the revenue comes from livestock production. Other agriculture-related sectors in the food supply chain contributed an additional $855 billion of gross domestic product and accounted for 21 million jobs.

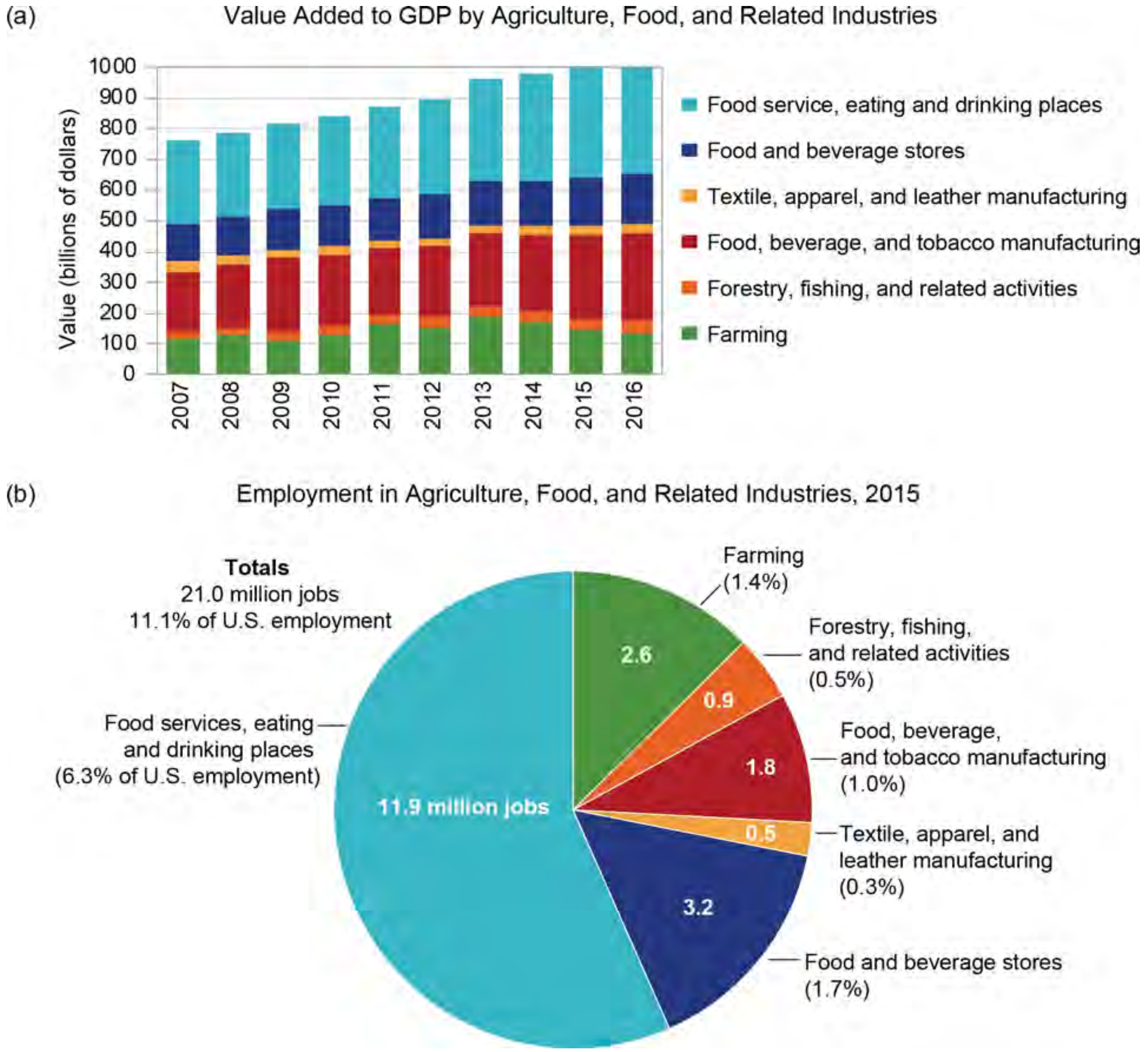
In 2013, about 46 million people, or 15% of the U.S. population, lived in rural counties covering 72% of the Nation's land area. From 2010 to 2015, a historic number of rural counties experienced population declines, and recent demographic trends point to relatively slow employment and population growth in rural areas as well as high rates of poverty. Rural communities, where livelihoods are more tightly interconnected with agriculture, are particularly vulnerable to the agricultural volatility related to climate.

Climate change has the potential to adversely impact agricultural productivity at local, regional, and continental scales through alterations in rainfall patterns, more frequent occurrences of climate extremes (including high temperatures or drought), and altered patterns of pest pressure. Risks associated with climate change depend on the rate and severity of the change and the ability of producers to adapt to changes. These adaptations include altering what is produced, modifying the inputs used for production, adopting new technologies, and adjusting management strategies.

U.S. agricultural production relies heavily on the Nation's land, water, and other natural resources, and these resources are affected directly by agricultural practices and by climate. Climate change is expected to increase the frequency of extreme precipitation events in many regions in the United States. Because increased precipitation extremes elevate the risk of surface runoff, soil erosion, and the loss of soil carbon, additional protective measures are needed to safeguard the progress that has been made in reducing soil erosion and water quality degradation through the implementation of grassed waterways, cover crops, conservation tillage, and waterway protection strips.

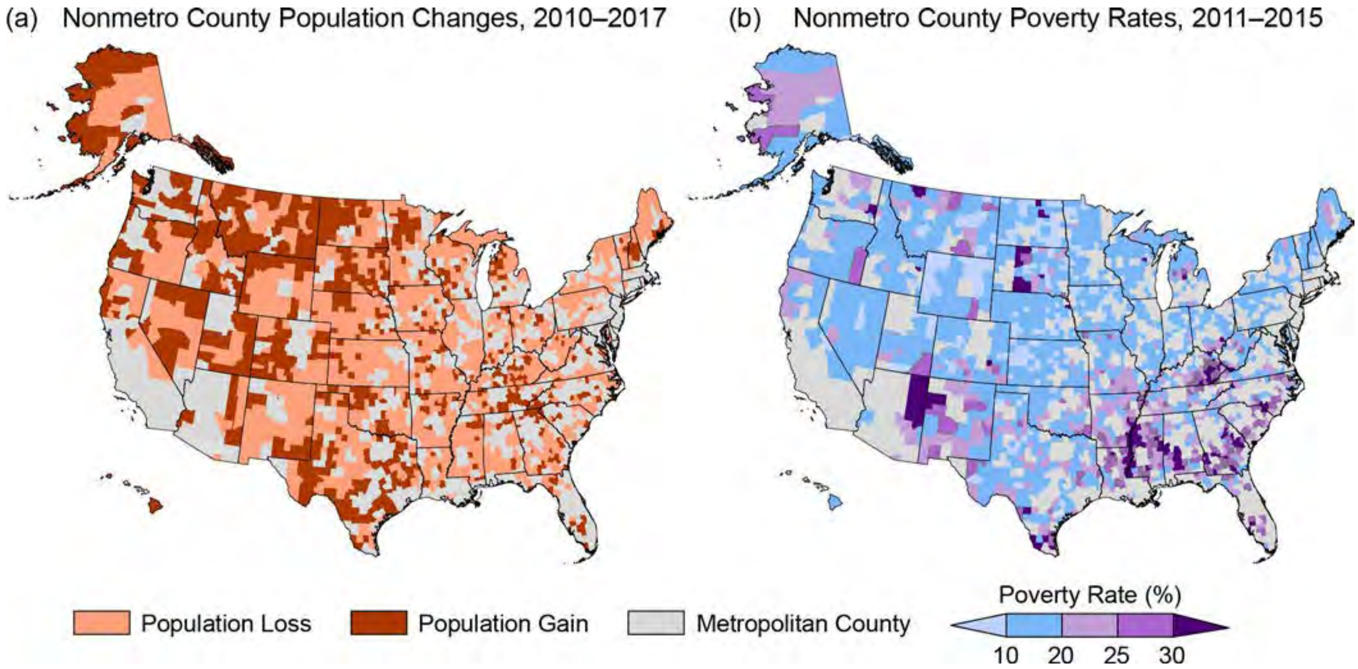
Climate change impacts, such as changes in extreme weather conditions, have a complex influence on human and livestock health. The consequences of climate change on the incidence of drought also impact the frequency and intensity of wildfires, and this holds implications for agriculture and rural communities. Rural populations are the stewards of most of the Nation's forests, watersheds, rangelands, agricultural land, and fisheries. Much of the rural economy is closely tied to the natural environment. Rural residents, and the lands they manage, have the potential to make important economic and conservation contributions to climate change mitigation and adaptation, but their capacity to adapt is impacted by a host of demographic and economic concerns.

Agricultural Jobs and Revenue



The figure shows (a) the contribution of agriculture and related sectors to the U.S. economy and (b) employment figures in agriculture and related sectors (as of 2015). Agriculture and other food-related value-added sectors account for 21 million full- and part-time jobs and contribute about $1 trillion annually to the United States economy. *From Figure 10.1 (Source: adapted from Kassel et al. 2017[1])*.

Population Changes and Poverty Rates in Rural Counties



The figure shows county-level (a) population changes for 2010–2017 and (b) poverty rates for 2011–2015 in rural U.S. communities. Rural populations are migrating to urban regions due to relatively slow employment growth and high rates of poverty. Data for the U.S. Caribbean region were not available at the time of publication of this report. *From Figure 10.2 (Sources: [a] adapted from ERS 2018[2]; [b] redrawn from ERS 2017[3]).*

State of the Agriculture and Rural Communities Sectors

U.S. farmers and ranchers are among the most productive in the world. The agricultural sector makes an important contribution to the U.S. economy, from promoting food and energy security to providing jobs in rural communities across the country. In 2015, U.S. farms contributed $136.7 billion to the economy, accounting for 0.76% of gross domestic product (GDP) and 2.6 million jobs (1.4% of total U.S. employment; Figure 10.1).[1] About half of the farm revenue comes from livestock production. Other agriculture- and food-related value-added sectors contributed an additional 4.74% ($855 billion) of GDP and accounted for 21 million full- and part-time jobs (11.1% of U.S. employment). U.S. agriculture enjoys a trade surplus in which the value of agricultural exports (both bulk and high-value products) accounts for more than 20% of total U.S. agricultural production. Top high-value exports include feedstocks, livestock products, horticulture products, and oilseeds and oilseed products, and these exports help support rural communities across the Nation.

A major portion of rural communities in the United States depend on agriculture and other related industries as economic drivers. During 2010–2012, a total of 444 counties were classified as farming dependent, of which 391 were rural counties.[4] In 2013, about 46 million people, or 15% of the U.S. population, lived in rural counties, covering 72% of the Nation's land area. From 2010 to 2017, a historic number of rural counties in the United States experienced population declines due to persistent outmigration of young adults.[2] However, some counties in the Northern Great Plains reversed decades of population loss to grow at a modest rate due to the energy boom in that region. Recent demographic trends point to relatively slow employment and population growth in rural areas, as well as higher rates of poverty in rural compared to urban regions (Figure 10.2).[1,5,6,7]

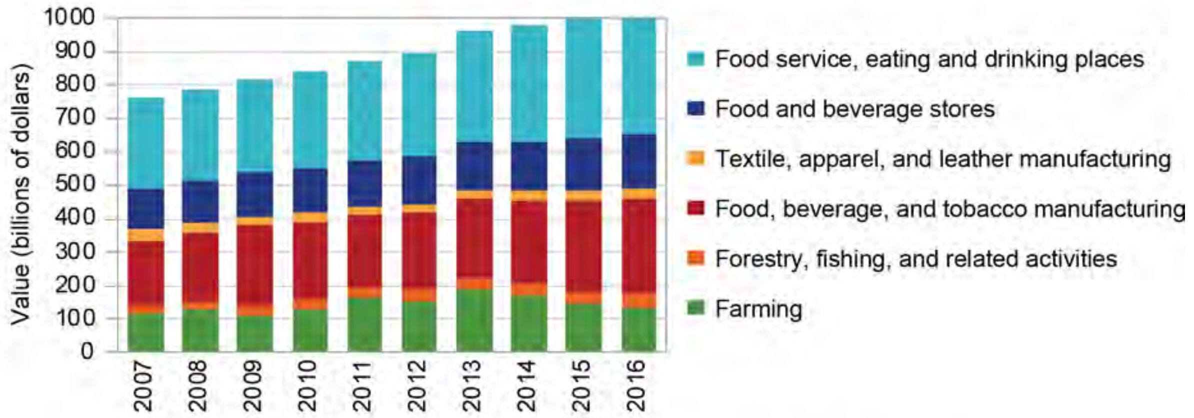
U.S. agricultural production relies heavily on the Nation's land, water, and other natural resources.[8] In 2012, about 40%, or 915 million acres, of U.S. land was farmland, of which 45.4% was permanent pasture, 42.6% was cropland, and 8.4% was woodland.[9] Only about 6% of the farmland was irrigated. Agricultural land use can change over time,[10,11] and these changes are sometimes reversible, such as when shifting between cropland and pastureland (Ch. 22: N. Great Plains, Table 22.3, Figure 22.4), and sometimes irreversible, such as when agricultural land is converted to urban uses.[12] These natural resource bases are affected continually by agricultural production practices and climate change.[13,14,15,16]

Bioenergy cropping is increasing and remains a major focus of research to develop appropriate dedicated feedstocks for different regions of the United States.[17,18,19,20,21,22] Crop residue harvest, particularly from corn, has the potential to provide additional income streams to producers and rural communities, but the impact on soil carbon sequestration and greenhouse gas (GHG) emissions indicates that only part of the residue can be harvested sustainably.[23,24,25,26] Biochar, a by-product of cellulosic bioenergy production, holds potential as a soil amendment[27,28] that in some soils provides a GHG mitigation[29] and adaptation benefit. However, many questions remain on how to develop sustainable crop- and grass-based bioenergy systems within a region.[30,31,32]

Technological advancements through concerted public and private efforts and the increasing availability of inputs (such as fertilizers, pesticides, and feed additives) have led to significant improvements in productivity while reducing agriculture's environmental

Agricultural Jobs and Revenue

(a) Value Added to GDP by Agriculture, Food, and Related Industries



(b) Employment in Agriculture, Food, and Related Industries, 2015

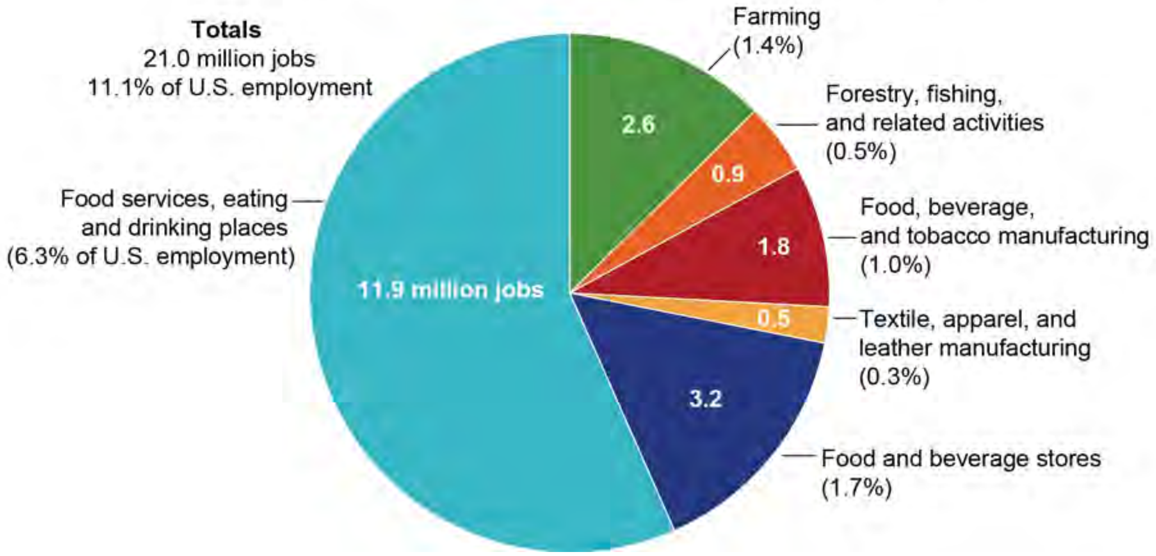


Figure 10.1: The figure shows (a) the contribution of agriculture and related sectors to the U.S. economy and (b) employment figures in agriculture and related sectors (as of 2015). Agriculture and other food-related value-added sectors account for 21 million full- and part-time jobs and contribute about $1 trillion annually to the United States economy. Source: adapted from Kassel et al. 2017.[1]

footprint.[33,34,35] However, there are some major challenges to the future of agriculture and food security.[36] The agricultural sector accounted for about 9% of the Nation's total GHG emissions in 2015,[37] so reducing emissions in the agriculture sector could have a significant impact on total U.S. emissions. Nonetheless, agriculture is one of the few sectors with the potential for significant increases in carbon sequestration to offset GHG emissions. Furthermore, water quality degradation, including eutrophication (an overload of nutrients) in the Great Lakes and coastal water bodies (for example, the northern Gulf of Mexico and the Chesapeake Bay) (see Ch. 18: Northeast, Box 18.6; Ch. 21: Midwest, Box 21.1; Ch. 23: S. Great Plains, KM 3), remains an ongoing challenge.

The current state of agricultural systems in different regions of the United States is the result of continuous efforts made by farmers, ranchers, researchers, and extension

Population Changes and Poverty Rates in Rural Counties

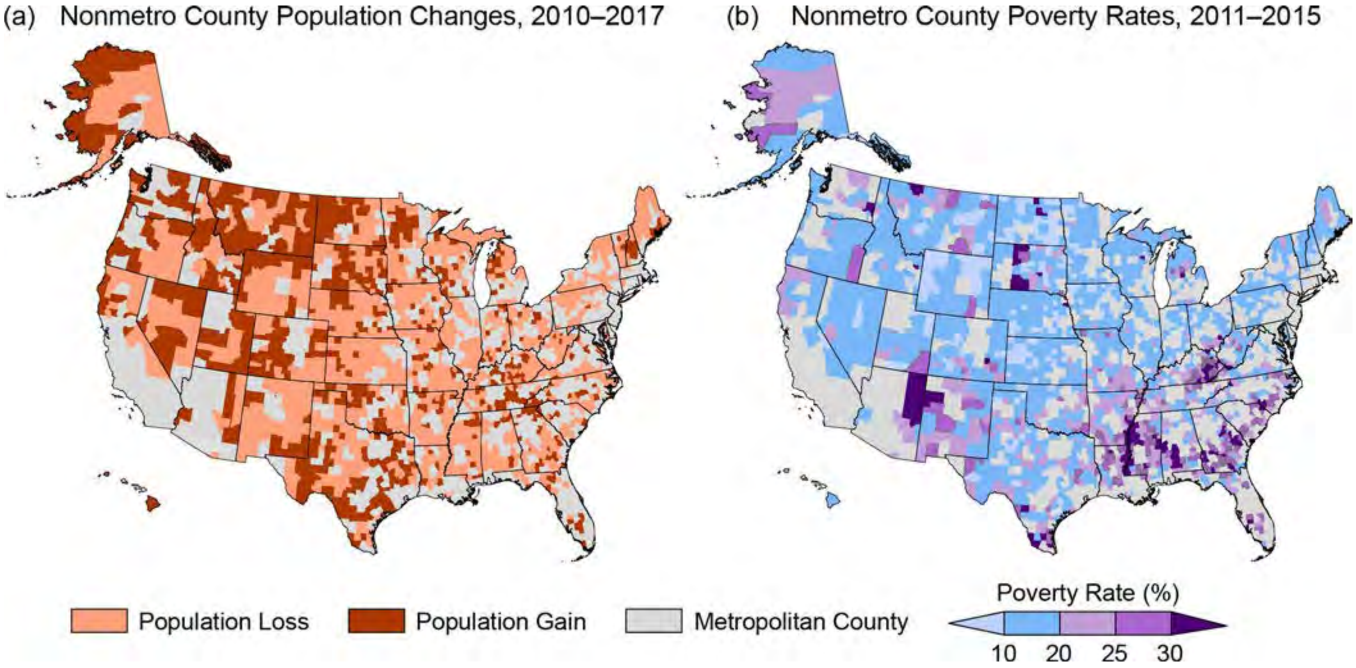


Figure 10.2: The figure shows county-level (a) population changes for 2010–2017 and (b) poverty rates for 2011–2015 in rural U.S. communities. Rural populations are migrating to urban regions due to relatively slow employment growth and high rates of poverty. Data for the U.S. Caribbean region were not available at the time of publication. Sources: (a) adapted from ERS 2018[2]; (b) redrawn from ERS 2017.[3]

specialists to identify opportunities, practices, and strategies that are viable in different climates. However, any change in the climate poses a major challenge to agriculture through increased rates of crop failure, reduced livestock productivity, and altered rates of pressure from pests, weeds, and diseases.[38,39] Rural communities, where economies are more tightly interconnected with agriculture than with other sectors, are particularly vulnerable to the agricultural volatility related to climate.[40]

Climate changes projected by global climate models are consistent with observed climate changes of concern to agriculture (Ch. 2: Climate).[41,42,43] Climate change has the potential to adversely impact agricultural productivity at local, regional, and continental scales.[44] Crop and livestock production in certain regions will be adversely impacted both by direct effects of climate change (such as increasing trends in daytime and nighttime temperatures; changes in rainfall patterns; and more frequent climate extremes, flooding, and drought) and consequent secondary effects (such as increased weed, pest, and disease pressures; reduced crop and forage production and quality; and damage to infrastructure). While climate change impacts on future agricultural production in specific regions of the United States remain uncertain, the ability of producers to adapt to climate change through planting decisions, farming practices, and use of technology can reduce its negative impact on production (Ch. 21: Midwest, Case Study “Adaptation in Forestry”).[45]

Risks associated with climate changes depend on the rate and severity of the changes and the ability of producers to adapt to changes. The severity of financial risks also depends on changes in food prices as well as local-to-global trade levels, as production and consumption patterns will likely be altered due to climate change.[10,46] Many countries are already experiencing rapid price increases for basic food commodities, mainly due to production losses associated with more frequent weather extremes and unpredictable weather events. The United States is a major exporter of agricultural commodities,[47] and a disruption in its agricultural production will affect the agricultural sector on a global scale. Food security, which is already a challenge across the globe, is likely to become an even greater challenge as climate change impacts agriculture.[48,49] Food security will be further challenged by projected population growth and potential changes in diets as the world seeks to feed a projected 9.8 billion people by 2050.[50,51,52]

In the late 1900s, U.S. agriculture started to develop significant capacities for adaptation to climate change, driven largely by public-sector investment in agricultural research and extension.[53] Currently, there are numerous adaptation strategies available to cope with adverse impacts of climate change.[38,54,55] These include altering what is produced in a region, modifying the inputs used for production, adopting new technologies, and adjusting management strategies. Crop management strategies include the selection of crop varieties/species that meet changes in growing degree days and changes in requirements for fertilizer rates, timing, and placement to match plant requirements.[56] Adaptation strategies also include changes in crop rotation, cover crops, and irrigation management.[57,58,59,60,61,62] With changes to rainfall patterns that greatly impact the environment, wider use of proven technologies will be required to prevent soil erosion, waterlogging, and nutrient losses.[44,63] Adaptation strategies for sustaining and improving livestock production systems include managing heat stress by altering diets,[64,65,66,67,68,69,70] providing adequate shade and clean drinking water supplies,[71,72] monitoring stock rates continuously to match forage availability,[73,74,75] altering the timing of feeding/grazing and reproduction,[76] and selecting the species/breeds that match climatic conditions.[54,77] Other strategies to reduce climate change impacts include integrated pest and disease management,[78,79] the use of climate forecasting tools,[80] and crop insurance coverage to reduce financial risk.[44,81,82] These strategies have proven effective as evidenced by continued productivity growth and efficiency. The proper implementation of combinations of these strategies has the potential to effectively manage negative impacts of moderate climate change. However, these approaches have limits under severe climate change impacts.[66,83,84,85]

Key Message 1

Reduced Agricultural Productivity

Food and forage production will decline in regions experiencing increased frequency and duration of drought. Shifting precipitation patterns, when associated with high temperatures, will intensify wildfires that reduce forage on rangelands, accelerate the depletion of water supplies for irrigation, and expand the distribution and incidence of pests and diseases for crops and livestock. Modern breeding approaches and the use of novel genes from crop wild relatives are being employed to develop higher-yielding, stress-tolerant crops.

Climate projections to the year 2100 suggest that increases are expected in the incidence of drought and elevated growing-season temperatures.[86] Elevated temperatures play a critical role in increasing the rate of drought onset, overall drought intensity, and drought impact through altered water availability and demand.[87,88] Increased evaporation rates caused by high temperatures, in association with drought, will exacerbate plant stress,[89] yield reduction,[90,91,92] fire risks,[93,94,95,96] and depletion of surface and groundwater resources.[97,98,99,100]

Soil carbon, important for enhancing plant productivity through a variety of mechanisms,[101] is depleted during drought due to low biomass productivity, which in turn decreases the resilience of agroecosystems.[23] In 2012, the United States experienced a severe and extensive drought, with more than two-thirds of its counties declared as disaster areas.[102] This drought greatly affected livestock, wheat, corn, and soybean production in the Great Plains and Midwest regions [44,103,104,105] and accounted for $14.5 billion in loss payments by the federal crop insurance program.[106] From 2013–2016, all of California faced serious drought conditions that depleted both reservoir and groundwater supplies. This lengthy drought, attributed in part to the influence of climate change,[88,107] resulted in the overdrawing of groundwater, primarily for irrigation, leading to large declines in aquifer levels (Ch. 3: Water, KM 1).[98,108] In 2014, the California state legislature passed the Sustainable Groundwater Management Act to develop groundwater management plans for sustainable groundwater use over the next 10–20 years.[109,110,111]

Average yields of many commodity crops (for example, corn, soybean, wheat, rice, sorghum, cotton, oats, and silage) decline beyond certain maximum temperature thresholds (in conjunction with rising atmospheric carbon dioxide [CO_2] levels), and thus long-term temperature increases may reduce future yields under both irrigated and dryland production.[37,91,92,97,103,112,113] In contrast, even with warmer temperatures, future yields for certain crops such as wheat, hay, and barley are projected to increase in some regions due to anticipated increases in precipitation and carbon fertilization.[97,114] However, yields from major U.S. commodity crops are expected to decline as a consequence of higher temperatures,[45] especially when these higher temperatures occur during critical periods of reproductive development.[115,116,117] Increasing temperatures are also projected to have an impact on specialty crops (fruits, nuts, vegetables, and nursery crops) (Ch. 25: Southwest, KM 6), although the effects will be variable depending on the crops and where they are grown.[118] Additional challenges involve the loss of synchrony of seasonal phenomena (for example, between crops and pollinators) (Ch. 7: Ecosystems; Ch. 25: Southwest, KM 6). Further, the interactive effects of rising atmospheric CO_2 concentrations, elevated temperatures, and changes in other climate factors are expected to enhance weed competitiveness relative to crops,[119] with temperature being a predominant factor.[120,121]

Irrigated agriculture is one of the major consumers of water supplies in the United States (Ch. 3: Water; Ch. 25: Southwest, KM 6). Irrigation is used for crop production in most of the western United States and since 2002 has expanded into the northern Midwest (Ch. 21: Midwest, KM 1) and Southeast (Ch. 19: Southeast, KM 4). Expanded irrigation is often proposed as a strategy to deal with increasing crop water demand due to higher trending temperatures coupled with decreasing growing-season precipitation. However, under long-term climate change, irrigated acreage is expected to decrease, due to a combination of declining water resources and a diminishing relative profitability of irrigated production.[97] Continuing or expanding existing levels of irrigation will be limited by the availability of water in many areas.[11,98,108] Surface water supplies are particularly vulnerable to shifts in precipitation and demand from nonagricultural sectors. Groundwater supplies are also in decline across major irrigated regions of the United States (see Case Study "Groundwater Depletion in the Ogallala Aquifer Region") (see also Ch. 3: Water, Figure 3.2; Ch. 25: Southwest, KM 1; Ch. 23: S. Great Plains, KM 1).

Crop productivity and quality may also be significantly reduced due to increased crop water demand coupled with limited water availability[122,123,124] as well as increased diseases and pest infestations (Ch. 25: Southwest, KM 6).[125] The expected demand for higher crop productivity and anticipated climate change stresses have driven advancements in crop genetics.[126,127] Seed companies have released numerous crop varieties that are tolerant to heat, drought, or pests and diseases. This trend is expected to continue as new crop varieties are developed to adapt to a changing climate.[128] Recent advances in genetics have allowed researchers to access large and complex genomes of crops and their wild relatives.[129] This has the potential to reduce the time and cost required to identify and incorporate useful traits in plant breeding and to develop crops that are more resilient to climate change. Currently, the United States has the largest gene bank in the world that manages publicly held crop germplasm (genetic material necessary for plant breeding). However, progress in this area has been modest despite advances in breeding techniques.[130,131,132,133] Further, institutional factors such as intellectual property rights, and a lack of international access to crop genetic resources, are affecting the availability and utilization of genetic resources useful for adaptation to climate change.[134] Investments by commercial firms alone are unlikely to be sufficient to maintain these resources, meaning higher levels of public investment would be needed for genetic resource conservation, characterization, and use. Societal concerns over certain crop breeding technologies likely will continue, but current assessments of genetically engineered crops have shown economic benefits for producers, with no substantial evidence of animal or human health or environmental impacts.[135]

Climate-smart agriculture[136] can reduce the impacts of climate change and consequent environmental conditions on crop yield.[137,138] Not only do producers take climate forecasts into consideration when deciding what to produce and how to produce it, they also adapt management strategies to cope with expected weather conditions. For example, drought resilience can be improved by adopting high-efficiency precision irrigation technologies.[139,140,141] In order for these systems to work effectively, a network of weather stations is required in agricultural regions. Currently, 23 states have one or more publicly funded agricultural weather networks, such as the Oklahoma Mesonet[142] and the Nebraska Agricultural Water Management Network.[143]

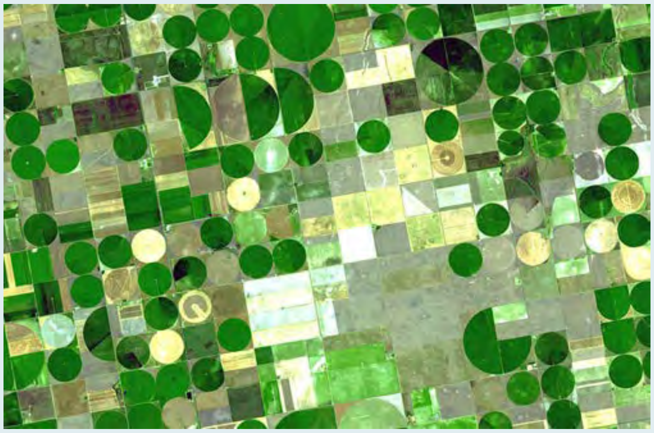
The same aspects of climate change that affect the incidence of drought also affect the frequency and intensity of wildfires, which pose major risks to agriculture and rural communities. Grassland, rangeland, and forest ecosystems, which support ruminant livestock production, represent more than half of the land area of the United States.[144] Wildfires are a normal occurrence in these ecosystems, and they play an important role in long-term ecosystem health. However, climate change threatens to increase the frequency and length of the wildfire season, as well as the size and extent of large fires.[95] Increasing temperatures also promote an increased spread of invasive or encroaching species,[145] which exacerbate wildfire risks. Beyond economic losses, wildfires also contribute to climate change by releasing CO_2 into the atmosphere (Ch. 6: Forests, KM 1; Ch. 13: Air Quality, KM 2). The increased extent of high-severity fire expanding into communities further reduces the capacity to provide other services and puts communities, personnel, and infrastructures at higher risk.[146,147] Tribal communities are particularly vulnerable to wildfires, due to a lack of fire-fighting resources, insufficient experienced internal staff, and remote locations (Ch. 15: Tribes).[148,149] In addition, firefighting in many tribal communities requires coordination across fire-prone landscapes with various jurisdictional controls.[150] On average, the United States spends about $1 billion annually to fight wildfires, but it spent more than $2.9 billion in 2017 due to extreme drought conditions in some regions.[151] States, local governments, and the private sector also absorbed additional costs of firefighting and recovery. (For more on wildfires, see Ch. 5: Land Changes; Ch. 6: Forests; Ch. 15: Tribes.)

Case Study: Groundwater Depletion in the Ogallala Aquifer Region

The Ogallala Aquifer region (OAR) is one of the most productive farm belts in the world. Irrigated agriculture uses more than 95% of the groundwater extracted from the Ogallala Aquifer, and the economy of the region depends almost entirely on irrigated agriculture. Overlying states produce one-fifth of the Nation's wheat, corn, and cotton, and the southern half of the region accounts for more than one-third of the beef cattle production.[152] In 2007, the market value of agricultural products from this region was about $35 billon, which accounted for 11.6% of the total market value of agricultural products in the United States.[153]

The management of agriculture, water, and soil in the OAR has come full circle over the past century. The conversion of native grasslands for crop production in the early part of the 20th century followed by prolonged drought led to severe dust storms that became known as the Dust Bowl of the 1930s. The adoption of soil conservation methods and irrigation with Ogallala water improved soil health and reduced soil erosion while expanding the region's economy. However, major portions of the Ogallala Aquifer should now be considered a nonrenewable resource. Reduced well outputs due to excessive pumping, especially in central and southern parts of the OAR (Figure 10.3), coupled with frequent and prolonged droughts have led to recent dust storms that were similar to those of the 1930s and 1950s. Climate change is projected to further increase the duration and intensity of drought over much of the OAR in the next 50 years.[39,86] Recent advances in precision irrigation technologies,[154,155] improved understanding of the impacts of different dryland and irrigation management strategies on crop productivity,[60,156,157,158,159] and the adoption of weather-based irrigation scheduling tools[160] as well as drought-tolerant crop varieties[161] have increased the ability to cope with projected heat stress and drought conditions under climate change.[162] However, current extraction for irrigation far exceeds recharge in this aquifer, and climate change places additional pressure on this critical water resource.

Dust storm approaching Stratford, Texas (in the state's panhandle), during the Dust Bowl of the 1930s. Photo credit: NOAA George E. Marsh Album.



Satellite image showing center pivot irrigation in Finney County, Kansas. This area utilizes irrigation water from the Ogallala aquifer. Image courtesy of NASA.

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Changes in the Ogallala Aquifer

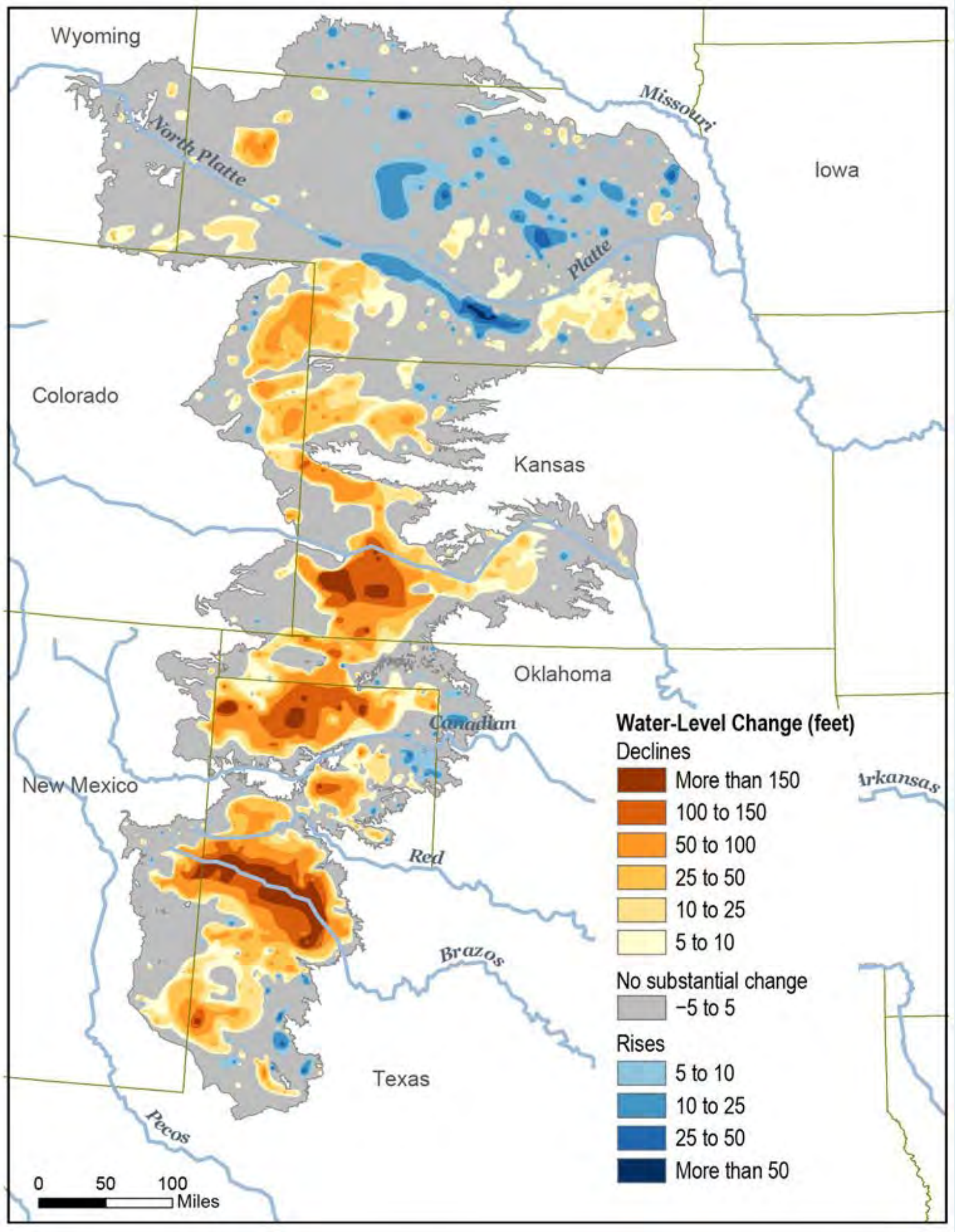

Figure 10.3: The figure shows changes in groundwater levels in the Ogallala Aquifer from predevelopment to 2015. Source: adapted from McGuire 2017.[163]

Key Message 2

Degradation of Soil and Water Resources

The degradation of critical soil and water resources will expand as extreme precipitation events increase across our agricultural landscape. Sustainable crop production is threatened by excessive runoff, leaching, and flooding, which results in soil erosion, degraded water quality in lakes and streams, and damage to rural community infrastructure. Management practices to restore soil structure and the hydrologic function of landscapes are essential for improving resilience to these challenges.

Soil erosion by water is one of the major environmental threats to sustainable crop production.[164,165] It can also adversely affect drainage networks, water quality,[166] and recreation[167]. Climate change is expected to increase the frequency of extreme precipitation events in many regions of the United States (Ch. 2: Climate). This, in turn, increases rainfall erosivity (the potential for soil to be eroded) and the sediment transport capacity of surface runoff from agricultural lands, both of which increase total soil erosion and sedimentation into receiving water bodies.[168] Therefore, increasing soil erosion rates have the potential to not only reduce agricultural productivity but also accelerate climate change effects through the loss of large stocks of carbon and nutrients stored in soil.[23,169,170]

An analysis of historical data on extreme single-day precipitation events in the United States occurring from 1910–2017 shows that the share of land area that experienced extreme precipitation regimes remained fairly steady until the 1980s but has risen significantly since then (Figure 10.4) (see also Ch. 19: Southeast, Figure 19.3).[171] This increase is expected to continue in this century. Because increased precipitation extremes elevate the risk of surface runoff, soil erosion, and loss of soil carbon, additional protective measures are needed to safeguard the progress that has been made in reducing soil erosion and water quality degradation from U.S. croplands through the implementation of grassed waterways, cover crops, conservation tillage, and waterway protection strips (Ch. 21: Midwest, KM 1).[23,172] Conservation strategies that are being implemented to reduce soil erosion and increase carbon sequestration use the estimates of expected average climate conditions derived from historical data. It is possible that these strategies could be improved by considering current and projected future climate extremes and local conditions.[23,173]

The degradation of freshwater and marine ecosystems due to sediment and nutrient loadings from agricultural landscapes is a major environmental challenge in the United States.[174,175,176,177] A strong correlation exists between extreme precipitation, high streamflow events, and large sediment and nutrient loadings entering river systems. Extreme precipitation events have been increasing across most of the United States over the past few decades; in particular, the frequency of heavy precipitation and streamflow events has increased in the central and eastern United States.[178,179,180,181] Large nutrient-rich sediment loadings, coupled with global warming, have caused increases in the duration, intensity, and extent of hypoxia (low-oxygen conditions) in coastal and freshwater systems over the past century (Ch. 21: Midwest, Case Study "Great Lakes Climate Adaptation Network").[182,183,184,185,186]

Hypoxia occurs when dissolved oxygen concentration is depleted to a certain low level below which aquatic organisms, especially

Land Area and Extreme Precipitation

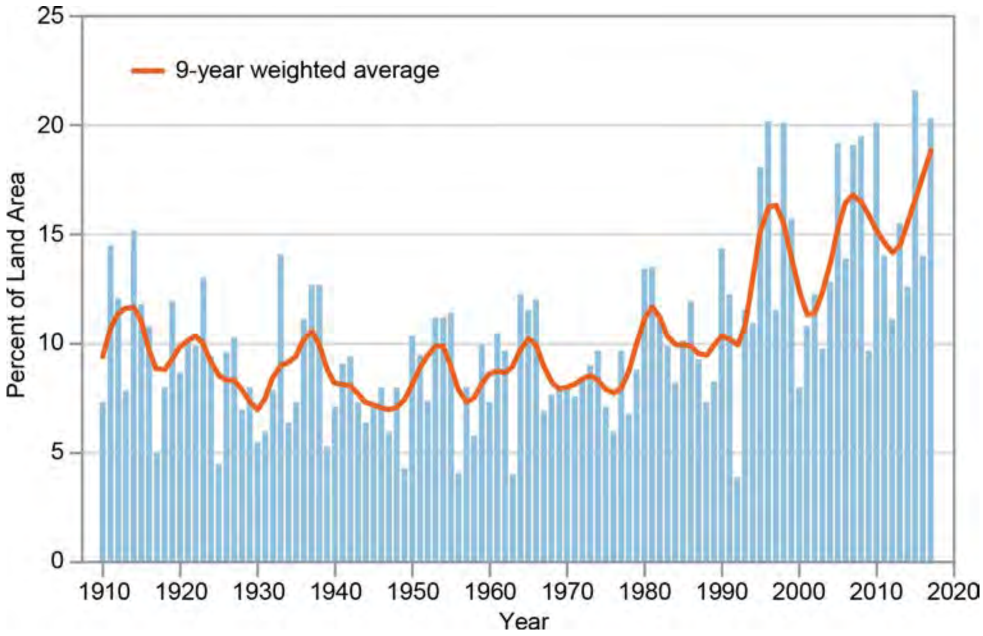

Figure 10.4: The figure shows the percent of land area in the contiguous 48 states experiencing extreme one-day precipitation events between 1910 and 2017. These extreme events pose erosion and water quality risks that have increased in recent decades. The bars represent individual years, and the orange line is a nine-year weighted average. Source: adapted from EPA 2016.[171]

immobile species such as oysters and mussels, endure severe stress or die.[187,188,189] The Chesapeake Bay,[185] the northern Gulf of Mexico,[190] and Mobile Bay[191] are common U.S. coastal locations for recurring hypoxic conditions. From 1960–2008, the incidences of hypoxia in the United States increased by a factor of 30,[192] threatening the U.S. coastal economy that in 2014, for example, generated more than $214 billion in sales and supported 1.83 million jobs.[193]

A recent study[182] found that a majority of the documented hypoxic zones around the world are in regions projected to experience an increase in temperature of 3.6°F (2˚C) by the end of century. Projections for hypoxia indicate a worsening trend, with increased frequency, intensity, and duration of hypoxic episodes.[194] The consequences of this projected trend for the environment, society, and local economies will depend on 1) a combination of climate change impacts, stemming primarily from global warming[195] and altered wind, precipitation, and ocean current patterns,[185,196,197] and 2) impacts resulting from land-use change (for example, streamflow and sediment and nutrient loadings).[182,189,194] Long-term, broad-scale efforts to reduce nutrient loads from landscapes impacted by human activity, especially agriculture, are required if water resources are to be adequately protected.[194] These efforts would require programs to monitor, study, and manage water quality problems on both regional and local scales. Numerous programs of this kind have already been established for a few major coastal water bodies, such as Lake Erie, the northern Gulf of Mexico, the Chesapeake Bay, and Long Island Sound.[198,199]

Flooding in agricultural and rural communities leads to the degradation of soil and water resources, negative impacts on human health, decreased economic activity, infrastructure damage, and environmental contamination.[200] Since the early 1900s, global sea level has risen by about 8 inches, and this has increased the frequency, magnitude, and duration of flooding affecting agriculture and rural communities along coastal regions (Ch. 8: Coastal; Ch. 18: Northeast, KM 1 and 2). Projected climate change, including increased storm intensity and elevated global temperatures, is expected to worsen the problem. The outer range of global average sea level rise is projected to be between 1 foot and 8 feet by 2100, with a very likely range of between 1 foot and 4.3 feet (Ch. 2: Climate, KM 4 and 9),[201,202] putting U.S. coastal communities at risk, including many rural communities located along low-lying rivers in the coastal plains. Coastal erosion in the United States accounts for about $500 million in damages every year, for which the Federal Government spends an average of $150 million per year for erosion control measures.[203] Damage to coastal communities includes coastal erosion and the loss of wetlands due to flooding, coupled with high tides and sea level rise; the contamination of irrigation and drinking water due to saltwater intrusion; the loss of traditional food sources due to the loss of marine habitats and coral reefs; and the loss of agricultural lands due to rising sea levels.[204] Low-relief islands and Pacific atolls are particularly at risk to both sea level rise and increasing storm surge intensity (Ch. 8: Coastal; Ch. 15: Tribes).[205]

Key Message 3

Health Challenges to Rural Populations and Livestock

Challenges to human and livestock health are growing due to the increased frequency and intensity of high temperature extremes. Extreme heat conditions contribute to heat exhaustion, heatstroke, and heart attacks in humans. Heat stress in livestock results in large economic losses for producers. Expanded health services in rural areas, heat-tolerant livestock, and improved design of confined animal housing are all important advances to minimize these challenges.

Climate change impacts, such as extreme weather conditions, have a complex influence on human health. Specific issues are discussed in more detail in Chapter 14: Human Health. Extreme heat can cause or contribute to potentially deadly conditions such as heat exhaustion, heatstroke, and heart attacks (Ch. 18: Northeast, Figure 18.11) and reduced human productivity (Ch. 19: Southeast, Figure 19.21). In the United States, some communities of color, low-income groups, certain immigrant groups, and tribal communities are vulnerable to impacts of climate change; pregnant women, children, and older people associated with these populations are the most at risk, considering their higher likelihood of living in risk-prone areas (such as isolated rural areas and areas with poor infrastructure).[149]

Higher temperatures and consequent longer growing seasons can also affect human health by prolonging the duration of the pollen and allergy seasons.[206] Further, higher atmospheric CO_2 levels enable ragweed and other plants to produce allergenic pollen in larger quantities.[207]

Since the beginning of the 20th century, the length of the average growing season has increased by nearly two weeks in the contiguous 48 states, with larger increases in the West (2.2 days per decade) than in the East (1 day per decade). Arizona and California have recorded the most dramatic increase, while the growing season has become shorter in a few southeastern states.

Health impacts to livestock are also an important concern. Livestock and poultry account for over half of U.S. agricultural cash receipts, exceeding $182 billion in 2012.[9] One study estimated average annual losses related to heat stress for the year 2000, even with adaptation-appropriate techniques, at about $897 million, $369 million, $299 million, and $128 million for dairy, beef, swine, and poultry industries, respectively.[208] Projected increases in daily maximum temperatures and heat waves will lead to further heat stress for livestock, although the severity of consequences will vary by region. Temperatures beyond the optimal range alter the physiological functions of animals, resulting in changes in respiration rate, heart rate, blood chemistry, hormones, and metabolism; such temperatures generally result in behavioral changes as well, such as increased intake of water and reduced feed intake.[83] Heat stress also affects reproductive efficiency.[209,210] High temperatures associated with drought conditions adversely affect pasture and range conditions and reduce forage crop and grain production, thereby reducing feed availability for livestock.[54,211,212] More variable winter temperatures also cause stress to livestock and, if associated with high-moisture blizzard conditions or freezing rain and icy conditions, can result in significant livestock deaths.[213,214]

Dairy cows are particularly sensitive to heat stress, as it negatively affects their appetite, rumen fermentation (a process that converts ingested feed into energy sources for the animal), and lactation yield.[215,216] Frequent higher temperatures also lower milk quality (reduced fat, lactose, and protein percentages).[217,218] In 2010, heat stress was estimated to have lowered annual U.S. dairy production by $1.2 billion. A recent study indicates that the dairy industry expects to see production declines related to heat stress of 0.60%–1.35% for the average dairy over the next 12 years, with larger declines occurring in the Southern Great Plains and the Southeast due to increasing relative stress (assuming producing regional herd inventories remain stable; Figure 10.5).[83,218] Similar heat stress losses impact beef cow-calf, stocker, and feedlot production systems; higher temperatures result in reduced appetites and grazing/feeding activity, which subsequently reduce production efficiencies. Extreme temperature events also increase feedlot mortality.

In contrast to beef and dairy production, a much larger segment of both pork and poultry production is housed in environmentally controlled facilities that lessen the impact of temperature extremes on production efficiencies. However, these systems rely on mechanized cooling systems that are more expensive to operate as temperatures increase and are subject to extreme losses associated with the failures of cooling equipment. Traditional outdoor pork and poultry production systems will be subject to the same temperature-related issues as the beef and dairy industries. Consequently, livestock systems (such as beef and dairy cattle) that are raised outside in range environments or pen-based concentrated animal feeding operations are expected to be impacted more negatively by heat stress and climate extremes than livestock that are produced in climate-controlled facilities (such as the majority of pork and poultry).[219] As a result, feedlots and dairy production centers are expected to continue to migrate to more

Projected Reduction in Milk Production

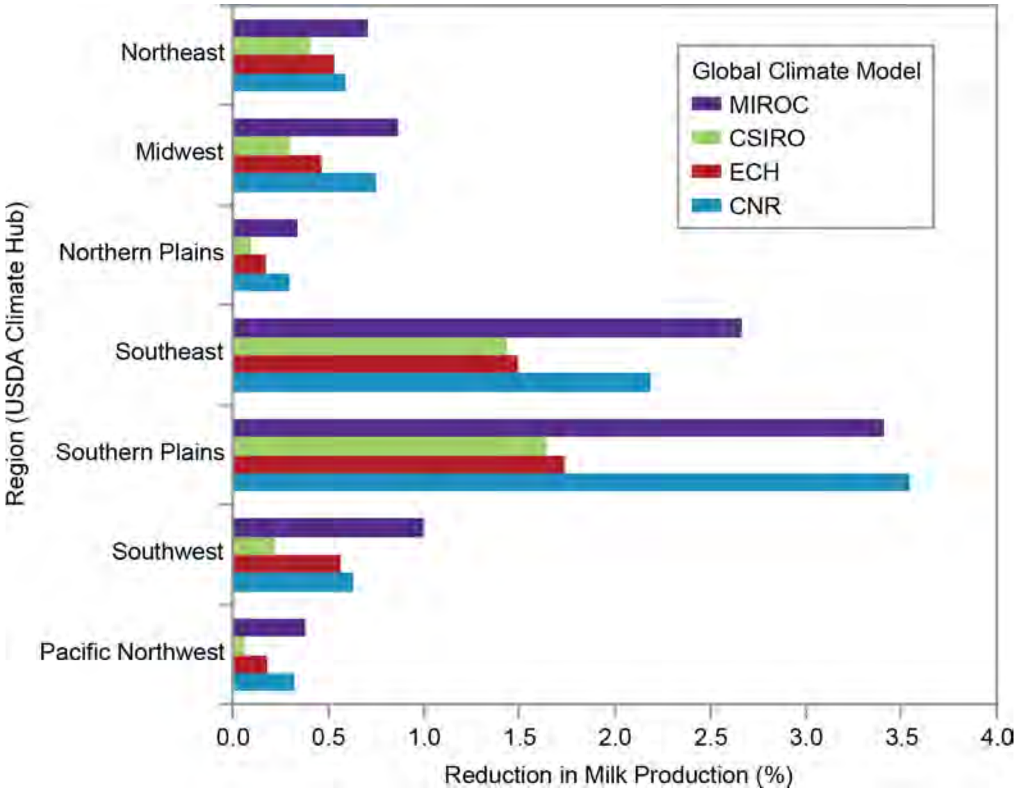

Figure 10.5: The figure shows the predicted reduction in annual milk production in 2030 compared to 2010 in climate change-induced heat stress. The regions are grouped according to USDA regional Climate Hubs (https://www.climatehubs.oce.usda.gov), and the colored bars show the four global climate models used. Source: redrawn from Key et al. 2014.[83]

temperate regions, due to heat stress, diminished water availability, and reduced crop/forage availability and quality.[54]

In the absence of migration of livestock production to more temperate climates, adaptation strategies are possible to a degree.[54] For example, as local temperatures increase, livestock can be genetically adapted to local conditions.[220] However, the physical mitigation of heat stress in livestock often requires long-term investments such as climate-controlled buildings, portable or permanent shading structures, and planted trees, as well as short-term production strategies such as altering feeds.[76,218] Studies have shown that shading in combination with fans and sprinkler or evaporative cooling technologies can mitigate the short-term effects of heat stress on animal production and reproductive efficiency.[221] Other strategies include aligning feeding and management practices with the cooler times of the day and reducing the effort required by animals to access food and water.[222]

Key Message 4

Vulnerability and Adaptive Capacity of Rural Communities

Residents in rural communities often have limited capacity to respond to climate change impacts, due to poverty and limitations in community resources. Communication, transportation, water, and sanitary infrastructure are vulnerable to disruption from climate stressors. Achieving social resilience to these challenges would require increases in local capacity to make adaptive improvements in shared community resources.

Climate change is an issue of great importance for rural communities. Rural populations are the stewards of most of the Nation's forests, watersheds, rangelands, agricultural land, and fisheries, and much of the rural economy is closely tied to its natural environment. Thus, rural residents and the lands that they manage have the potential to make important economic and conservation contributions to climate change mitigation and adaptation. However, rural residents are also highly vulnerable to climate change effects due to their economic dependence on their natural resource base, which is subject to multiple climate stressors (Ch. 19: Southeast, Figures 19.15 and 19.16; Ch. 2: Climate). Migrant workers, who provide much of the agricultural labor in some regions and some enterprises, are particularly vulnerable. Climate change has already had direct impacts on rural populations and economies (Ch. 26: Alaska, Figures 26.3 and 26.4) and will inevitably have repercussions for rural livelihoods and prosperity in the future.[223]

The ability of a rural community to adjust to climate disturbances, take advantage of economic opportunities, and cope with the consequences of change depends on a host of demographic and economic factors. Specifically, rural areas have higher percentages of people living in poverty than do urban areas, and poverty rates among historically vulnerable populations such as children, the elderly, and racial and ethnic minorities tend to be higher (Ch. 15: Tribes, Figure 15.2; Ch. 19: Southeast, Figure 19.22; Ch. 21: Midwest, KM 6, Case Study "Great Lakes Climate Adaptation Network;" KM 6; Ch. 23: S. Great Plains, KM 5).[1] The social, economic, and institutional contexts in which these vulnerable populations are embedded can further influence their individual vulnerabilities and collective capacity to communicate, cooperate, and cope with a climate disturbance event.[224] Rural communities are less likely to have local land-use regulations and building codes than urban communities, and those that do exist are more likely to be loosely enforced.[225] Lack of economic diversity, limited access to the internet, and relatively limited infrastructure, resources, and political clout further detract from the adaptive capacity of rural communities.[226,227,228] As a result, rural communities are subject to a "climate gap" defined by disproportionate and unequal impacts of climate change and extreme climate events.[229]

Vulnerability to climate change is a function of exposure, sensitivity, and adaptive capacity (Ch. 28: Adaptation). Developing the capacity to implement strategies that avoid stress or reduce system sensitivity can minimize vulnerability. Knowledge of climate change is underutilized in adaptation because procedures for incorporating climate information into decision-making have not been adequately developed.[230,231] Flexibility is a central feature of successful adaptation to climate change.[232] Adaptive capacity is highly diverse in terms of a community's ability to plan, recognize, and manage risk and then to adopt and implement adaptation strategies.[230,233] This necessitates a range of flexible and cost-effective adaptation strategies that can address varied sensitivities and adaptive capacities (Ch. 15: Tribes, Box 15.1; Ch. 24: Northwest, Figure 24.14, Box 24.5). Innovative efforts to build capacity in rural and Indigenous communities are described in Chapter 20: U.S. Caribbean, Key Message 6 and Chapter 21: Midwest, Key Message 6.

Emerging Issues and Research Gaps

Agriculture is a highly complex system that is tightly integrated with local-to-global food systems and interlinked with rural communities that both rely on agricultural production for economic viability and support agricultural labor, input, and market requirements. Since the Third National Climate Assessment,[234] there have been significant technological advances and a renewed emphasis on conservation management and precision agriculture, especially as it relates to climate. Climate-smart agricultural initiatives (such as cover crops, specialized irrigation, and nutrient management) are being implemented to respond to or prepare for climate variability and change. In addition, genomics and plant breeding have targeted specific climate-related issues such as drought or increased ranges of pests. However, our understanding of the challenges posed by climate change is evolving, and new technologies and improved scientific understanding is warranted. Examples of these emerging issues and research gaps include the following:

- Considerable private- and public-sector research is focused on the genetic improvement of crops to enhance resilience under climate stress. However, most of the research has focused on a few major species, with minimal public resources invested in genetic improvement of specialty crops. Additionally, these efforts have focused largely on yield and much less on quality improvements that have significant nutritional and economic implications.

- Additional research would improve our understanding of the interactive effects of CO_2 concentration levels in the atmosphere, temperature, and water availability on plant physiological responses, particularly in highly dynamic field environments.

- Field-scale research has been conducted on the potential of cellulosic bioenergy crops, including grasses, fast-growing woody species, and corn residue harvest. However, the cascading effects of land-use change (from food to bioenergy crops) on rural economies, labor, and the environment remain uncertain.

- Scientific understanding of climate change impacts on beneficial and pest insects, pathogens and beneficial microorganisms, and weeds is limited, as is knowledge about the interactions of these organisms within complex agricultural landscapes.

- The Agricultural Model Intercomparison and Improvement Project (AgMIP) applies state-of-the art climate, crop/livestock, and agricultural economic models, along with stakeholder input, to coordinate multi-model regional and global assessments of climate impacts and adaptation. AgMIP is developing a rigorous process to evaluate agricultural models and thus is promoting continuous model improvement as well as supporting data sharing and the identification of adaptation technologies and policies. Currently, there is no comparable modeling framework to address animal agriculture or to evaluate the cascading effects of production on the broader food systems and food security issues.

- Agriculture has the ability to mitigate greenhouse gas emissions through carbon sequestration in the soil and perennial vegetation, through improved nutrient-use efficiency of fertilizers, and through reduced methane emissions from ruminant livestock and manure. However, the magnitude of potential mitigation, particularly of nitrous oxides from soil and soil methanogens are poorly understood. Better understanding of the soil, rhizosphere, and rumen microbiomes would improve our ability to develop mitigation strategies.

- A systems approach for research would facilitate understanding of the vulnerabilities of food systems to climate change and quantifying the costs of business as usual relative to the adoption of adaptation and mitigation strategies.

- Social science research would improve understanding of the vulnerability of rural communities, strategies to enhance adaptive capacity and resilience, and barriers to adoption of new strategies.

Acknowledgments

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Traceable Accounts

Process Description

Each regional author team organized a stakeholder engagement process to identify the highest-priority concerns, including priorities for agriculture and rural communities. Due to the heterogeneous nature of agriculture and rural communities, the national chapter leads (NCLs) and coauthor team put in place a structured process to gather and synthesize input from the regional stakeholder meetings. Where possible, one or more of the authors or the chapter lead author listened to stakeholder input during regional stakeholder listening sessions. Information about agriculture and rural communities was synthesized from the written reports from each regional engagement workshop. During the all-authors meeting on April 2–3, 2017, the NCL met with authors from each region and other national author teams to identify issues relevant to this chapter. To finalize our regional roll-up, a teleconference was scheduled with each regional author team to discuss agriculture and rural community issues. Most of the regional author teams identified issues related to agricultural productivity, with underlying topics dominated by drought, temperature, and changing seasonality. Grassland wildfire was identified as a concern in the Northern and Southern Great Plains. All regional author teams identified soil and water vulnerabilities as concerns, particularly as they relate to soil and water quality impacts and a depleting water supply, as well as reduced field operation days due to wet soils and an increased risk of soil erosion due to precipitation on frozen soil. Heat stress in rural communities and among agricultural workers was of concern in the Southeast, Southern Great Plains, Northwest, Hawai‘i and Pacific Islands, U.S. Caribbean, and Northeast. Livestock health was identified as a concern in the Northeast, Midwest, U.S. Caribbean, and Southern Great Plains. Additional health-related concerns were smoke from wildfire, pesticide impacts, allergens, changing disease vectors, and mental health issues related to disasters and climate change. Issues related to the vulnerability and adaptive capacity of rural communities were identified by all regions. Discussions with the regional teams were followed by expert deliberation on the draft Key Messages by the authors and targeted consultation with additional experts. Information was then synthesized into Key Messages, which were refined based on published literature and professional judgment.

Key Message 1

Reduced Agricultural Productivity

Food and forage production will decline in regions experiencing increased frequency and duration of drought (*high confidence*). Shifting precipitation patterns, when associated with high temperatures, will intensify wildfires that reduce forage on rangelands, accelerate the depletion of water supplies for irrigation, and expand the distribution and incidence of pests and diseases for crops and livestock (*very likely*, *high confidence*). Modern breeding approaches and the use of novel genes from crop wild relatives are being employed to develop higher-yielding, stress-tolerant crops.

Description of evidence base

The Key Message and supporting text summarize extensive evidence documented in the U.S. Global Change Research Program's (USGCRP) *Climate Science Special Report*[84] indicating increasing drought frequency or severity in many parts of the United States, increased temperature, and increased frost-free days. An increased probability of hot days concurrent with drought has been reported by Mueller and Seneviratne (2012),[235] Mazdiyasni and AghaKouchak (2015),[236] and Diffenbaugh et al. (2015).[107] The warming of minimum temperatures (lack of hard freezes) is contributing to expanding ranges for many insect, disease, and weed species.[237] Bebber et al. (2013)[238] report an average poleward shift of 2.7 km/year (1.68 miles/year) since 1960 of numerous pests and pathogens.

Agricultural production: Walthall et al. (2012)[38] synthesize a wide body of literature that documents the impacts of climate, including drought, on crop and livestock productivity and on the natural resources that support agricultural production. Marshall et al. 2015[97] also quantified climate change impacts on the yield of major U.S. crops as well as the reduced ability in the future to mitigate drought by irrigation. Havstad et al. (2016)[239] describe the resilience of livestock production on rangelands in the Southwest and identify adaptation management strategies needed in an increasingly arid and variable climatic environment. Liang et al. (2017)[240] found that total factor productivity (TFP) for the U.S. agriculture sector is related to regional and seasonal temperature and precipitation factors. Rosenzweig et al. (2014)[241] indicated strong negative effects of climate change on crop yields, particularly at higher levels of warming and lower latitudes. While technological improvements have outweighed the aggregate negative impacts of climate to date, projected climate change indicates that U.S. agriculture TFP could drop to pre-1980s levels by 2050. Ray et al. (2015)[242] estimate that climate accounts for about one-third of global yield variability.

Crop heat stress: Novick et al. (2016)[243] indicate that atmospheric vapor pressure deficits play a critical role in plant function and productivity and that it will become more important at higher temperatures as an independent factor, relative to available soil moisture. For instance, high temperature has been documented to decrease yields of major crops, including wheat, corn, rice, and soybean.[92,113,120,244] Multimodel simulations indicated that grain yield reductions of wheat at high temperature were associated with reduced grain number per head[120] and that yield reductions were increased with higher temperature increases across a wide range of latitudes.[241] Hatfield et al. (2017)[245] report that yield gaps for Midwest corn were negatively related to July maximum and August minimum temperatures but positively related to July–August rainfall, and that soybeans were less sensitive to projected temperature changes than corn. For corn, projected yield gaps showed a strong North–South gradient, with large gaps in southern portions of the region. Kukal and Irmak (2018)[246] reported that changes in the variability of maize, sorghum, and soybean yield patterns in the Great Plains from 1968–2013 were linked to temperature and precipitation, with irrigated crops showing low variability compared to rainfed crops. Temperature increases were detrimental to sorghum and soybean yield but not to corn during this period. Tebaldi and Lobbell (2015)[247] projected that corn would benefit from greenhouse gas mitigation to limit temperature increases throughout this century. For wheat, but less so for corn, impacts of exposure to extremely high temperatures would be partially offset by carbon dioxide fertilization effects. Tack et al. (2015)[248] report that the largest drivers of Kansas wheat yield loss over 1985–2013 were freezing temperatures in the fall and extreme heat events in the spring.[249,250] The overall effect of warming on yields was negative, even after accounting for the benefits of reduced exposure to freezing temperatures. Warming effects were partially offset by increased spring precipitation. Of concern was evidence that recently released wheat varieties are less able to resist high temperature stress than older varieties. Gammans et al. (2017)[251] found that wheat and barley yields in France were negatively related to spring and summer temperatures. Liu et al. (2016)[252] report that with a 1.8°F (1°C) global temperature increase, global wheat yield is projected to decline between 4.1% and 6.4%, with the greatest losses in warmer wheat-producing regions. Wienhold et al. (2017)[253] identify an increase in the number of extreme temperature events (higher daytime highs or nighttime lows) as a vulnerability of Northern Great Plains crops due to increased plant stress during critical pollination and grain fill periods. Burke and Emerick (2016)[254] found that adaptation appeared to have mitigated less than half of the negative impacts of extreme heat on productivity.

Wildfire and rangelands: Margolis et al. (2017)[255] report that fire scars in tree rings for the years 1599–1899 indicate that large grassland fires in New Mexico are strongly influenced by the current year cool-season moisture, but that fires burning mid-summer to fall are also influenced by monsoon moisture. Wet conditions several years prior to the fire year, resulting in increased fuel load, are also important for spring through late-summer fires. Persistent cool-season drought lasting longer than three years may inhibit fires due to the lack of moisture to replenish surface fuels. Donovan et al. (2017)[95] reported that wildfires greater than 400 hectares increased from 33.4 ± 5.6 per year during the period 1985–1994 to 116.8 ± 28.8 wildfires per year for the period 2005–2014 and that the total area burned in the Great Plains by large wildfires increased 400%.

Water supply: Dai and Zhao (2017)[256] quantify historical trends in drought based on indices derived from the self-calibrated Palmer Drought Severity Index and the Penman–Monteith potential evapotranspiration index. For greater reliability, they compare these results with observed precipitation change patterns, streamflow, and runoff in three different periods: 1950–2012, 1955–2000, and 1980–2012. They indicate that spatially consistent patterns of drying have occurred in many parts of the Americas, that evaporation trends were slightly negative or slightly positive (exclusive of 1950–1980), and that drought has been increasingly linked to increased vapor pressure deficits since the 1980s.

Pest pressures: Integrated pest management is rapidly evolving in the face of intensifying pest challenges to crop production.[257] There is considerable capacity for genetic improvement in agricultural crops and livestock breeds, but the ultimate ability to breed increased heat and drought tolerance into germplasm while retaining desired agronomic or horticultural attributes remains uncertain.[258] The ability to breed pest-resistant varieties into a wide range of species to address rapidly evolving disease, insect, and weed species[237] is also uncertain.

Major uncertainties

Drought impacts on crop yields and forage are critical at the farm economic scale and are well documented.[38,97] However, the extent to which drought impacts larger-scale issues of food security depends on a wide range of economic and social factors that are less certain. Chavez et al. (2015)[259] lay out a framework for food security assessment that incorporates risk mitigation, risk forecast, and risk transfer instruments. There is considerable uncertainty in what is expected for the frequency and severity of future droughts.[260] However, retrospective analyses and global climate modeling of 1900–2014 drought indicators show consistent results. The applied global climate models project 50%–200% increases in agricultural drought frequency in this century, even under low forcing scenarios. There is uncertainty about the interactive effects of carbon dioxide concentration, temperature, and water availability on plant physiological responses, particularly in highly dynamic field environments. There is uncertainty about future technological advances in agriculture and about changes in diet choices and food systems.

Description of confidence and likelihood

The USGCRP[84] determined that recent droughts and associated heat waves have reached record intensities in some regions of the United States; however, by geographic scale and duration, the 1930s Dust Bowl remains the benchmark drought and extreme heat event in the historical record since 1895 (*very high confidence*). The confidence is *high* that drought negatively impacts crop yield and quality, increases the risk of range wildfires, and accelerates the depletion of water supplies (*very likely and high confidence*).

Key Message 2

Degradation of Soil and Water Resources

The degradation of critical soil and water resources will expand as extreme precipitation events increase across our agricultural landscape (*high confidence*). Sustainable crop production is threatened by excessive runoff, leaching, and flooding, which results in soil erosion, degraded water quality in lakes and streams, and damage to rural community infrastructure (*very likely*, *very high confidence*). Management practices to restore soil structure and the hydrologic function of landscapes are essential for improving resilience to these challenges.

Description of evidence base

Evidence of long-term changes in precipitation is based on analyses of daily precipitation observations from the National Weather Service's Cooperative Observer Network.[261]

Groisman et al. (2012)[262] reported that for the central United States, the frequency of very heavy precipitation increased by 20% from 1979–2009 compared to 1948–1978. Slater and Villarini (2016)[263] report a significant increase in flooding frequency in the Southern Plains, California, and northern Minnesota; a smaller increase in the Southeast; and a decrease in the Northern Plains and Northwest. Mallakpour and Villarini (2015)[264] report an increasing frequency of flooding in the Midwest, primarily in summer, but find limited evidence of a change in magnitude of flood peaks.

Infrastructure: Severe local storms constituted the largest class of billion-dollar natural disasters from 1980 to 2011, followed by tropical cyclones and nontropical floods.[265] Špitalar et al. (2014)[266] evaluate flash floods from 2006 to 2012 and find that the floods with the highest human impacts, based on injuries and fatalities, are associated with small catchment areas in rural areas. Rural areas face particular challenges with road networks and connectivity.[267]

Soil and water: Soil carbon on agricultural lands is decreased due to land-use change and tillage,[268,269] resulting in decreased hydrologic function.[101] Practices that increase soil carbon have an adaptation benefit through improved soil structure and infiltration, improved water-holding capacity, and improved nutrient cycling. There are many practices that can enhance agricultural resilience through increased soil carbon sequestration.[75,268,270,271,272,273] Houghton et al. (2017)[274] identify the health effects associated with poor water quality that can be associated with nutrient transport to water bodies and subsequent eutrophication.

Major uncertainties

Floods are highly variable in space and time,[86] and their characteristics are influenced by a number of non-climate factors.[275] Groissman et al. (2012)[262] note that the lack of sub-daily data to analyze precipitation intensity means that daily data are normally used, which limits the ability to detect the most intense precipitation rates. While many practices are available to protect soil and reduce nutrient runoff from agricultural lands,[268,272] adoption rates by producers are uncertain. Additionally, there is uncertainty about the extent to which agribusiness will invest in soil improvement to mitigate risks associated with a changing climate and its effects on water, energy, and plant and animal supply chains.[276]

Description of confidence and likelihood

The evidence on increasing precipitation intensity, with the largest increases occurring in the Northeast, is high (*very likely, high confidence*). The increase in flooding is less certain (*likely, medium confidence*). The evidence of the impact of precipitation extremes on infrastructure losses, soil erosion, and contaminant transport to water bodies is well established (*very likely, high confidence*). Based on *medium confidence* on flooding but *high confidence* in increasing precipitation intensity and the impacts of precipitation extremes, there is *high confidence* in this Key Message.

Key Message 3

Health Challenges to Rural Populations and Livestock

Challenges to human and livestock health are growing due to the increased frequency and intensity of high temperature extremes (*very likely*, *high confidence*). Extreme heat conditions contribute to heat exhaustion, heatstroke, and heart attacks in humans (*very likely*, *high confidence).* Heat stress in livestock results in large economic losses for producers (*very likely*, *high confidence*). Expanded health services in rural areas, heat-tolerant livestock, and improved design of confined animal housing are all important advances to minimize these challenges.

Description of evidence base

The Key Message and supporting text summarize extensive evidence documented in the USGCRP's *Climate Science Special Report*.[84]

Humans: Houghton et al. (2017)[274] synthesize the literature that presents strong evidence of climate change impacts on human health in rural areas. Anderson et al. (2018)[278] find that heat waves pose risks to human mortality but that the risk associated with any single heat wave depends on many factors, including heat wave length, timing, and intensity. On average, heat waves increase daily mortality risk by approximately 4% in the United States,[279] but extreme heat waves present significantly higher risks. While research on heat-related morbidity has focused on urban areas, Jagai et al. (2017)[280] analyzed heat waves in Illinois over 1987–2014 and found that there were 1.16 hospitalizations per 100,000 people in the most rural, thinly populated areas, compared to 0.45 hospitalizations per 100,000 in metropolitan areas. Consequently, a 1.8°F (1°C) increase in maximum monthly temperature was associated with a 0.34 increase in hospitalization rates in rural areas compared to an increase of 0.02 per 100,000 in urbanized counties. The mean cost per hospital stay was $20,050. Fechter-Leggett et al. (2016),[281] Hess et al. (2014),[282] and Sugg et al.

(2016)[283] also report an elevated risk in rural areas for emergency room visits for heat stress. Additionally, rural areas have a high proportion of outdoor workers who are at additional risk for heat stress.[280,284,285] Merte (2017)[286] analyzed data from 1960 to 2015 for 27 European countries and found that 0.61% of all deaths were caused by extreme heat.

Major uncertainties

Humans: Much of the literature focuses on heat-related mortality in urban areas (e.g., Oleson et al. 2015, Marsha et al. 2017.[287,288]) Vulnerability and exposure in rural areas are not well understood, but Oleson et al. (2015),[287] in quantifying projected future temperature impacts, indicate that urban areas will experience more summer heat days and reduced winter cold temperature days than rural areas. Huber et al. (2017)[289] identify uncertainties in estimated impacts of death from cardiovascular diseases from a 1.8°F (1°C) increase in global temperature. Anderson et al. (2018)[278] discuss uncertainties associated with changes in the size and age of the population and the breadth of plausible socioeconomic scenarios. Jones et al. (2015)[290] identify uncertainties in the migration of population due to a changing climate and how that would impact exposure. Hallstrom et al. (2017)[291] evaluated the possible effects of future diet choices on various health indicators, many of which would have impacts on an individual's sensitivity to high temperature.

Livestock: Walthall et al. (2012)[38] synthesize a wide body of literature that documents the impacts of extreme temperature effects on livestock health and productivity. Ruminant livestock support rural livelihoods and produce high-quality food products from land that is otherwise unsuited to crop agriculture.[292,293]

Description of confidence and likelihood

Extreme temperatures are projected to increase even more than average temperatures. The temperatures of extremely cold days and extremely warm days are both projected to increase. Cold waves are projected to become less intense, while heat waves will become more intense (*very likely, very high confidence*).[277]

Lehner et al. (2017)[294] indicate a high likelihood and high confidence that there will be increased record-breaking summer temperatures by the end of the century. Evidence of challenges to human and livestock health due to temperature extremes is well established (*very likely, very high confidence*).

Key Message 4

Vulnerability and Adaptive Capacity of Rural Communities

Residents in rural communities often have limited capacity to respond to climate change impacts, due to poverty and limitations in community resources (*very likely*, *high confidence*). Communication, transportation, water, and sanitary infrastructure are vulnerable to disruption from climate stressors (*very likely*, *high confidence*). Achieving social resilience to these challenges would require increases in local capacity to make adaptive improvements in shared community resources.

Description of evidence base

A wealth of data shows that residents of rural areas generally have lower levels of education and lower wages for a given level of education compared to residents of urban areas.[295] Higher levels of poverty, particularly childhood poverty,[7] and food insecurity in rural compared to urban areas are also well documented.[49] There is also research that documents the disproportionate impacts of climate change on areas with multiple socioeconomic disadvantages, such as an increased risk of exposure to extreme heat and poor air quality, lack of access to basic necessities, and fewer job opportunities.[229]

Major uncertainties

There is uncertainty about future economic activity and employment in rural U.S. communities. However, the patterns of lower education levels, higher poverty levels, and high unemployment have been persistent and are likely to require long-term, focused efforts to reverse.[6,49,295] There are numerous federal programs (such as the USDA's regional Climate Hubs, the National Oceanic and Atmospheric Administration's Regional Integrated Sciences and Assessments program, and the U.S. Department of the Interior's Climate Adaptation Science Centers) that focus on outreach and capacity building to rural and underserved communities. Additionally, the Cooperative Extension Service and state agencies, as well as various nongovernmental organizations, provide support and services to build the adaptive capacity of individuals and communities.

Description of confidence and likelihood

Lower levels of education, poverty, limited infrastructure, and lack of access to resources will limit the adaptive capacity of individuals and communities (*very likely, high confidence*). Adaptive capacity in rural communities is being increased through federal, state, and local capacity building efforts (*likely, low to medium confidence*). However, the outreach to rural communities varies greatly in different parts of the United States.

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11 Built Environment, Urban Systems, and Cities

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Impacts, Risks, and Adaptation in the United States: Fourth National Climate Assessment, Volume II

11 Built Environment, Urban Systems, and Cities

Cleveland, Ohio

Key Message 1

Impacts on Urban Quality of Life

The opportunities and resources in urban areas are critically important to the health and well-being of people who work, live, and visit there. Climate change can exacerbate existing challenges to urban quality of life, including social inequality, aging and deteriorating infrastructure, and stressed ecosystems. Many cities are engaging in creative problem solving to improve quality of life while simultaneously addressing climate change impacts.

Key Message 2

Forward-Looking Design for Urban Infrastructure

Damages from extreme weather events demonstrate current urban infrastructure vulnerabilities. With its long service life, urban infrastructure must be able to endure a future climate that is different from the past. Forward-looking design informs investment in reliable infrastructure that can withstand ongoing and future climate risks.

Key Message 3

Impacts on Urban Goods and Services

Interdependent networks of infrastructure, ecosystems, and social systems provide essential urban goods and services. Damage to such networks from current weather extremes and future climate will adversely affect urban life. Coordinated local, state, and federal efforts can address these interconnected vulnerabilities.

Key Message 4

Urban Response to Climate Change

Cities across the United States are leading efforts to respond to climate change. Urban adaptation and mitigation actions can affect current and projected impacts of climate change and provide near-term benefits. Challenges to implementing these plans remain. Cities can build on local knowledge and risk management approaches, integrate social equity concerns, and join multicity networks to begin to address these challenges.

Executive Summary

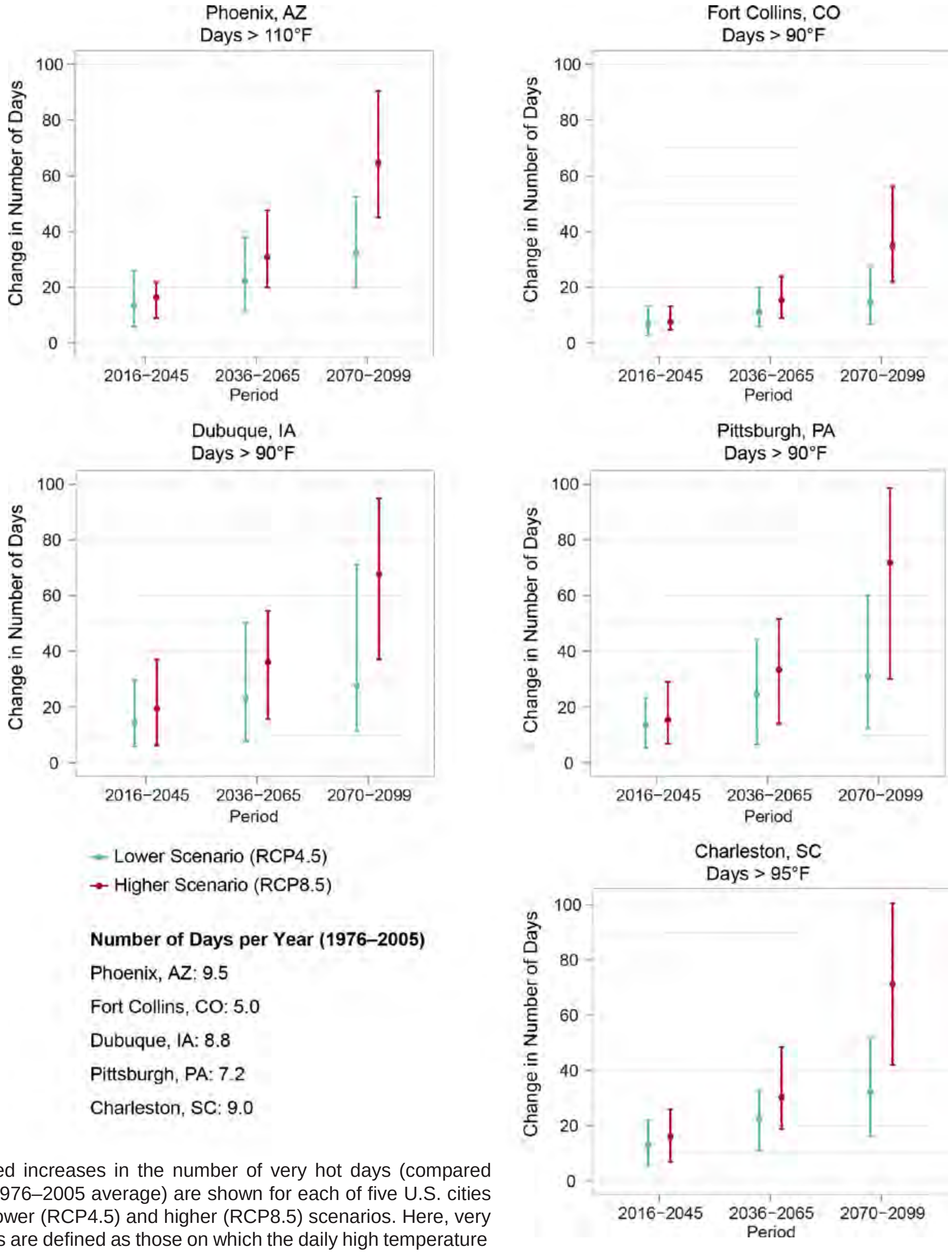
Urban areas, where the vast majority of Americans live, are engines of economic growth and contain land valued at trillions of dollars. Cities around the United States face a number of challenges to prosperity, such as social inequality, aging and deteriorating infrastructure, and stressed ecosystems. These social, infrastructure, and environmental challenges affect urban exposure and susceptibility to climate change effects.

Urban areas are already experiencing the effects of climate change. Cities differ across regions in the acute and chronic climate stressors they are exposed to and how these stressors interact with local geographic characteristics. Cities are already subject to higher surface temperatures because of the urban heat island effect, which is projected to get stronger. Recent extreme weather events reveal the vulnerability of the built environment (infrastructure such as residential and commercial buildings, transportation, communications, energy, water systems, parks, streets, and landscaping) and its importance to how people live, study, recreate, and work.

Heat waves and heavy rainfalls are expected to increase in frequency and intensity. The way city residents respond to such incidents depends on their understanding of risk, their way of life, access to resources, and the communities to which they belong. Infrastructure designed for historical climate trends is vulnerable to future weather extremes and climate change. Investing in forward-looking design can help ensure that infrastructure performs acceptably under changing climate conditions.

Urban areas are linked to local, regional, and global systems. Situations where multiple climate stressors simultaneously affect multiple city sectors, either directly or through system connections, are expected to become more common. When climate stressors affect one sector, cascading effects on other sectors increase risks to residents’ health and well-being. Cities across the Nation are taking action in response to climate change. U.S. cities are at the forefront of reducing greenhouse gas emissions and many have begun adaptation planning. These actions build urban resilience to climate change.

Projected Change in the Number of Very Hot Days



Number of Days per Year (1976–2005)

Phoenix, AZ: 9.5

Fort Collins, CO: 5.0

Dubuque, IA: 8.8

Pittsburgh, PA: 7.2

Charleston, SC: 9.0

Projected increases in the number of very hot days (compared to the 1976–2005 average) are shown for each of five U.S. cities under lower (RCP4.5) and higher (RCP8.5) scenarios. Here, very hot days are defined as those on which the daily high temperature exceeds a threshold value specific to each of the five U.S. cities shown. Dots represent the modeled median (50th percentile) values, and the vertical bars show the range of values (5th to 95th percentile) from the models used in the analysis. Modeled historical values are shown for the same temperature thresholds, for the period 1976–2005, in the lower left corner of the figure. These and other U.S. cities are projected to see an increase in the number of very hot days over the rest of this century under both scenarios, affecting people, infrastructure, green spaces, and the economy. Increased air conditioning and energy demands raise utility bills and can lead to power outages and blackouts. Hot days can degrade air and water quality, which in turn can harm human health and decrease quality of life. *From Figure 11.2 (Sources: NOAA NCEI, CICS-NC, and LMI)*.

Introduction

Recent extreme weather events reveal the vulnerability of the built environment (infrastructure, such as residential and commercial buildings, transportation, communications, energy, water systems, parks, streets, and landscaping) and its importance to how people live, study, recreate, and work in cities. This chapter builds on previous assessments of urban social vulnerability and climate change impacts on urban systems.[1,2,3] It discusses recent science on urban social and ecological systems underlying vulnerability, impacts on urban quality of life and well-being, and urban adaptation. It also reviews the increase in urban adaptation activities, including investment, design, and institutional practices to manage risk. Examples of climate impacts and responses from five cities (Charleston, South Carolina; Dubuque, Iowa; Fort Collins, Colorado; Phoenix, Arizona; and Pittsburgh, Pennsylvania) illustrate the diversity of American cities and the climate risks they face.

State of the Sector

Urban areas in the United States, where the vast majority of Americans live, are engines of economic growth and contain land valued at trillions of dollars. In 2015, nearly 275 million people (about 85% of the total U.S. population) lived in metropolitan areas, and 27 million (about 8%) lived in smaller micropolitan areas.[4] Metropolitan areas accounted for approximately 91% of U.S. gross domestic product (GDP) in 2015, with over 23% coming from the five largest cities alone.[5] Urban land values are estimated at more than two times the 2006 national GDP.[6] Urbanization trends are expected to continue (Figure 11.1), and projections suggest that between 425 and 696 million people will live in metropolitan and micropolitan areas combined by 2100.[7] All of these factors affect how urban areas respond to climate change.

Cities around the United States face a number of challenges to prosperity, such as social inequality, aging and deteriorating infrastructure, and stressed ecosystems. Urban social inequality is evident in disparities in per capita income, exposure to violence and environmental hazards, and access to food, services, transportation, outdoor space, and walkable neighborhoods.[9,10,11,12] Cities are connected by networks of infrastructure, much of which is in need of repair or replacement. Failing to address aging and deteriorating infrastructure is expected to cost the U.S. GDP as much as $3.9 trillion (in 2015 dollars) by 2025.[13] Current infrastructure and building design standards do not take future climate trends into account.[14] Urbanization affects air, water, and soil quality and increases impervious surface cover (such as cement and asphalt).[15,16,17] Urban forests, open space, and waterways provide multiple benefits, but many are under stress because of land-use change, invasive species, and pollution.[18] These social, infrastructure, and environmental challenges affect urban exposure and susceptibility to climate change effects.

Urban areas, where the majority of the U.S. population lives and most consumption occurs, are the source of approximately 80% of North American human-caused greenhouse gas (GHG) emissions, despite only occupying 1%–5% of the land. Therefore, changes to urban activities can have a significant impact on national GHG emissions.[19] Land use and land-cover change contribute to radiative forcing, and infrastructure design can lock in fossil fuel dependency, so urban development patterns will continue to affect carbon sources and sinks in the future (Ch. 5: Land Changes).[19,20,21] Many cities in the United States are working to reduce their GHG emissions and can be key leverage points in mitigation efforts.

Current and Projected U.S. Population

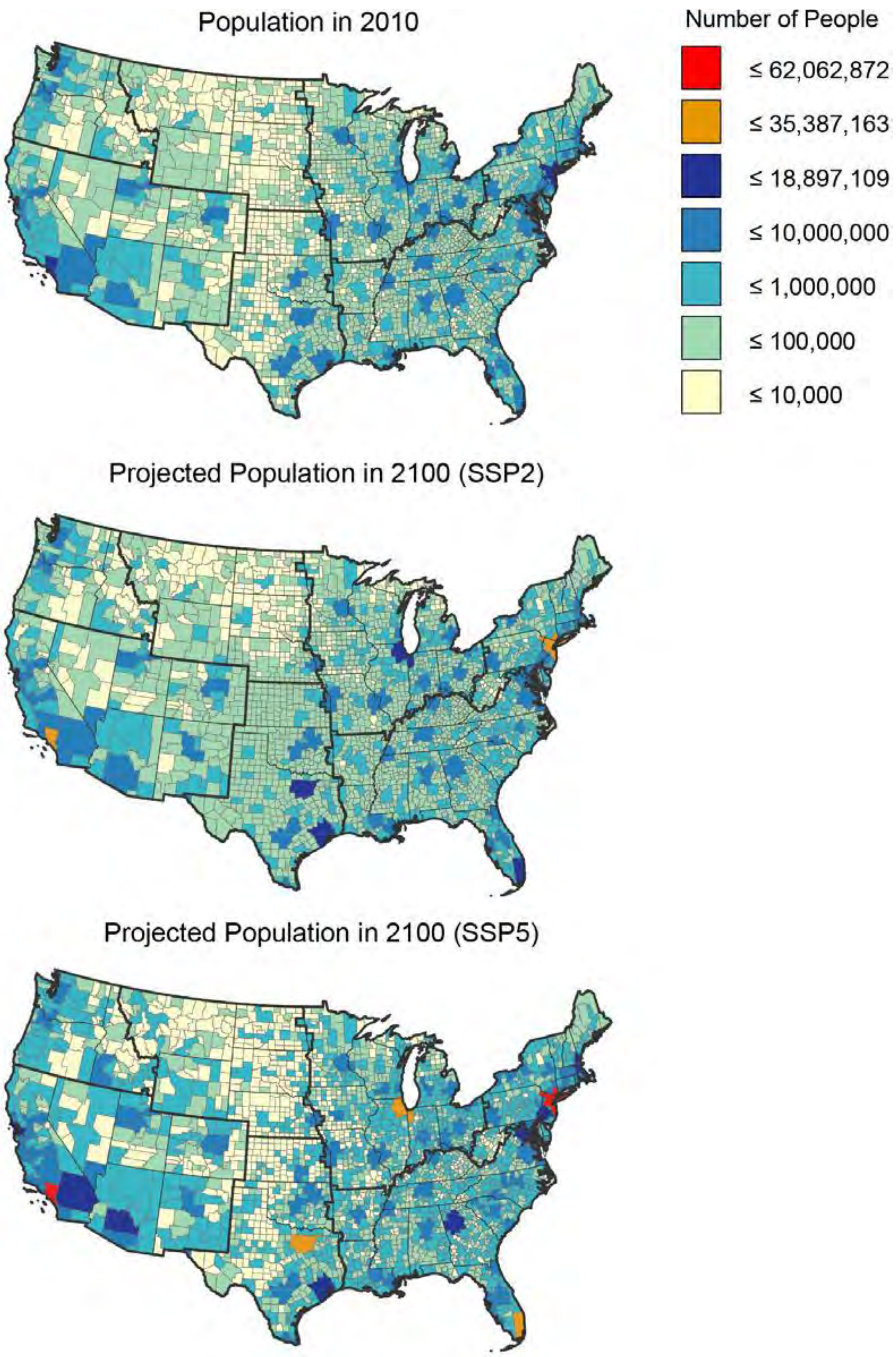


Figure 11.1: These maps show current population along with population projections by county for the year 2100. Projected populations are based on Shared Socioeconomic Pathways (SSPs)—a collection of plausible future pathways of socioeconomic development.[8] The middle map is based on demography consistent with the SSP2, which follows a middle-of-the-road path where trends do not shift markedly from historical patterns. The bottom map uses demography consistent with SSP5, which follows a more rapid technical progress and resource-intensive development path. Increasing urban populations pose challenges to planners and city managers as they seek to maintain and improve urban environments. Data are unavailable for the U.S. Caribbean, Alaska, and Hawai‘i & U.S.-Affiliated Pacific Islands regions. Source: EPA

Regional Summary

Urban areas in the United States are already experiencing the effects of climate change. Across regions, U.S. cities differ in the acute and chronic climate stressors they are exposed to and how these stressors interact with local geographic characteristics.[1] In coastal areas, the built environment is subject to storm surge, high tide flooding, and saltwater intrusion (Ch. 8: Coastal, KM 1). Wildfires are on the rise in the West, lowering air quality and damaging property in cities near the wildland–urban interface (Ch. 6: Forests, KM 1; Ch. 13: Air Quality, KM 2; Ch. 14: Human Health, KM 1; Ch. 24: Northwest, KM 3; Ch. 25: Southwest, KM 2). In 2017, Los Angeles witnessed the largest wildfire in its history, with over 700 residents ordered to evacuate. The fire began during a heat wave and burned over 7,100 acres.[22] Key climate threats in the Northeast, on the other hand, are from precipitation and flooding: between 2007 and 2013, Pittsburgh experienced 11 significant flash flooding events[23,24] (Ch. 18: Northeast, KM 3). Heat waves (Figure 11.2) and heavy rainfalls (Figure 11.3) are expected to increase in frequency and intensity (Ch. 2: Climate KM 2 and 5).[25,26,27] The way city residents respond to such incidents depends on their understanding of risk, their way of life, access to resources, and the communities to which they belong.[28]

In other parts of the country, drought conditions coupled with extreme heat increase wildfire risk, and rainfall after wildfires raises flood risks.[21] In 2012 and 2013, fires destroyed hundreds of homes in the Fort Collins area of the Northern Great Plains region. In those same years, floods washed out transportation infrastructure and caused $2 billion (in 2013 dollars) in total damages.[34,35]

Despite these differences, U.S. cities experience some climate impacts in similar ways. For example, prolonged periods of high heat affect urban areas around the country.[21] Cities are already subject to higher surface temperatures because of the urban heat island (UHI) effect, which can also affect regional climate.[29] The UHI is projected to get stronger with climate change.[29] Another commonality is that most cities are subject to more than one climate stressor. Exposure to multiple climate impacts at once affects multiple urban sectors, and the results can be devastating.[30] Over a four-day period in 2015, the coastal city of Charleston in the Southeast region experienced extreme rainfall, higher sea levels, and high tide flooding. These impacts combined to cause dam failures, bridge and road closures, power outages, damages to homes and businesses, and a near shutdown of the local economy (Ch. 19: Southeast, KM 2).[31,32,33] These kinds of incidents are expected to continue as climate change brings a higher number of intense hurricanes, high tide flooding, and accelerated sea level rise (Ch. 8: Coastal, KM 1).[21]

Projected Change in the Number of Very Hot Days

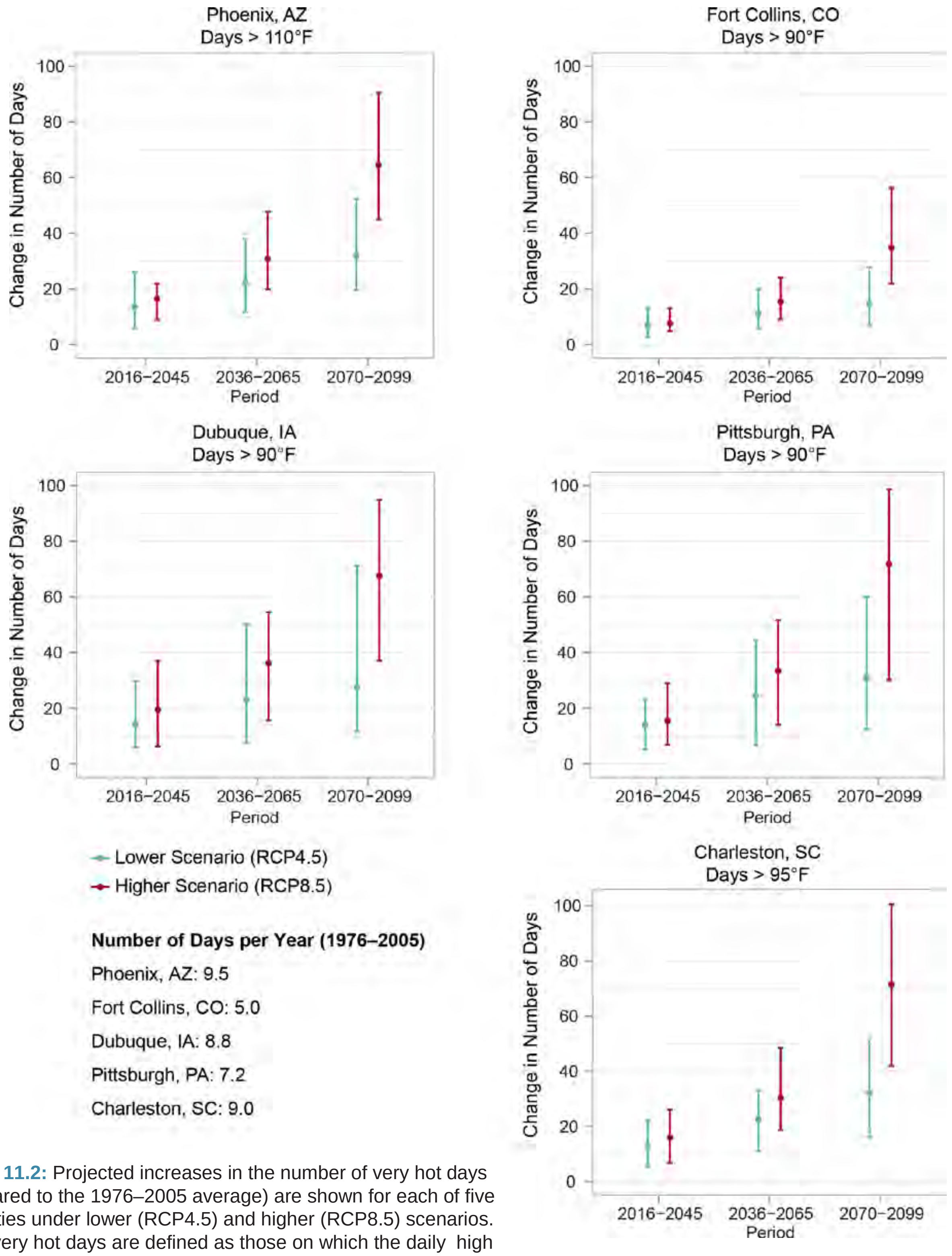
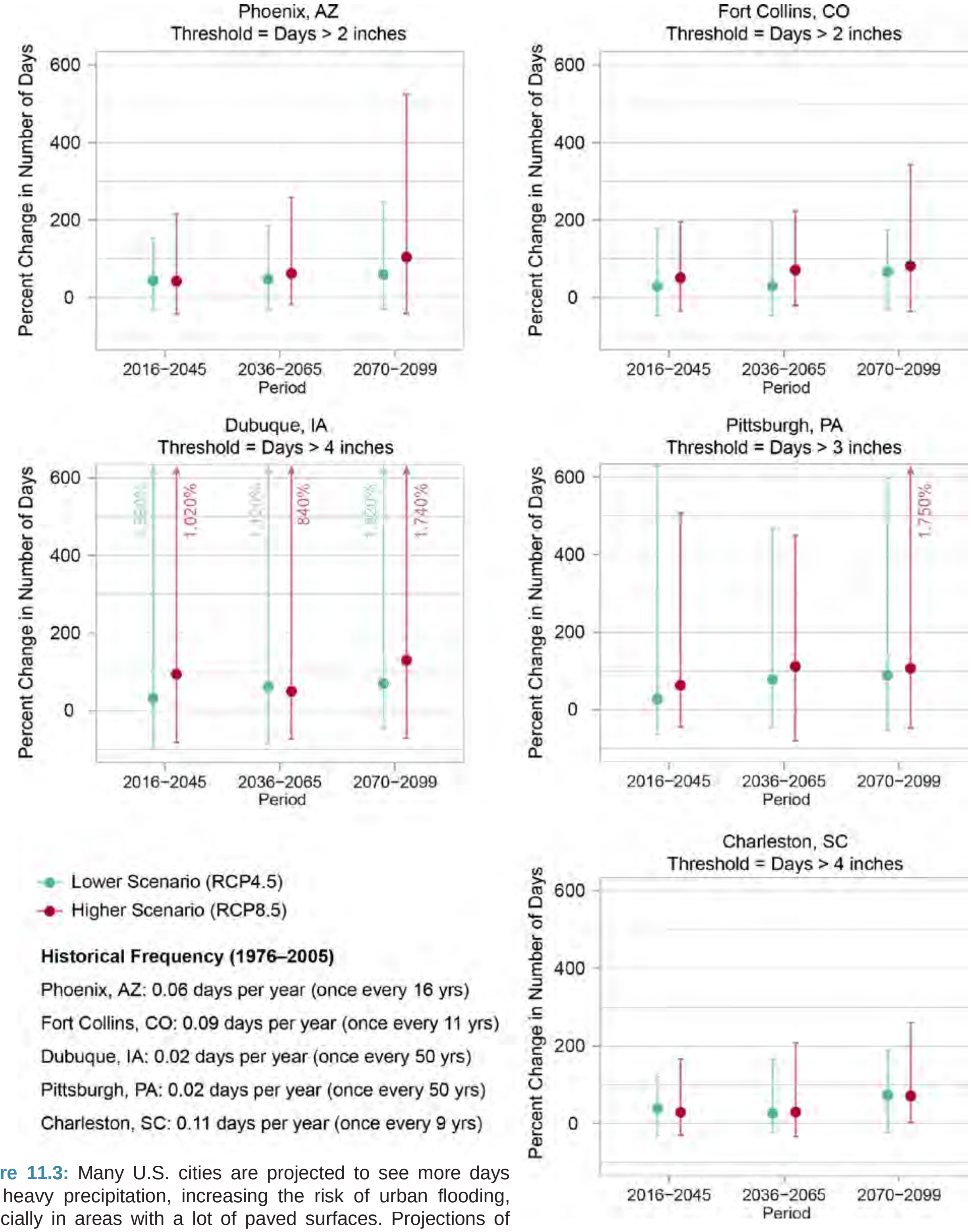


Figure 11.2: Projected increases in the number of very hot days (compared to the 1976–2005 average) are shown for each of five U.S. cities under lower (RCP4.5) and higher (RCP8.5) scenarios. Here, very hot days are defined as those on which the daily high temperature exceeds a threshold value specific to each of the five U.S. cities shown. Dots represent the modeled median (50th percentile) values, and the vertical bars show the range of values (5th to 95th percentile) from the models used in the analysis. Modeled historical values are shown for the same temperature thresholds, for the period 1976–2005, in the lower left corner of the figure. These and other U.S. cities are projected to see an increase in the number of very hot days over the rest of this century under both scenarios, affecting people, infrastructure, green spaces, and the economy. Increased air conditioning and energy demands raise utility bills and can lead to power outages and blackouts. Hot days can degrade air and water quality, which in turn can harm human health and decrease quality of life. Sources: NOAA NCEI, CICS-NC, and LMI.

Projected Change in the Number of Days with Heavy Precipitation



Historical Frequency (1976–2005)

Phoenix, AZ: 0.06 days per year (once every 16 yrs)

Fort Collins, CO: 0.09 days per year (once every 11 yrs)

Dubuque, IA: 0.02 days per year (once every 50 yrs)

Pittsburgh, PA: 0.02 days per year (once every 50 yrs)

Charleston, SC: 0.11 days per year (once every 9 yrs)

Figure 11.3: Many U.S. cities are projected to see more days with heavy precipitation, increasing the risk of urban flooding, especially in areas with a lot of paved surfaces. Projections of percent changes in the number of days with heavy precipitation (compared to the 1976–2005 average) are shown for each of five U.S. cities under lower (RCP4.5) and higher (RCP8.5) scenarios. Here, days with heavy precipitation are defined as those on which the amount of total precipitation exceeds a threshold value specific to each city. Dots represent the modeled median (50th percentile) values, and the vertical bars show the range of values (5th to 95th percentile) from the models used in the analysis. Modeled historical values are shown for the same thresholds, for the period 1976–2005, in the lower left corner of the figure. Historical values are given in terms of frequency (days per year) and return period (average number of years between events). Sources: NOAA NCEI, CICS-NC, and LMI.

Another similarity cities share is that when climate stressors affect one city sector, cascading effects on other sectors increase risks to residents' health and well-being (Ch. 17: Complex Systems). Higher temperatures can increase energy loads, which in turn can lead to structural failures in energy infrastructure, raise energy bills, and increase the occurrence of power outages (Ch. 4: Energy, KM 1). These changes strain household budgets, increase people's exposure to heat, and limit the delivery of medical and social services. For all cities, the duration of exposure to a climate stressor determines the degree of impacts. In recent years in the Southwest region, California experienced exceptional drought conditions. Urban and rural areas saw forced water reallocations and mandatory water-use reductions. Utilities had to cut back on electricity production from hydropower because of insufficient surface water flows and water in surface reservoirs (Ch. 25: Southwest, KM 1 and 5).[36,37,38]

Urban areas are linked to local, regional, and global systems.[39,40,41] For example, changes in regional food production and global trade affect local food availability.[42] Likewise, urban electricity supply often relies on far-off reservoirs, generators, and grids. Situations where multiple climate stressors simultaneously affect multiple city sectors, either directly or through system connections, are expected to become more common.[12,43,44]

Cities in all regions of the country are undertaking adaptation and mitigation actions. Several cities have climate action plans in place (see Bierbaum et al. 2013 for a review of U.S. urban adaptation plans[45]). Pittsburgh made commitments to reduce GHG emissions. Fort Collins initiated the Fort Collins ClimateWise Program. Phoenix is taking measures to reduce the UHI effect. These actions build urban resilience to climate change.

Key Message 1

Impacts on Urban Quality of Life

The opportunities and resources in urban areas are critically important to the health and well-being of people who work, live, and visit there. Climate change can exacerbate existing challenges to urban quality of life, including social inequality, aging and deteriorating infrastructure, and stressed ecosystems. Many cities are engaging in creative problem solving to improve quality of life while simultaneously addressing climate change impacts.

Cities are places where people learn, socialize, recreate, work, and live together. Quality of life for urban residents is associated with social and economic diversity, livelihood opportunities, and access to education, nature, recreation, healthcare, arts, and culture. Urban areas can foster economic prosperity and a sense of place. Yet, many cities in the United States face challenges to prosperity, including social inequality, aging and deteriorating infrastructure, and stressed ecosystems (Ch. 18: Northeast, KM 3).[13,18,46] These problems are intertwined. Climate change impacts exacerbate existing challenges to urban quality of life and adversely affect urban health and well-being.

Urban populations experiencing socioeconomic inequality or health problems have greater exposure and susceptibility to climate change.[12,47] Climate susceptibility varies by neighborhood, housing situation, age, occupation, and daily activities. People without access to housing with sufficient insulation and air conditioning (for example, renters and the homeless) have greater exposure to heat stress. Children playing outside, seniors living alone, construction workers, and athletes are also vulnerable to extreme heat (Figure 11.4).[12,48]

Threats from Extreme Heat

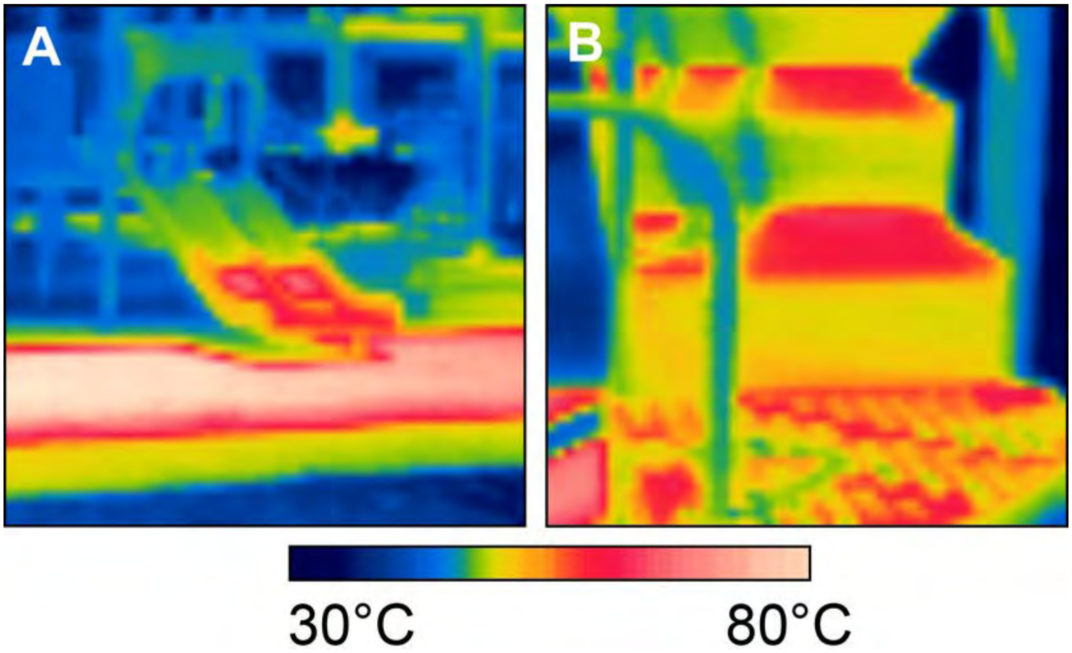


Figure 11.4: These images show surface temperatures of playground equipment in metropolitan Phoenix, Arizona. Children are particularly susceptible to high heat[12] and can be exposed through daily activities. (A) A slide and dark rubber surface in the sun (orange/red colors) are shown reaching temperatures of 71°C (160°F) and 82°C (180°F), respectively. The blue/green colors are under a shade sail. (B) Playground steps made of black powder-coated metal are shown reaching a temperature of 58°C (136°F) in the direct sunlight. Images use infrared thermography and were taken mid-day on September 15, 2014. Credit: Vanos et al. 2016.[49]

In addition to temperature extremes, climate change adversely affects urban population health through air and water quality and vector-borne diseases (Ch. 14: Human Health, KM 1). Urban residents feel economic impacts from food price volatility and the costs of insurance, energy, and water.[12,50] Climate change also threatens the integrity of personal property, ecosystems, historic landmarks, playgrounds, and cultural sites such as libraries and museums, all of which support an urban sense of place and quality of life (Ch. 24: Northwest, KM 2).[51,52,53] For example, historic landmarks in Charleston are at risk from sea level rise.[54] Urban ecosystems are further stressed by often unpredictable climate-related changes to tree species ranges, water cycles, and pest regimes.[55]

Coastal city flooding can result in forced evacuation, adversely affecting family and community stability, as well as mental and physical health (Ch. 14: Human Health, KM 1).[12] It also poses significant challenges to inland urban areas receiving these populations.[56,57] Many cities are undertaking creative problem solving to address climate change impacts and quality of life. They use approaches from urban design, sustainability, and climate justice.[58,59,60] For example, New York City's Trees for Public Health program targets street tree planting in neighborhoods of greatest need to improve the UHI effect, asthma rates, crime rates, and property values.[61]

Key Message 2

Forward-Looking Design for Urban Infrastructure

Damages from extreme weather events demonstrate current urban infrastructure vulnerabilities. With its long service life, urban infrastructure must be able to endure a future climate that is different from the past. Forward-looking design informs investment in reliable infrastructure that can withstand ongoing and future climate risks.

Urban infrastructure needs to perform reliably throughout its long service life. Infrastructure designed for historical climate trends is more vulnerable to future weather extremes and climate change. Impacts include changes in building enclosure vapor drive, energy performance, and corrosion of structures.[14,62] Above- and below-grade transportation systems are at increased risk from flooding and degradation that reduce expected service life (Ch. 12: Transportation, KM 1). Higher temperatures increase stress on cooling systems to perform as designed. High indoor temperatures reduce thermal comfort and office worker productivity, potentially requiring building closures. Over time, sea level rise and flooding are expected to destroy, or make unusable, properties and public infrastructure in many U.S. coastal cities (Ch. 8: Coastal, KM 1). Investor costs increase when infrastructure is degraded, damaged, or abandoned ahead of its anticipated useful life.[63,64]

Damages from extreme weather events demonstrate existing infrastructure vulnerabilities. Long-term, gradual risks such as sea level rise further exacerbate these vulnerabilities. Current levels of infrastructure investment in the United States are not enough to cover needed repairs and replacement.[13] Infrastructure age and disrepair make failure or interrupted service from extreme weather even more likely.[13] Heavy rainfall during Arizona's 2014 monsoon season shut down freeways and city streets in Phoenix because key pumping stations failed.[65] Climate change has already altered the likelihood and intensity of some extreme events, and there is emerging evidence that many types of extreme events will increase in intensity, duration, and frequency in the future.[27,66,67,68,69] Projecting specific changes in extreme events in particular places remains a challenge.

Costs are felt nationally as business operations, production inputs, and supply chains are affected.[70,71] Higher temperatures reduce labor productivity in construction and other outdoor industries.[12,44,72,73] Upgrades to buildings and the electrical grid are needed to handle higher temperatures.[74,75,76] Risk portfolios in the housing finance, municipal bond, and insurance industries may need to be adjusted.[44,72,77] Forward-looking design and risk management approaches support the achievement of design and investment performance goals.[78,79,80,81]

Incorporating climate projections into infrastructure design, investment and appraisal criteria, and model building codes is uncommon.[82,83,84,85,86,87,88,89] Standardized methodologies do not exist,[62,90,91,92] and the incorporation of climate projections is not required in the education or licensing of U.S. design, investment, or appraisal professionals.[80,93,94,95] Building codes and rating systems tend to be focused on current short-term, extreme weather. Investment and design standards, professional education and licensing, building codes, and zoning that use forward-looking design can protect urban assets and limit investor risk exposure.[83,96,97,98]

A handful of cities have begun to take a longer-term view toward planning.[99,100,101]

These cities have developed adaptation plans, resilience guidelines, and risk-informed frameworks. However, they do not yet have a portfolio of completed projects.[59,102] Adaptation planning is not always informed by technical analysis of changing hazards, climate vulnerability assessments, and monitoring and control systems.[79] U.S. cities can examine methods and learn from completed projects, such as those developed by Engineers Canada and UKCIP Design for Future Climate.[62,90] Managing climate risks promotes the integrity, efficiency, and safety of infrastructure to ensure reliable performance over the infrastructure's service life.[14,81]

Flash Flooding Impacts Urban Infrastructure and Well-Being

Figure 11.5: Flash flooding overwhelmed drainage systems and swamped roadways in Pittsburgh, Pennsylvania, in 2011. The flooding disrupted businesses and commutes, damaged homes, and caused four deaths. Photo credit: *Pittsburgh Post-Gazette*.

Key Message 3

Impacts on Urban Goods and Services

Interdependent networks of infrastructure, ecosystems, and social systems provide essential urban goods and services. Damage to such networks from current weather extremes and future climate will adversely affect urban life. Coordinated local, state, and federal efforts can address these interconnected vulnerabilities.

The essential goods and services that form the backbone of urban life are increasingly vulnerable to climate change. Cities are hubs of production and consumption of goods, and they are enmeshed in regional-to-global supply chains. They rely on local services and interdependent networks for telecommunications, energy, water, healthcare, transportation, and more (Ch. 4: Energy, KM 1; Ch. 3: Water, KM 1; Ch. 14: Human Health, KM 2; Ch. 12: Transportation, KM 2; Ch. 17: Complex Systems, KM 1). Gradual and abrupt climate changes disrupt the flow of these goods and services.[44] For example, the 2012 High Park Fire in Colorado had wide-reaching impacts on air and water quality. The city of Fort Collins experienced air quality that was seven times worse than the daily average (Ch. 13: Air Quality, KM 2).[103] Storms washed ash and debris into the Cache la Poudre River, polluting the city's drinking water source for residents and industries.[104] In another example, two inches of rain fell in a single hour in Pittsburgh in August 2011. Four people died in the resulting flash flood. Impervious surfaces and combined sewer systems contribute to urban flash flooding risks (Figure 11.5).[105] For similar examples of cascading impacts, see Chapter 17: Complex Systems, Box 17.1 on Hurricane Harvey and Box 17.5 on the 2003 Northeast Blackout.

Cascading Consequences of Heavy Rainfall for Urban Systems

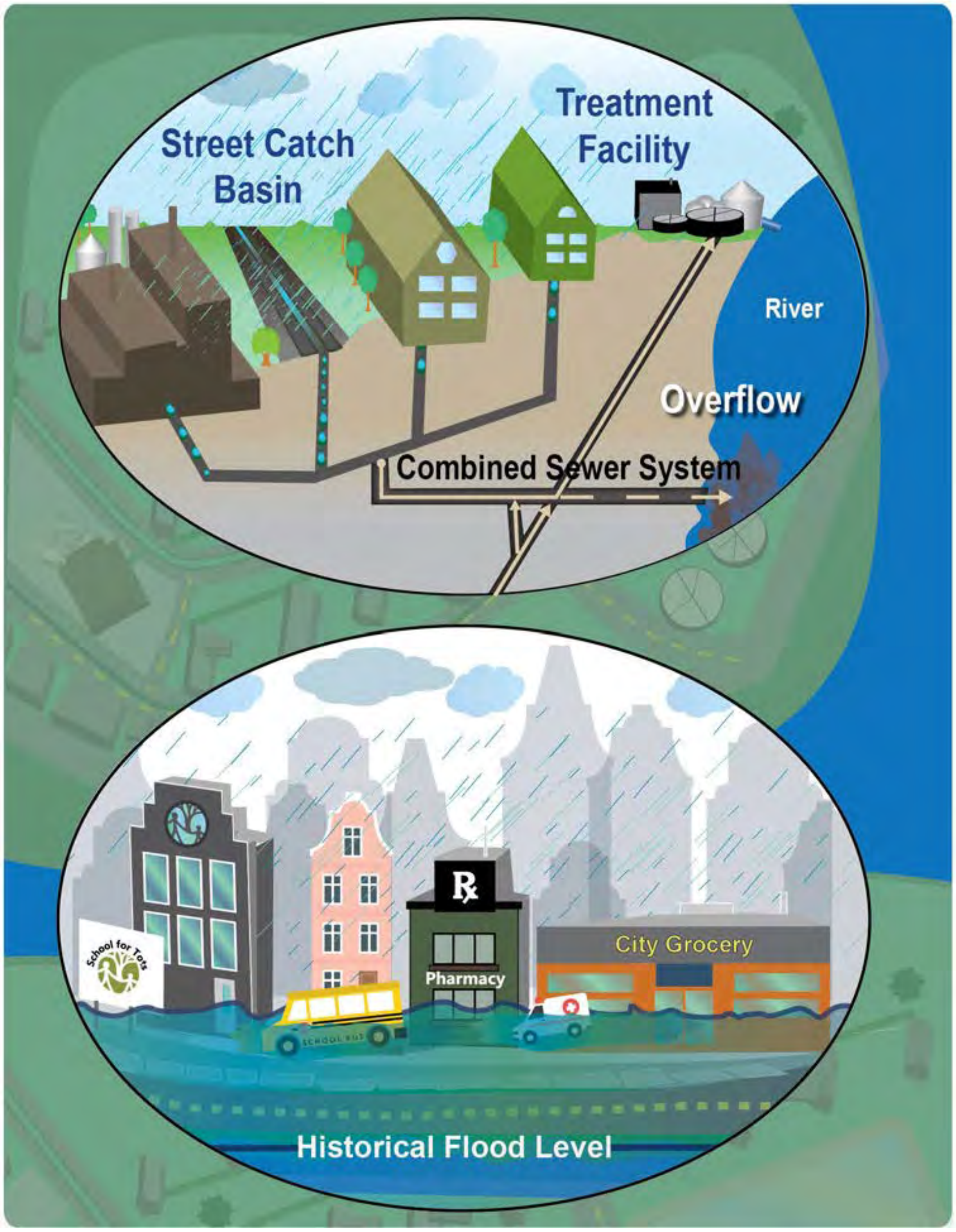


Figure 11.6: With heavy downpours increasing nationally, urban areas experience costly impacts. (top) In cities with combined sewer systems, storm water runoff flows into pipes containing sewage from homes and industrial wastewater. Intense rainfall can overwhelm the system so untreated wastewater overflows into rivers. Overflows are a water pollution concern and increase risk of exposure to waterborne diseases. (bottom) Intense rainfall can also result in localized flooding. Closed roads and disrupted mass transit prevent residents from going to work or school and first responders from reaching those in need. Home and commercial property owners may need to make costly repairs, and businesses may lose revenue. Source: EPA.

Figure 11.6 describes how heavy rainfalls, which are projected to increase with climate change, can disrupt the flow of goods and services to urban residents through increased runoff and localized flooding.

As interconnections among sectors increase, urban areas are more vulnerable to disruptions.[106] For example, energy and water systems are closely intertwined (Ch. 3: Water; Ch. 4: Energy; Ch.17: Complex Systems). Both higher water temperatures and extreme weather that causes power outages affect urban drinking water treatment and distribution. Higher air temperatures increase urban energy demand for cooling and water demand for landscaping. Elevated water temperatures affect cooling for electricity production. Higher river temperatures during periods of low flow can require power plants to shut down or curtail power generation to stay within defined regulatory temperature limits. Higher energy loads raise the risk of power outages. Flooding can drown electrical substations. Disruptions to water and power supplies can result in problems—such as unsafe drinking water, limited access to money systems, no functioning gas stations, few available modes of transportation, no air conditioning or heating, and limited ability to communicate with others—that pose risks to urban dwellers.

Climate change also threatens food security in urban areas.[107,108] Loss of electricity from extreme weather leads to food spoilage. Transportation disruptions along the supply chain limit food mobility. Heat effects on agricultural labor impact product availability. Changes to the food supply generally lead to price volatility and food shortages, affecting household budgets and nutrition, cultural foodways, and food service profits. Urban populations who already experience food insecurity are likely to be affected the most.

Targeted coordination that addresses interconnected vulnerabilities can build urban resilience to climate change.[109,110,111] Coordination may involve municipal offices, public–private partnerships, or state and local agencies. The Charleston Resilience Network, for example, brought together public safety and health services, business organizations, and the state transportation department to discuss their performance during the region's October 2015 floods and to identify best practices to improve resilience.[112]

Key Message 4

Urban Response to Climate Change

Cities across the United States are leading efforts to respond to climate change. Urban adaptation and mitigation actions can affect current and projected impacts of climate change and provide near-term benefits. Challenges to implementing these plans remain. Cities can build on local knowledge and risk management approaches, integrate social equity concerns, and join multicity networks to begin to address these challenges.

Cities across the United States are taking action in response to climate change for a number of reasons: recent extreme weather events, available financial resources, motivated leaders, and the goal of achieving co-benefits.[113,114,115,116] One strategy being used is to mainstream adaptation and mitigation into land-use, hazard mitigation, development, and capital investment planning.[45,115,117] Municipal departments from public works to transportation play roles, as do water and energy utilities, professional societies, school boards, libraries, businesses, emergency responders, museums, healthcare systems, philanthropies, faith-based organizations, nongovernmental organizations, and residents. City governments use a variety of policy mechanisms to achieve adaptation and mitigation goals. They adopt building codes, prioritize green purchasing, enact energy conservation measures, modify zoning, and buy out properties in floodplains. Nongovernmental stakeholders take action through voluntary protocols, rating systems, and public–private partnerships, among other strategies.

U.S. cities are at the forefront of reducing greenhouse gas (GHG) emissions (Ch. 29: Mitigation, KM 1). Urban mitigation actions include acquiring high-performance vehicle fleets and constructing energy efficient buildings. A number of cities are conducting GHG inventories to inform decisions and make commitments to reduce their emissions. Comprehensive urban carbon management involves decisions at many levels of governance.[19]

Many U.S. cities have also begun adaptation planning. A common approach is to enhance physical protection of urban assets from extreme weather. For example, protection against sea level rise and flooding can involve engineering (such as seawalls and pumps) and ecological solutions (such as wetlands and mangroves) (Ch. 8: Coastal, KM 2).[118] Green infrastructure lowers flood risk by reducing impervious surfaces and improving storm water infiltration into the ground.[72,119] Green roofs use rooftop vegetation to absorb rainfall. Urban drainage systems can be upgraded to handle increased runoff.[72] Climate-resilient building and streetscape design reduces exposure to high temperatures through tree canopy cover and cool roofs with high albedo that reflect sunlight. Ensuring that critical urban infrastructure, such as drinking water systems, continues to provide services through floods or droughts involves a combination of technology, physical protection, and outreach (Ch. 3: Water, KM 3; Ch. 19: Southeast, KM 1).[120,121,122]

Social and institutional changes are central to urban responses to climate change (Figure 11.7).[59,114] Urban development patterns reflect social, economic, and political inequities. As such,

Urban Adaptation Strategies and Stakeholders

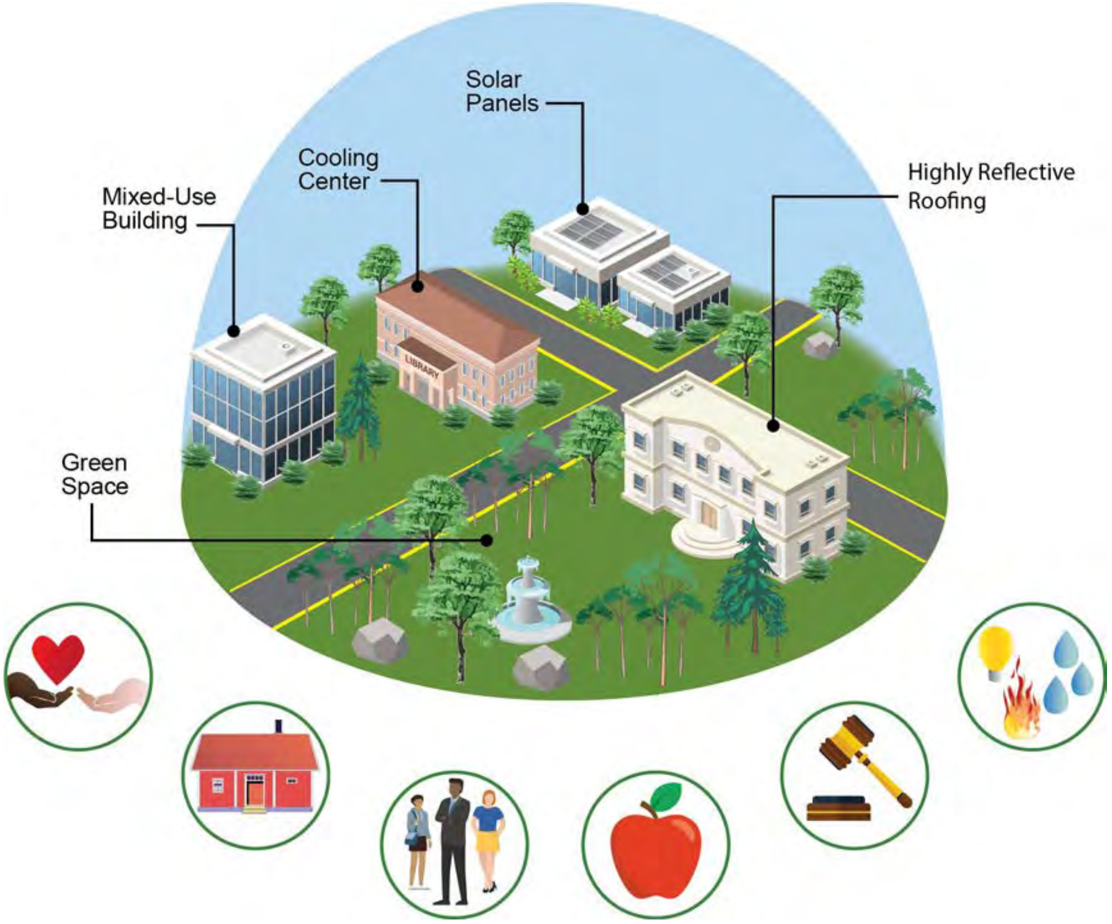


Figure 11.7: Protecting vulnerable people and places from the impacts of climate change involves infrastructure design (for example, green space and highly reflective roofing), along with social and institutional change (such as designating cooling centers). Social equity is supported by widespread participation in adaptation decision-making by non-profit organizations, local businesses, vulnerable populations, school districts, city governments, utility providers, and others. Source: EPA.

decisions about where to prioritize physical protections, install green infrastructure, locate cooling centers, or route public transportation have differential impacts on urban residents.[60,123,124,125] If urban responses do not address social inequities and listen to the voices of vulnerable populations, they can inadvertently harm low-income and minority residents.[60,123,124]

Urban actions can reduce climate change impacts on cities.[12,126,127,128,129,130] Urban adaptation plans often begin with small steps, such as improving emergency planning or requiring that development be set back from waterways (Ch. 28: Adaptation).[59,131] Not all plans address weightier concerns, tradeoffs, behaviors, and values. For example, coastal cities at risk from sea level rise may be constructing storm surge protections, but not discussing the possibility of eventual relocation or retreat (Ch. 8: Coastal, KM 3).[59,131] Increasing tree canopy and planting vegetation to manage storm water and provide cooling can increase water use, which may present difficulties for water-strapped cities.[132,133]

Urban adaptation and mitigation actions can provide near-term benefits to cities, including co-benefits to the local economy and quality of life (Ch. 29: Mitigation, KM 4).[3,19,113,134,135,136,137] Tree canopies and greenways increase thermal comfort and improve storm water management. They also enhance air quality, recreational opportunities, and property values (Figure 11.8). Wetlands serve to buffer flooding and are also a source of biodiversity and ecosystem regulation.

Urban climate change responses are often constrained by funding, technical resources,

Greenway in Dubuque, Iowa

Figure 11.8: In response to a history of flooding, Dubuque, Iowa, installed the Bee Branch Creek Greenway to control flooding and provide recreational space.[138] Photo credit: City of Dubuque, Iowa.

existing social inequities, authority, and competing priorities.[19,114,119,139,140,141] Coordinating among multiple jurisdictions and agencies is a challenge. Using scarce resources to address future risks is often a lower priority than tackling current problem areas. The absence of locally specific climate data and a standard methodology for estimating urban GHG emissions poses additional obstacles to urban responses.[19,72,114] Cities are dependent on state and national policies to modify statewide building codes, manage across landscapes and watersheds, incentivize energy efficiency, and discourage development that puts people and property in harm's way. Strong leadership and political will are central to addressing these challenges.[59,131,142] Many U.S. cities participate in networks such as the U.S. Conference of Mayors, ICLEI, the C40 Cities Climate Leadership Group (C40), and 100 Resilient Cities. Others participate in regional coalitions such as the Southeast Florida Regional Climate Change Compact. Multicity networks support development of urban climate policies and peer-to-peer learning (Ch. 28: Adaptation).[59,110,113,117,120,143] Effective urban planning to respond to climate change addresses social inequities and quality of life, uses participatory processes and risk management approaches, builds on local knowledge and values, encourages forward-looking investment, and coordinates across sectors and jurisdictions (Ch. 8: Coastal, KM 3).[59,60,115,120,124,140,142,144]

Acknowledgments

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Opening Image Credit

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Traceable Accounts

Process Description

Report authors developed this chapter through technical discussions of relevant evidence and expert deliberation and through regular teleconferences, meetings, and email exchanges. (For additional information on the overall report process, see App. 1: Process.) The author team evaluated scientific evidence from peer-reviewed literature, technical reports, and consultations with professional experts and the public via webinar and teleconferences. The scope of this chapter is urban climate change impacts, vulnerability, and response. It covers the built environment and infrastructure systems in the socioeconomic context of urban areas. This chapter updates findings from the Third National Climate Assessment and advances the understanding of previously identified urban impacts by including emerging literature on urban adaptation and emphasizing how urban social and ecological systems are related to the built environment and infrastructure. The five case-study cities were selected because they represent a geographic diversity of urban impacts from wildfire, sea level rise, heat, and inland flooding. The author team was selected based on their experiences and expertise in the urban sector. They bring a diversity of disciplinary perspectives and have a strong knowledge base for analyzing the complex ways that climate change affects the built environment, infrastructure, and urban systems.

Key Message 1

Impacts on Urban Quality of Life

The opportunities and resources in urban areas are critically important to the health and well-being of people who work, live, and visit there (*very high confidence*). Climate change can exacerbate existing challenges to urban quality of life, including social inequality, aging and deteriorating infrastructure, and stressed ecosystems (*high confidence*). Many cities are engaging in creative problem solving to improve quality of life while simultaneously addressing climate change impacts (*medium confidence*).

Description of evidence base

Urban areas provide resources and opportunities for residents' quality of life.[145,146] However, many cities face challenges to prosperity, including aging and deteriorating infrastructure,[13] social inequalities,[9,46] and lack of economic growth.[147,148] These challenges play out differently depending on a city's geographic location, economic history, urban development pattern, and governance. Studies link urban development with lower air,[15] water,[16] and soil[17] quality; altered microclimates (for example, urban heat islands);[149,150] increased risk of certain vector-borne diseases;[151] and adverse effects on biodiversity and ecosystem functioning.[152,153,154] Exposure to temperature extremes,[155] allergens,[156] and toxic substances[157] and limited access to healthy food[10,158,159] and green space[11,160,161] create environmental and social vulnerabilities for urban populations. Vulnerabilities are distributed unevenly within cities and reflect social inequalities related to differences in race, class, ethnicity, gender, health, and disability.[1] These populations of concern are at a greater risk of exposure to climate change and its impacts.[3,46,123]

Climate change combines with other trends to increase stress on the health and well-being of urban residents.[10,46,155,158] Research demonstrates that climate change can exacerbate many of the vulnerabilities described above. It raises temperatures, alters weather patterns, and increases the frequency and severity of extreme weather events, creating risks to urban ecosystems (such as urban tree cover),[162,163,164] infrastructure both above and below grade,[165,166,167] historic and cultural sites,[51,52,164,168,169,170] and residents' physical and mental health.[171,172,173,174] Coupled with climate change, urban expansion increases the risk of infectious disease[175,176] and air quality problems from wildfires.[55,177]

Metropolitan areas often have more resources than rural ones, as reflected in income per capita, employment rates, and workforce education.[178,179] Innovative urban problem solving that builds on these resources can take the form of policies and institutional collaborations,[58,180] technologies,[145,181] eco- and nature-based solutions,[182,183] public–private partnerships,[59] social network and climate justice initiatives,[60,184] "smart" cities,[106,145,181] or a combination of approaches. However, cities vary greatly in their capacity to innovate for reasons related to size, staffing, and existing resources.

Major uncertainties

It is difficult to predict future urban trends with certainty. Many factors influence the size and composition of urban populations, development patterns, social networks, cultural resources, and economic growth.[180] The degree to which climate change will exacerbate existing urban vulnerabilities depends in part on the frequency and intensity of extreme weather events,[145] which are projected with far less certainty than incremental changes in average conditions.[81] Moreover, projections are not often made at the city scale.[185] Climate change may accelerate urban tree growth, but overall effects on growing conditions depend on a variety of factors.[186] These uncertainties make it difficult to predict how climate change and other factors will intersect to affect urban quality of life. Furthermore, quality of life is difficult to measure, although some metrics are available.[187]

Urban climate vulnerability depends on local social, political, demographic, environmental, and economic characteristics.[59,110,145] Urban exposure to climate change depends on geographic factors (such as latitude, elevation, hydrology, distance from the coast).[145] Some places may be able to protect quality of life from minor climate stresses but not from extreme, though rare, events.[145] The speed and pace of innovative problem solving is difficult to predict, as is its effect on quality of life..[59]

Description of confidence and likelihood

There is *very high confidence* that the opportunities and resources available in a particular urban area influence the health and well-being of its residents. There is *high confidence* that climate change exacerbates challenges to aging and deteriorating infrastructure, degrading urban ecosystems, and urban residents' health and well-being. There is *medium confidence* that many cities are engaging in creative problem solving to address the challenges to quality of life posed by climate change. The effectiveness of this response depends on many factors (for example, intensity of extreme weather events, stakeholder collaboration, and internal and external resources available).

Key Message 2

Forward-Looking Design for Urban Infrastructure

Damages from extreme weather events demonstrate current urban infrastructure vulnerabilities (*very high confidence*). With its long service life, urban infrastructure must be able to endure a future climate that is different from the past (*very high confidence*). Forward-looking design informs investment in reliable infrastructure that can withstand ongoing and future climate risks (*high confidence*).

Description of evidence base

There is wide agreement that architects, engineers, and city planners need to consider a range of future climate conditions in urban infrastructure design to guarantee that assets perform for the duration of their expected service lives.[14,62,80,81,188,189,190,191,192] Many researchers and professionals from various industries—engineering,[80,81,193,194] water resources,[195,196] architecture, construction and building science,[62,190,197,198,199,200,201,202] transportation,[203,204,205] energy,[206] and insurance[207,208]—are actively developing or have proposed strategies to integrate climate change science and infrastructure design. The Government Accountability Office, the State of California, and a variety of professional organizations have recognized the importance of incorporating forward-looking climate information (planning for or anticipating possible future events and conditions) in design standards, building codes, zoning requirements, and professional education and training programs to protect and adapt built systems and structures. This includes the need to develop and adopt design methodologies using risk management principles for uncertainty (see Ch. 28: Adaptation, KM 3 for more discussion)[90] and the integration of climate projections, nonstationarity, and extreme value analysis to inform designs that can adapt to a range of future conditions.[8,14,80,81,90,188,190,209,210,211,212,213,214,215] Similarly, there is support for incorporating climate change risk considerations into the preparation of financial disclosures.[44,96,191,216,217] Reports from multiple sectors highlight the need for licensed design professionals, property industry professionals, and decision-makers to be aware of emerging legal liabilities linked to climate change risks.[80,95,208,218,219,220]

Numerous studies document substantial economic damages in urban areas following extreme weather events and predict an increase in damages through time as these events occur with greater frequency and intensity.[14,165,166,167,205,221] Due to underinvestment in urban infrastructure[13,222] and well-documented urban vulnerabilities to the effects of climate change and extreme weather,[80,81,223] forward-looking design strategies are critical to the future reliability of urban infrastructure.[14,80]

Major uncertainties

There are gaps in our understanding of the performance capacity of existing structures exposed to climate change stressors and of the available resources and commitment (at the state, local, tribe, and federal level) to implement forward-looking designs in investments.[192,224] The scale and speed with which climate security design principles will be integrated into infrastructure design, investments, and funding sources are difficult to predict, as are the implications for municipal bonds, solvency, and investment transparency.[77,83,96,97,98,192] There is also uncertainty regarding how the U.S. legal system will determine the limits of professional liability for climate-related risks for licensed design professionals, attorneys, and investors.[95,218,219,220,225]

The extent to which key climate stressors will change over the design life of urban systems and structures is uncertain. It depends on the rate of global climate change as well as regional and local factors.[150,185,192] Engineering and architectural design is largely concerned with weather extremes,[80,81,190,226] which are generally projected with far less certainty than changes in average conditions.[81] Action depends on how individual decision-makers weigh the costs and benefits of implementing designs that attempt to account for future climate change. The extent to which the U.S. market is able to innovate to provide these services to the global market is unknown.

Description of confidence and likelihood

There is *very high confidence* that the integrity of urban infrastructure is and will continue to be threatened by exposure to climate change stressors (for example, more frequent and extreme precipitation events, sea level rise, and heat) and that damages from weather events demonstrate infrastructure vulnerability. Many urban areas have endured high costs from such events, and many of those costs can be attributed to infrastructure failures or damages. There is *very high confidence* that urban infrastructure will need to endure a future climate that is different from the past in order to fulfill its long service life. There is *high confidence* that investment in forward-looking design provides a foundation for reliable infrastructure that can withstand ongoing and future climate risks. How much implementing forward-looking design will reduce risks is less clear, since much depends on other factors such as changes in urban population, social inequalities, the broader economy, and rates of climate change.

Key Message 3

Impacts on Urban Goods and Services

Interdependent networks of infrastructure, ecosystems, and social systems provide essential urban goods and services (*very high confidence*). Damage to such networks from current weather extremes and future climate will adversely affect urban life (*medium confidence*). Coordinated local, state, and federal efforts can address these interconnected vulnerabilities (*medium confidence*).

Description of evidence base

Research focusing on urban areas shows that climate change has or is anticipated to have a net negative effect on transportation,[43,205,223,227] food,[44,107,108] housing,[228] the economy,[44,228,229,230,231] ecology,[3,152] public health,[2,3,12,44,231,232] energy,[43,44,233,234] water,[43,122,228,235] and sports and recreation.[2,235,236]

Researchers have modeled and documented how negative effects on one system that provides urban goods and services cascade into others that rely on it.[3,43,44,109,122,229,231,233,234] Several draw on the example of Superstorm Sandy. These effects scale up to the national economy and across to other sectors, creating longer-term hazards and vulnerabilities.[44,99,109,227] The energy–water nexus, defined as the reliance of energy and water systems on each other for functionality, is a good example of documented system interdependency.[43,234] Research indicates that direct or high-level climate impacts on a variety of urban sectors (such as transportation, energy, drinking water, storm water) have cascading economic, socioeconomic, and public health consequences.[3,12,44,229,231]

The literature shows that coordinated resilience planning across sectors and jurisdictions to address interdependencies involves using models and plans,[3,43,108,111,227,237,238] finding effective intervention points,[109] creating system redundancy,[43,237] and motivating behavioral change. Recent reports discuss how interdependencies among energy, water, transportation, and communications services inform adaptation strategies that span sectors.[43,227]

Major uncertainties

Interconnections among urban systems have been studied less extensively than climate change effects on individual urban sectors, and there are still gaps to be filled.[239,240,241] The complexity of urban systems leads to uncertainty and modeling challenges. System models need to account for interconnections, feedback loops, and cascading effects from rural areas, among urban sectors, and within a sector. Creating a comprehensive framework to understand these connections is difficult.[239,242] There is a lack of forward-looking models of how projected climate changes will impact interdependent urban systems. Cities do not usually have the range of data needed to fully analyze system connections.[102,111] Mixed methods analysis, where professional experience and qualitative data supplement available datasets, may partially compensate for this problem.[241] Despite information gaps, urban stakeholders are beginning to address system interconnections in adaptation efforts.[59]

While it has been demonstrated that climate change affects urban systems, the extent to which climate change will affect a given urban system is difficult to predict. It depends on the unique strengths and vulnerabilities of that system as well as the regional and local climate conditions to which the system is exposed.[110,223,243] Modifying factors include spatial layout, age of infrastructure, available resources, and ongoing resilience efforts.[43,244] Similarly, critical points of intervention are unique to each urban area. Local-scale analysis of vulnerability and resilience has not been done for most U.S. cities.[102,241]

The severity of future climate impacts and cascading consequences for urban networks depends on the magnitude of global climate change.[223] Urban systems may be able to tolerate some levels of stress with only minor disruptions. Stresses of greater frequency, longer duration, or greater intensity may compromise a system's ability to function.[36,43,109,122,227] Models can reveal changes in the likelihood or frequency of occurrence for a particular type of extreme event (such as a 100-year flood), but they cannot predict when these events will occur or whether they will hit a particular city or town.[245]

Description of confidence and likelihood

There is *very high confidence* that urban areas rely on essential goods and services that are vulnerable to climate change because they are part of interdependent networks of infrastructure, ecosystems, and social systems. There is *high confidence* that extreme weather events have resulted in adverse cascading effects across urban sectors and systems, as there is documentation of a significant number of case studies of urban areas demonstrating these effects. It is projected with *medium confidence* that network damages from future climate change will disrupt many aspects of urban life, given that the complexity of urban life and the many factors affecting urban resilience to climate change make future disruptions difficult to predict. Similarly, there is *medium confidence* that addressing interconnected vulnerabilities via coordinated efforts can build urban resilience to climate change.

Key Message 4

Urban Response to Climate Change

Cities across the United States are leading efforts to respond to climate change (*high confidence*). Urban adaptation and mitigation actions can affect current and projected impacts of climate change and provide near-term benefits (*medium confidence*). Challenges to implementing these plans remain. Cities can build on local knowledge and risk management approaches, integrate social equity concerns, and join multicity networks to begin to address these challenges (*high confidence*).

Description of evidence base

Multiple review studies have documented that cities in all parts of the United States are undertaking adaptation and mitigation actions.[45,115,246] Municipal departments, including public works, water systems, and transportation, along with public, private, and civic actors, work to assess vulnerability and reduce risk. Actions include land-use planning, protecting critical infrastructure and ecosystems, installing green infrastructure, and improving emergency preparedness and response.[45,114,115,117,247] Many cities are part of multicity networks (for example, the Great Lakes Climate Adaptation Network, ICLEI, and C40 Cities Climate Leadership Group) that provide opportunities for peer-to-peer learning, sharing best practices, and technical assistance.[59,114,117,120] Researchers have recognized the benefits of shared motivation and resource pooling across cities[59] and of incorporating local knowledge, priorities, and values into adaptation planning.[45,248] The private sector, utilities, nongovernmental organizations, libraries, museums, and civic organizations are involved with urban adaptation and mitigation.[2,45,59,115,196,249,250] Studies are beginning to analyze the social, economic, and political factors that shape whether and how cities carry out climate change response.[114,115,116,131,142]

Numerous studies have examined the ways in which adaptation actions reduce the impacts of weather extremes in urban areas. Documented benefits include reductions in urban heat risk[48,126,127,128,130,251] and flooding impacts.[118,252,253] These actions can provide additional public health and economic benefits.[59,254,255,256,257] Studies have also noted that low-regret and incremental urban adaptation are not likely to significantly reduce the impacts of projected climate change.[59,131,258] In addition, several studies discuss how urban adaptation can cause adverse consequences related to existing socioeconomic and spatial inequalities and the uneven distribution of urban climate risks.[60,123,124,125]

Major uncertainties

While urban adaptation actions can reduce the effects of extreme weather, there is uncertainty regarding the effectiveness of these actions against future climate change.[115,246] Much of this uncertainty arises from the difficulties inherent in predicting the future impacts of climate change. This uncertainty is compounded by a lack of regional and local data for many cities, by the difficulty of evaluating the effects of climate change on local extremes,[150,251] and by the inability of knowing how climate changes intersect with other urban changes.[67,185] Moreover, there is a lack of forward-looking models and standardized monitoring strategies to test the costs, co-benefits, and effectiveness of urban response. Adaptation actions that focus solely on physical protection of urban assets are not likely to effectively address social vulnerability.[114,123] Urban adaptation effectiveness depends heavily on local characteristics. While cities do learn best practices through multicity networks, one city's strategy may not be as applicable to other cities.

Research on drivers of and challenges to urban response is in the incipient stage, with divergent results about social and political requirements for effective response.[114,116,142] Although cities are leading the way in adaptation and mitigation, many face significant barriers such as resource challenges, which will affect the rate of spread, extent, and duration of urban response.[45,145] There is little research on the effectiveness of different incentives for urban response or how to best support action in low-income communities.

Description of confidence and likelihood

There is *high confidence* that municipal governments and other institutions in many U.S. cities are planning and implementing climate change adaptation and mitigation actions. There is *high confidence* that urban adaptation and mitigation can provide additional near-term benefits, although the distribution of benefits and harms within cities is uneven. There is *medium confidence* in the effect these actions have and will have on current and future climate change impacts. If cities take only small actions, they are unlikely to fully protect urban residents from devastating impacts, particularly given projected levels of climate change. There is *high confidence* that cities face challenges in responding to climate change and that when cities build on local knowledge, use risk management approaches, explicitly address social vulnerability, and participate in multicity networks, their ability to respond to climate change is improved. The degree of improvement depends on other factors that affect urban response outcomes.

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12 Transportation

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12 Transportation

St. Louis, Missouri

Key Message 1

Transportation at Risk

A reliable, safe, and efficient U.S. transportation system is at risk from increases in heavy precipitation, coastal flooding, heat, wildfires, and other extreme events, as well as changes to average temperature. Throughout this century, climate change will continue to pose a risk to U.S. transportation infrastructure, with regional differences.

Key Message 2

Impacts to Urban and Rural Transportation

Extreme events that increasingly impact the transportation network are inducing societal and economic consequences, some of which disproportionately affect vulnerable populations. In the absence of intervention, future changes in climate will lead to increasing transportation challenges, particularly because of system complexity, aging infrastructure, and dependency across sectors.

Key Message 3

Vulnerability Assessments

Engineers, planners, and researchers in the transportation field are showing increasing interest and sophistication in understanding the risks that climate hazards pose to transportation assets and services. Transportation practitioner efforts demonstrate the connection between advanced assessment and the implementation of adaptive measures, though many communities still face challenges and barriers to action.

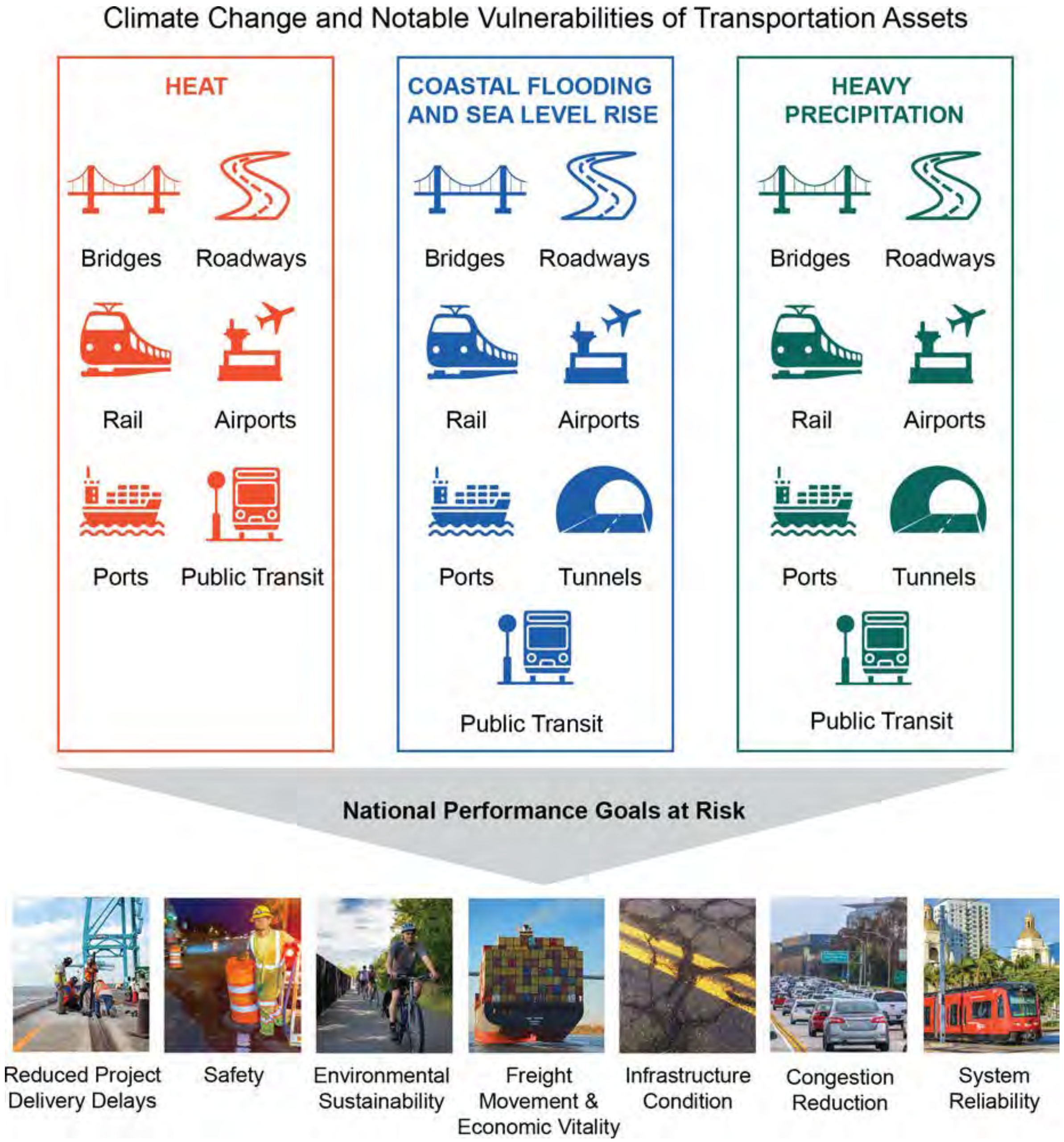
Executive Summary

Transportation is the backbone of economic activity, connecting manufacturers with supply chains, consumers with products and tourism, and people with their workplaces, homes, and communities across both urban and rural landscapes. However, the ability of the transportation sector to perform reliably, safely, and efficiently is undermined by a changing climate. Heavy precipitation, coastal flooding, heat, wildfires, freeze–thaw cycles, and changes in average precipitation and temperature impact individual assets across all modes. These impacts threaten the performance of the entire network, with critical ramifications for economic vitality and mobility, particularly for vulnerable populations and urban infrastructure.

Sea level rise is progressively making coastal roads and bridges more vulnerable and less functional. Many coastal cities across the United States have already experienced an increase in high tide flooding that reduces the functionality of low-elevation roadways, rail, and bridges, often causing costly congestion and damage to infrastructure.[1,2] Inland transportation infrastructure is highly vulnerable to intense rainfall and flooding. In some regions, the increasing frequency and intensity of heavy precipitation events reduce transportation system efficiency[3] and increase accident risk. High temperatures can stress bridge integrity[4,5] and have caused more frequent and extended delays to passenger and freight rail systems and air traffic.[4,6]

Transportation is not only vulnerable to impacts of climate change but also contributes significantly to the causes of climate change. In 2016, the transportation sector became the top contributor to U.S. greenhouse gas emissions.[7] The transportation system is rapidly growing and evolving in response to market demand and innovation. This growth could make climate mitigation and adaptation progressively more challenging to implement and more important to achieve. However, transportation practitioners are increasingly invested in addressing climate risks, as evidenced in more numerous and diverse assessments of transportation sector vulnerabilities across the United States.

U.S. Transportation Assets and Goals at Risk



Heavy precipitation, coastal flooding, heat, and changes in average precipitation and temperature affect assets (such as roads and bridges) across all modes of transportation. The figure shows major climate-related hazards and the transportation assets impacted. Photos illustrate national performance goals (listed in 23 U.S.C. § 150) that are at risk due to climate-related hazards. *From Figure 12.1 (Source: USGCRP. Photo credits from left to right: JAXPORT, Meredith Fordham Hughes [CC BY-NC 2.0]; Oregon Department of Transportation [CC BY 2.0]; NPS–Mississippi National River and Recreation Area; Flickr user Tom Driggers [CC BY 2.0]; Flickr user Mike Mozart [CC BY 2.0]; Flickr user Jeff Turner [CC BY 2.0]; Flickr user William Garrett [CC BY 2.0] — see https://creativecommons.org/licenses/ for specific Creative Commons licenses).*

State of the Sector

Transportation is the backbone of economic activity, connecting manufacturers with supply chains, consumers with products and tourism, and people with their workplaces, homes, and communities across both urban and rural landscapes. In 2017, the transportation sector added over $400 billion to the U.S. gross domestic product.[9] Transportation is also an important lifeline during emergencies, which may become increasingly common under climate change scenarios (see Kossin et al. 2017[10]). In the event of a disaster, roads, airports, and harbors may serve as key modes of evacuation and often become hubs for emergency personnel and relief supplies.

The transportation sector consists of a vast, interconnected system of assets and derived services, but a changing climate undermines the system's ability to perform reliably, safely, and efficiently (Figure 12.1). Heavy precipitation, coastal flooding, heat, and changes in average precipitation and temperature impact individual assets across all modes. These impacts threaten the performance (defined by national goals listed in 23 U.S.C. § 150[8]) of the entire network,[11] with critical ramifications for safety, environmental sustainability, economic vitality and mobility, congestion, and system reliability, particularly for vulnerable populations and urban infrastructure. Fortunately, transportation professionals have made progress understanding and managing risks, though barriers persist.

Particularly as impacts compound, climate change threatens to increase the cost of maintaining infrastructure[12] approaching or beyond its design life—infrastructure that is chronically underfunded.[13] Without considering climate impacts, the American Society of Civil Engineers[14] estimates that there is already a $1.2 trillion gap in transportation infrastructure needs. The transportation network is also interdependent on other sectors, such as energy and telecommunications, which have their own climate-related vulnerabilities and existing costs.

Transportation is vulnerable to the impacts of climate change, but it also contributes significantly to the causes of climate change. In 2016, the transportation sector became the top contributor to U.S. greenhouse gas emissions.[7] Low fuel prices, which lead to more driving, coupled with increasing volumes of freight trucking, containerized shipments, and air cargo, underlie the rise in transportation emissions.[15]

The transportation system is rapidly growing and evolving in response to market demand and innovation. Passenger miles traveled on highways and on commuter rail have increased approximately 250% and 175%, respectively, since 1960,[16] and similar trends are expected to continue.[15] Projected population growth of 30% to 50% by mid-century and significant expansion of existing urban centers and surrounding communities[17] will require the transportation system to grow and will place additional demands on the existing network. Long-haul freight is expected to increase 40% by 2040,[18] while air and marine transportation will continue to grow in tandem with economic growth and international trade. This population growth and land-use change can make climate mitigation, environmental sustainability, and adaptation progressively more challenging to implement and more important to achieve.

The shifting future of transportation presents new, pressing complexities and challenges. Transportation innovations such as shared mobility (for example, car sharing, carpooling, and ride-sourcing), transit-oriented development (TOD; that is, efforts to create compact, pedestrian-oriented, mixed-use communities centered around train systems), autonomous and electrified vehicles, Next Generation air transportation technologies, megaships, and hull-cleaning robots are emerging, but their impact on and vulnerability to climate change are still largely uncertain. For example, TOD, one of the older innovative transportation solutions, is very likely to reduce emissions and help build resilience.[19,20,21,22,23] Fuel consumption impacts of autonomous vehicles could vary greatly, depending on how they are deployed.[24] Similarly unclear is the impact that new transportation patterns, combined with deteriorating infrastructure, population growth, and land-use change, will have on the system's ability to adapt to climate change.

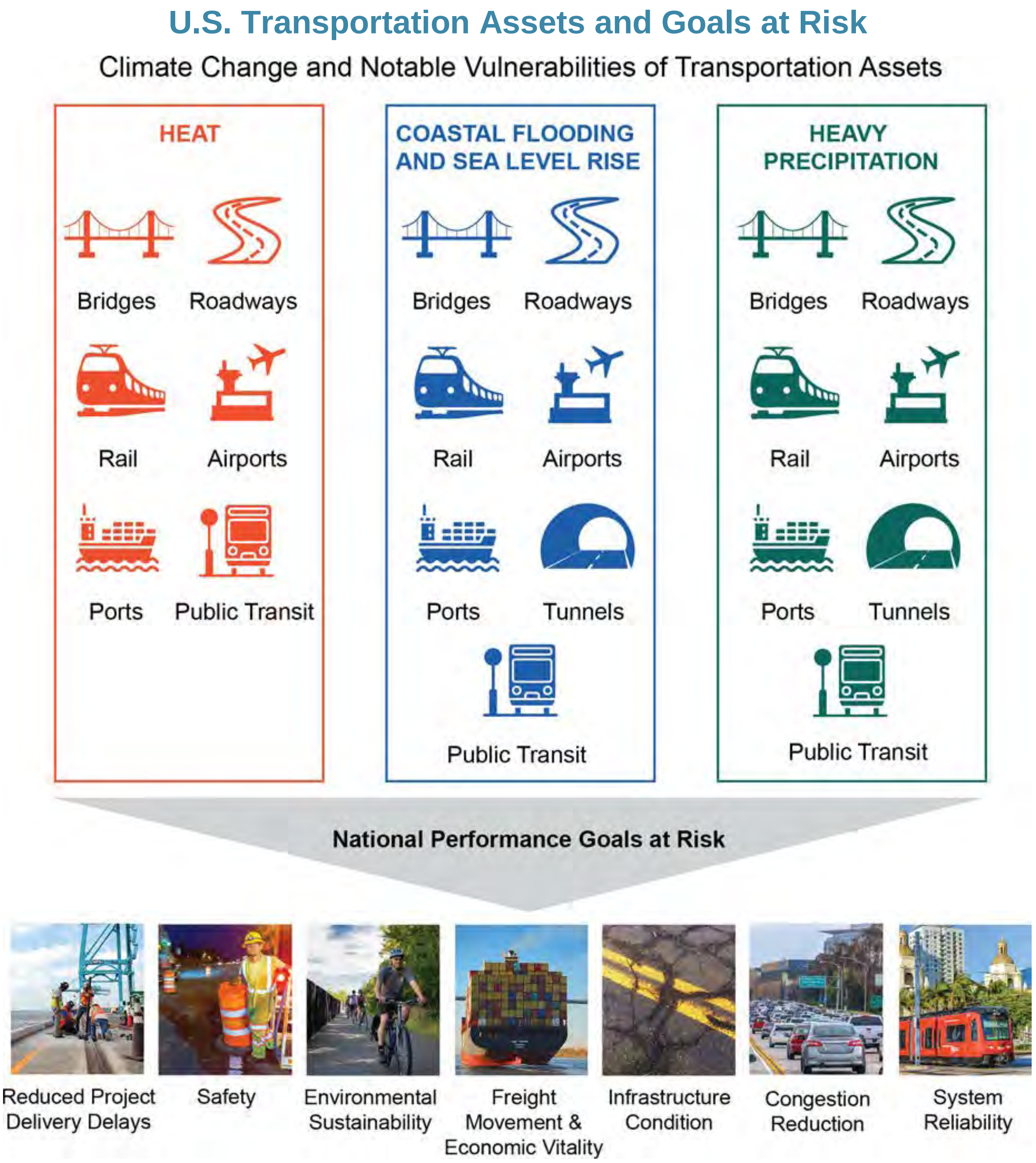


Figure 12.1: Heavy precipitation, coastal flooding, heat, and changes in average precipitation and temperature affect assets (such as roads and bridges) across all modes of transportation. The figure shows major climate-related hazards and the transportation assets impacted. Photos illustrate national performance goals (listed in 23 U.S.C. § 150[8]) that are at risk due to climate-related hazards. Source: USGCRP. Photo credits from left to right: JAXPORT, Meredith Fordham Hughes [CC BY-NC 2.0]; Oregon Department of Transportation [CC BY 2.0]; NPS–Mississippi National River and Recreation Area; Flickr user Tom Driggers [CC BY 2.0]; Flickr user Mike Mozart [CC BY 2.0]; Flickr user Jeff Turner [CC BY 2.0]; Flickr user William Garrett [CC BY 2.0].

Regional Summary

Precipitation changes are projected to vary across the country, with certainty about impacts much higher in some regions than others (Ch. 18: Northeast).[25] In the Northeast, rainfall volume and intensity have increased[25,26] and may impact transportation performance due to roadway washouts, bridge scour, and heaving or rutting due to freeze–thaw cycles, depending on site-specific conditions.[12,27,28,29] Intense precipitation at Northeast and mid-Atlantic airports has cascading effects on other airports and cargo movement networks, such as trucking and rail, due to delayed or canceled flights and stranded crews.[30,31,32] The projected increases in tropical cyclone wind speeds and rainfall intensity[33] by the end of the century indicate that shipments in Hawaiʻi and the Pacific Islands may be interrupted more frequently and for longer periods.[34] Storms also cause erosion and dramatic changes to island coastlines, with associated damages to roadways, harbors, and airports (Ch. 27: Hawaiʻi & Pacific Islands, KM 3).

In the Midwest, which has experienced an increase in riverine flooding resulting in long-term interstate freeway closures, future flooding is the main concern for transportation infrastructure (Ch. 21: Midwest, KM 5).[30] In Northeast urban regions, transportation network disruptions from high tide flooding are increasing and further stressing congested networks and storm water management systems (Ch. 18: Northeast, KM 3). Similarly, flooding in the Northwest has repeatedly blocked railways, flooded interstates, and halted freight movement, impacting access to critical services (Ch. 24: Northwest, KM 3 and 5). In the first three months of 2017, Spokane County, Washington, had already spent $2 million more than its yearly budget for road maintenance due to flooding from rapid snowmelt.[35] Flooding in the Pacific Northwest may also threaten access to recreation on federal lands, an economic driver for the region.[36]

Lack of precipitation is also a concern for the transportation network. In the past, high and low extremes in water levels in the Mississippi River and Great Lakes have limited boat traffic, affecting jobs and the ability of goods to get to domestic and international markets[37,38,39] and potentially increasing shipping costs in the future (Ch. 21: Midwest).[40]

In the Midwest, Northeast, Northern Great Plains, and Alaska, in particular, warming winters with fewer extremely cold days[41] and fewer snow and icing events[25] will likely extend the construction season, reduce winter road maintenance demand, and reduce vehicle accident risk.[42,43,44] However, when ice roads that run over a frozen water surface, such as a river or lake, start to thaw and allowable vehicle weight is therefore reduced, trucking and logging industries lose money due to limited access to road networks,[45] thus increasing transport costs (Ch. 26: Alaska, KM 5). Warming winters will also change the timing and location of freeze and thaw events, potentially increasing pavement cracking and pothole conditions in northern states.[12,45] In Alaska, near-surface permafrost thaw is responsible for severe damages to roads, airport runways, railroads, and pipelines (Ch. 26: Alaska).[46]

Climate change is projected to increase the costs of maintaining, repairing, and replacing infrastructure, with regional differences proportional to the magnitude and severity of impacts. Nationally, the total annual damages from temperature- and precipitation-related damages to paved roads are estimated at up to $20 billion under RCP8.5 in 2090 (in 2015 dollars, undiscounted, five-model average) (see the Scenario Products section of App. 3 for more on the RCPs). Inland flooding, projected to increase over the coming century, threatens approximately 2,500 to 4,600 bridges across the United States and is anticipated to result in average annual damages of $1.2 to $1.4 billion each year by 2050 (in 2015 dollars, undiscounted, five-model average).[47]

The transportation chapter of the Third National Climate Assessment highlighted Arctic warming, ports, weather-related disruptions, and adaptation strategies.[48] New research indicates that those findings are still valid concerns for the transportation sector. Some new research highlighted in this chapter includes 1) socioeconomic disparities in response to transportation vulnerabilities, 2) intermodal and cross-sector dependencies and strategies (moving toward a more holistic system as opposed to an asset-based analysis), and 3) communities' challenges, including rural communities, to identify and justify investment in transportation.

The three Key Messages discuss the physical impacts of specific climate hazards on the transportation system, economic implications of interrupted transportation, and the efforts transportation engineers, planners, and researchers are taking to understand and address current and future vulnerabilities.

Key Message 1

Transportation at Risk

A reliable, safe, and efficient U.S. transportation system is at risk from increases in heavy precipitation, coastal flooding, heat, wildfires, and other extreme events, as well as changes to average temperature. Throughout this century, climate change will continue to pose a risk to U.S. transportation infrastructure, with regional differences.

Coastal Risks

Sea level rise (SLR) is progressively making coastal roads and bridges more vulnerable and less reliable. The more than 60,000 miles of U.S. roads and bridges in coastal floodplains are clearly already vulnerable to extreme storms and hurricanes that cost billions in repairs.[49] Higher sea levels will cause more severe flooding and more damage during coastal storms and hurricanes.[50] Recent modeling shows how 1 foot of SLR combined with storm surge can result in more than 1 foot of increased storm surge.[51,52] Low-clearance bridges are particularly vulnerable to increased wave loads from storm surges that can dislodge a bridge deck.[53,54] Since the Third National Climate Assessment, new work has found that SLR has already contributed to damage of one major U.S. bridge during a hurricane: the 3-mile-long bridge carrying I-10 over Escambia Bay, in Pensacola, Florida, was severely damaged during Hurricane Ivan in 2004 (the same mechanism was observed in 2005 after Hurricane Katrina) by wave-induced loads due to a historically high storm surge.[53,55] Ports, which serve as a gateway for 99% of U.S. overseas trade,[56] are particularly vulnerable to climate impacts from extreme weather events associated with rising sea levels and tropical storm activity.[57] SLR and storm surge also threaten coastal airports.[58]

Global average sea levels are expected to continue to rise by at least several inches over the next 15 years and by 1–4 feet by 2100. This 1-to-4-foot range includes the likely projected ranges under all the RCP scenarios.[2] However, a rise of as much as 8 feet by 2100 is scientifically plausible due to possible Antarctic ice sheet instabilities.[2] Coastal infrastructure will be exposed to the effects of relative SLR, which includes vertical land motion in addition to regional variations in the distribution of the global SLR. For example, relative SLR will be higher than the global average on the East and Gulf Coasts of the United States because of the sum of these effects.[2] It is common practice for assessment and planning purposes to develop a range of scenarios of future sea levels that are consistent with these scientific estimates but not specifically based on any one. Scenarios developed by the Federal Interagency Sea Level Rise and Coastal Flood Hazard Scenarios and

Tools Task Force span the scientifically plausible range and include an Intermediate-Low scenario of 1.6 feet of global average sea level rise by 2100, an Intermediate scenario of 3.3 feet, and an Extreme scenario of 8.2 feet.[59] The relative SLR corresponding to some of these scenarios is used below to estimate increased coastal flooding delays.

Many coastal cities across the United States have experienced an increase in high tide flooding (Ch. 27: Hawaiʻi & Pacific Islands),[2] causing areas of permanent inundation and increased local flooding that reduce the functional performance for low-elevation roadways, rail, and bridges and often causing costly congestion and damage to infrastructure.[1,2] In Hampton Roads, Virginia, one-third of residents report flooding in their neighborhoods at least a couple of times a year, and nearly half of residents were not able to get in or out of their neighborhoods at least once within the past year due to high tide flooding.[60] On the U.S. East Coast alone, more than 7,500 miles of roadway are located in high tide flooding zones. Unmitigated, this flooding has the potential to nearly double the current 100 million vehicle-hours of delay likely by 2020 (representing an 85% increase from 2010), with a 10-fold increase by 2060 even under the Intermediate-Low SLR scenario (Figure 12.2).[61] US Route 17 in Charleston, South Carolina, currently floods more than 10 times per year and is expected to experience up to 180 floods annually by 2045, with each flood costing the city $12.5 million (in 2009 dollars, undiscounted; $13.75 million in 2015 dollars) (Ch. 19: Southeast).[2] Even if a roadway is not inundated, higher groundwater tables from SLR can impact tunnels and utility corridors and weaken roadway base materials in low-lying coastal regions.[62,63,64,65]

Precipitation and Flooding Risks

In most parts of the United States, heavy precipitation is increasing in frequency and intensity, and more severe precipitation events are anticipated in the future.[25] Inland transportation infrastructure is highly vulnerable to intense rainfall and flooding, with impacts including less reliable transportation systems[3] and increased accident risk.[66,67] Extreme precipitation events annually shut down parts of the Interstate Highway System for days or weeks due to flooding and mudslides, as happened in the first five months of 2017 in, for example, northern California (I-80) and southern California (I-880) in January, north central California (I-5) in February, Idaho (I-86) in March, and the central United States including Missouri (I-44 and I-55) in May.

Nationally, projected future increases in inland precipitation over this century will threaten approximately 2,500 to 4,600 bridges by 2050, and 5,000 to 6,000 bridges by 2090, respectively, for the lower and higher scenarios (RCP4.5 and RCP8.5).[47] Bridge failure is most common during unprecedented floods.[68] Damage due to bridge scour can result during less extreme events. This occurs when sediment around piers and abutments is washed away, compromising bridges' structural integrity.[68] Increases in rainfall intensity can accelerate bridge foundation erosion and compromise the integrity and stability of scour-critical bridges.[69]

Freight movement at major international ports can be delayed under extreme weather events that include heavy rains and/or high winds affecting crane operations and truck service.[57] Even without such disruptions, major international trade gateways, hubs, and distribution centers already experience some of the worst congestion in the country.[15]

Transportation systems that are most vulnerable to the recent observed and projected increases in precipitation intensity[25] are those where drainage is already at capacity, where projected heavy rainfall events will occur over prolonged periods, and where changing winter

Annual Vehicle-Hours of Delay Due to High Tide Flooding

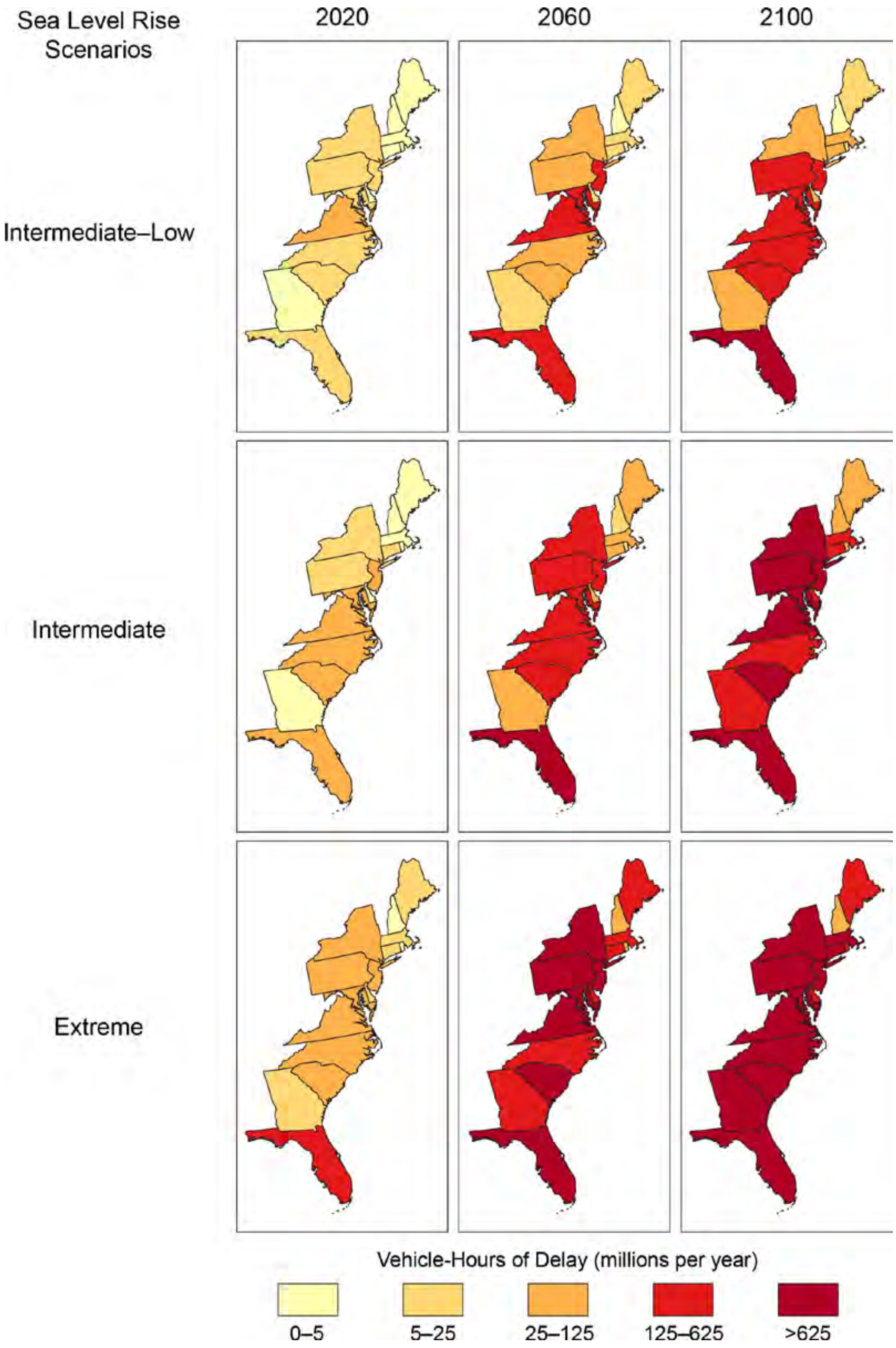


Figure 12.2: The figure shows annual vehicle-hours of delay for major roads (principal arterials, minor arterials, and major collectors) due to high tide flooding by state, year, and sea level rise scenario (from Sweet et al. 2017).[59] Years are shown using decadal average (10-year) values (that is, 2020 is 2016–2025), except 2100, which is a 5-year average (2096–2100). One vehicle-hour of delay is equivalent to one vehicle delayed for one hour. Source: Jacobs et al. 2018,[61] Figure 3, reproduced with permission of the Transportation Research Board.

precipitation increases transportation hazards from landslides and washouts.[50] In the western United States, large wildfires have increased and are likely to increase further in the future.[70] Debris flows, which consist of water, mud, and debris, are post-wildfire hazards that can escalate the vulnerability of transportation infrastructure to severe precipitation events[71] by blocking culverts and inundating roads.[72]

Rising Temperature Risks

The frequency of summer heat waves has increased since the 1960s, and average annual temperatures have increased over the past three decades; these temperature changes are projected to continue to increase in the future.[41] Across the United States, record-breaking summer temperatures and heat waves have immediate and long-term impacts on transportation. Through the urban heat island effect, heat events may become hotter and longer in cities than in the surrounding rural and suburban areas (Ch. 11: Urban).

High temperatures can stress bridge integrity.[4,5] Extreme temperatures cause frequent and extended delays to passenger and freight rail systems and air traffic when local safe operating guidelines are exceeded.[4,6] Rail tracks expand and weaken, sometimes even bend, under extreme heat.[73] Air transport is sensitive to extreme heat because hotter air makes it more difficult for airplanes to generate lift (the force required for an airplane to take flight), especially at higher elevations, requiring weight reductions and/or longer takeoff distances that may require runway extensions.[74,75]

Heat also compromises worker and public safety. Temperature extremes cause vehicles to overheat and tires to shred, while buckled roadway joints can send vehicles airborne.[76,77] Elevated temperature, combined with increased salinity and humidity, accelerates deterioration in bridges and roads constructed with concrete.[78,79] Higher ambient temperatures and extreme heat events can negatively impact pavement performance and, in turn, increase costs due to material upgrades to accommodate higher temperatures; these costs are only modestly reduced by less frequent maintenance.[12] For example, fixing pavement distress caused by a 2011 heat wave and drought cost the Texas Department of Transportation (DOT) $26 million (dollar year unspecified).[80]

Heat waves and drought require state DOTs to allocate resources to repair damaged pavement. For example, Virginia DOT has dedicated crews who quickly repair roads during extreme heat events.[81] Protocols that govern worker safety limit construction during heat waves[3,76,82] and result in lost productivity.[83] Increased cooling needed to alleviate passenger discomfort and cargo overheating[84] can cause mechanical failures and reduced service, as well as greater greenhouse gas emissions.

An additional 20–30 days per year with temperatures exceeding 90°F (32°C) are projected in most areas by mid-century under a higher scenario (RCP8.5), with increases of 40–50 days in much of the Southeast.[41] In the United States, 5.8 million miles of paved roads are susceptible to increased rutting, cracking, and buckling when sustained temperatures exceed 90°F.[85] Climate change is anticipated to increase the current $73 billion in temperature-induced railway delay costs by $25–$60 billion (in 2015 dollars, discounted at 3%).[6] Heat impacts to airports are expected to increase in the future[74] and, in some cases, are the most critical vulnerability for a region.[86]

It is possible that projected warmer conditions could have some positive effects. Milder winters will lengthen the shipping season in northern inland ports, including the Great Lakes and the Saint Lawrence Seaway.[87,88] The reduction of snow and icing events in southern regions will likely benefit transportation safety, because snow has a significantly higher vehicle accident risk than rainfall.[66,82] Damage to bridges and roads caused by potholes and frost heaves costs hundreds of millions of dollars annually,[4] and changing winter conditions will likely alleviate expenditures in some regions but amplify expenditures in others.[12] However, thawing and freezing rain events may reduce some of the winter maintenance savings. The Alaska Department of Transportation and Public Facilities is anticipating significant challenges due to the effects of warming temperatures on roadways, and it may see increased costs in anti-icing measures in areas that previously rarely had mid-winter thawing and freezing rain.[89]

Key Message 2

Impacts to Urban and Rural Transportation

Extreme events that increasingly impact the transportation network are inducing societal and economic consequences, some of which disproportionately affect vulnerable populations. In the absence of intervention, future changes in climate will lead to increasing transportation challenges, particularly because of system complexity, aging infrastructure, and dependency across sectors.

Urban Transportation Network

The urban transportation network can be highly complex and in high demand, with populations relying on many modes of transportation across air, water, and land. U.S. urban highways tend to accommodate more than double the vehicle miles traveled compared to rural highways.[90] A high percentage of the urban population relies on public transit,[91] with greatest usage in the Northeast.[92]

The urban setting tends to amplify climate change impacts, such as flooding, on the performance of the transportation network. Combined sewer and storm sewer systems used in many cities are often not designed to withstand the capacity demand currently experienced during heavy rainfall events or rising high tides (Ch. 11: Urban). This situation is becoming increasingly problematic with more frequent localized flooding, leading to more frequent travel disruptions for commuters, travelers, and freight.[93,94] The effect is compounded in cities with older infrastructure, such as Philadelphia, Miami, Chicago, and Charleston.[94,95,96,97]

Interdependencies among transportation and other critical infrastructure sectors (such as energy) introduce the risk of significant cascading impacts on the operational capacity of the transportation urban network (Ch. 17: Complex Systems, KM 1 and 3). For example, in December 2017, Atlanta's Hartsfield–Jackson International Airport was shut down for nearly 11 hours due to a catastrophic power outage, which caused the cancellation of 1,400 flights.

In an urban environment, there is a greater chance of transportation network redundancy during an extreme weather event. For example, in the New York City metro area after Superstorm Sandy, additional bus service was able to partially compensate for flooded subway and commuter tunnels.[98,99,100] Walking also serves as an essential backstop in urban environments. For cargo, if a portion of a railway suffers damage due to a future flood event, there may be opportunities to redirect freight to highways and/or waterways.

Disruptions to the transportation network during extreme weather events can disproportionately affect low-income people, older adults, people with limited English proficiency, and other vulnerable urban populations.

These populations have fewer mobility options, reduced access to healthcare, and reduced economic ability to purchase goods and services to prepare for and recover from events.[101,102,103]

With growing suburban populations, there is increasing dependence on a variety of transportation systems. For example, in Boston, almost 130,000 people take commuter rail daily.[104] During extreme events, workers in suburban areas often cannot commute to urban offices, leading to economic losses. Evidence of this is seen from the transportation interruptions resulting from storms such as Hurricane Irene, which impacted Philadelphia and New York City, and Superstorm Sandy, which impacted the Northeast Corridor.[105] Telecommuting can mitigate some of these impacts, but a notable component of suburban areas and their economies remains dependent on a reliable transportation system.

Rural Transportation Network

The rural transportation network may lack redundancy, which increases the social and economic dependence on each road and affects agriculture, manufacturing, tourism, and more. Flood events are prolific and exemplify the dependency that rural areas have on their transportation networks. This dependence is illustrated by the 2013 flooding in Boulder, Colorado, where a 200-year flood event (an event having about a 0.5% chance of occurring in a given year) resulted in 485 miles of damaged or destroyed roadways and 1,100 landslide and hillslope failures that cut off many rural towns for weeks.[106,107] In 2016, more than 10 inches of rain caused widespread flooding throughout eastern Iowa and isolated towns along the Cedar River.[108] In 2017, Hurricane Irma entirely cut off road access to the Florida Keys.

Relative to urban areas, rural areas have fewer options for funding the maintenance and rebuilding of roads.[109] During recovery efforts, rural areas have logistical challenges that include the ability to transport the needed construction materials and a dependency on freight networks to support the population.[110] Rural communities face rebuilding challenges that often take additional time and inflict long-term economic damage to residents and local economies.[111]

Resilience Planning

Many federal, state, and municipal agencies have developed frameworks and tools to assess climate change transportation resilience, in some cases in response to legislative and policy actions. There has been an emergence of climate resilience design guidelines for new transportation infrastructure, as well as considerations of climate change in infrastructure regulations and permitting. For example, the City of New York and the Port Authority of New York and New Jersey have issued guidance that instructs project teams on how to incorporate future climate data into capital expenditures.[112,113] However, it is not only large, urban areas that are addressing potential climate impacts to transportation systems. Municipalities in states such as Wisconsin, North Carolina, Mississippi, and Tennessee are including considerations for climate vulnerability and adaptation in long-range planning.[114]

Challenges remain in the development of resilience plans. In the urban environment, issues such as predicting the potential costs of repair and identifying the rippling disruptions are required to inform the investment decision of implementing mitigation strategies.[115] Compared to urban areas, rural areas sometimes struggle to create structures and justify resilience plans, which are both cost effective and address the potential risk from climate change. As illustrated by vulnerable areas such as the

Gulf Coast, increasing storm intensity suggests the need for investments in both improved emergency management planning techniques[116] and increased transportation redundancy. Similarly, in rural mountain areas, where increased precipitation can lead to landslides, the cost of preventive actions may be difficult to justify given the uncertainty of occurrence.[117]

Key Message 3

Vulnerability Assessments

Engineers, planners, and researchers in the transportation field are showing increasing interest and sophistication in understanding the risks that climate hazards pose to transportation assets and services. Transportation practitioner efforts demonstrate the connection between advanced assessment and the implementation of adaptive measures, though many communities still face challenges and barriers to action.

Motivation for Vulnerability Assessments

Transportation practitioners are increasingly invested in addressing climate risks, as evidenced in more numerous and diverse assessments of transportation sector vulnerabilities across the United States. These assessments address the direct and indirect reactions to extreme events, funding opportunities and technical assistance and expertise, and the improved availability of climate model outputs. Federal agencies and others have made funding and tools available to evaluate asset-specific and system-wide vulnerabilities in the transportation sector.[118,119,120] For example, the Federal Highway Administration (FHWA) funded 24 pilot studies between 2010 and 2015; these pilots road-tested and advanced frameworks for conducting vulnerability assessments.[120,121,122,123] In the airport sector, the Transportation Research Board supported research and developed guidance for climate risk assessments,[124] adaptation strategies, the integration of climate risk into airport management systems, and benefit–cost analyses. A review of more than 60 vulnerability assessments published between 2012 and 2016 was conducted for this chapter. Results of this review are summarized below and depicted in Figure 12.3.

Vulnerability Assessments Synopsis

Transportation vulnerabilities to climate change can be very different from one location to another. Examining the commonality and differences among place-based vulnerability assessments provides insights into what communities feel are their greatest vulnerabilities. While early climate risk assessment relied on readily available indicators (such as location, elevation, and condition) to screen assets for exposure to climate risks, asset owners and operators have increasingly conducted more focused studies of particular assets that consider multiple climate hazards and scenarios in the context of asset-specific information, such as design lifetime. Of the 60 studies included in the online version of Figure 12.3, roadways were the most commonly assessed asset, followed by bridges and rail. Most assessments used geospatial data to identify vulnerabilities; more sophisticated assessments utilized models as well (for example, Transportation Engineering Approaches to Climate Resiliency, GC2, and the Massachusetts Department of Transportation).[125,126,127] Building on guidance from the FHWA and others,[28] some agencies engaged stakeholders to ground-truth and/or fortify their results.[128]

Most studies focus on multiple climate stressors, including both chronic issues (such as sea level rise) and extreme events (such as flooding, storm surge, and extreme heat). Sea level rise and flooding are the most commonly assessed individual stressors. Although combined risks are rarely assessed, sea level rise and storm surge are sometimes considered together. The majority of

Transportation Vulnerability and Risk Assessments

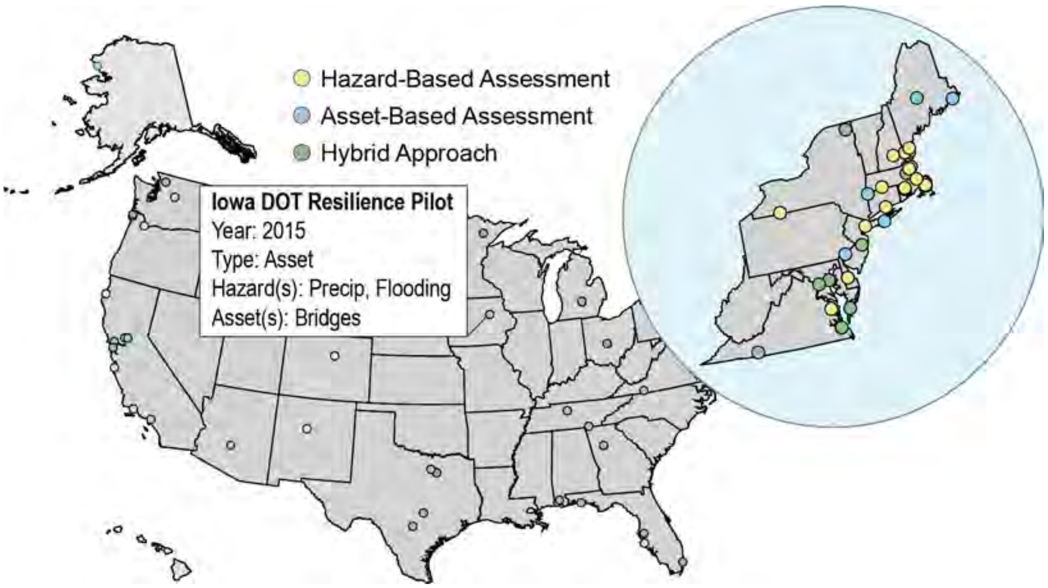


Figure 12.3: This figure shows transportation vulnerability and/or risk assessments from 2012 to 2016 by location. Cumulatively, these vulnerability assessments elucidate national-scale vulnerabilities and progress. Data for the U.S. Caribbean region were not available. See the online version of this map at http://nca2018.globalchange.gov/chapter/12#fig-12-3 to access the complete set of vulnerability and risk assessments. Sources: ICF and U.S. Department of Transportation.

assessments consider only asset-specific vulnerabilities and not transportation system-wide vulnerabilities or vulnerabilities influencing or arising from interdependencies with other sectors (such as water or energy).

The few studies that quantify the costs and benefits from adaptation primarily focus on single assets, rather than the system, and do not quantify both the direct and indirect (such as labor costs) economic costs of transportation system disruptions. The U.S. DOT Hampton Roads Climate Impact Quantification Initiative, currently underway, seeks to demonstrate a replicable approach to considering these costs.[129]

Implementation of Resilience Measures

Proactive implementation of resilience measures is still limited. Resilient solutions for transportation facilities vary greatly depending on the climate stressor, the specifics of a given site, and the availability of funding for implementation (see "Three Case Studies of Resilience Measures for Highway Facilities"). Building the business case for adaptation and aligning the required long-term investments with existing time frames for decision-making is difficult.[3,130,131] Uncertainties associated with projections of future climate hazards in specific geographic locations[130,132,133] and the lack of specific, detailed adaptation strategies[134] make assessment more complicated. However, in the wake of extreme events, some transportation agencies implemented resilience measures to withstand similar events in the future.

Future changes to and uncertainties about transportation technologies and transportation-related behaviors complicate agencies' ability to assess the adaptive capacity of transportation systems, their ability to withstand and recover from a disruption, and opportunities for cost-effective risk mitigation strategies (such as workplace telecommuting policies).

Case Study: Three Case Studies of Resilience Measures for Highway Facil

In Florida, storm surges overwashing US 98 on Okaloosa Island undermined the highway foundation during Hurricane Ivan in 2004 and then again during other tropical storms in 2005. To prevent damage from overwash in the future, the Florida Department of Transportation installed buried erosion protection along the edge of the road. FHWA's analysis found that this proactive countermeasure was economically justified when it was done in 2006 and, further, that the benefit-cost ratio will quadruple over the next 50 years as sea levels continue to rise.[135]

Shore Road in Brookhaven, New York, is experiencing wave-induced bank erosion during storms. The road elevation is about 2 feet higher than the typical high tide today, and a recent study determined that constructing a coastal marsh can protect the roadway for decades at a low cost while enhancing ecosystems. At a later point, the town could increase the elevation of the road and install more expensive sheet pile walls or rock revetments if needed.[136]

In 2013 in Colorado, precipitation following wildfires caused massive debris flows that overwhelmed culverts and damaged US 24 (see Figure 12.4 for similar case). Recognizing the seriousness of this type of impact, engineering tools driven by future climate simulations were used to evaluate changing wildfire-induced debris flows and precipitation risks to culverts when rebuilding a similar highway (US 34). The best approach identified was to quickly adapt a culvert if and when a wildfire occurs in that watershed, with the goal of upsizing the structure before a rainfall event can cause it to fail. Adapting every culvert to account for wildfire risk would be prohibitively costly, especially given the high uncertainty and low probability that any particular culvert will be impacted by a wildfire over its service life.[72]

Flood Impacts on Colorado Highway

Figure 12.4: Flooding events can result in serious damage to road infrastructure. Here, debris flow covers US Highway 14 (Poudre Canyon) after the High Park Fire in 2012. Photo credit: Justin Pipe, Colorado Department of Transportation.

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Opening Image Credit

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Traceable Accounts

Process Description

We sought an author team that could bring diverse experiences and perspectives to the chapter, including some who have participated in prior national-level assessments within the sector. All are experts in the field of climate adaptation and transportation infrastructure. The team represents geographic expertise in the Northeast, Mid-Atlantic, South, Central, and Western regions, including urban and rural as well as coastal and inland perspectives. Team members come from the public (federal and city government and academia) and private sectors (consulting and engineering), with practitioner and research backgrounds.

The chapter was developed through technical discussions of relevant evidence and expert deliberation by the report authors at several workshops and teleconferences and via email exchanges. The authors considered inputs and comments submitted by the public, 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 with transportation experts during multiple listening sessions.

Because the impacts of climate change on transportation assets for the United States and globally have been widely examined elsewhere, including in the Third National Climate Assessment (NCA3),[137] this chapter addresses previously identified climate change impacts on transportation assets that persist nationally, with a focus on recent literature that describes newly identified impacts and advances in understanding. Asset vulnerability and impacts are of national importance because there are societal and economic consequences that transcend regional or subregional boundaries when a transportation network fails to perform as designed; a chapter focus is the emerging understanding of those impacts. Further, place-based, societally relevant understanding of transportation system resilience has been strongly informed by numerous recent local and state assessments that capture regionally relevant climate impacts on transportation and collectively inform national level risks and resilience. The chapter synthesizes the transportation communities' national awareness of and readiness for climate threats that are most relevant in the United States.

Key Message 1

Transportation at Risk

A reliable, safe, and efficient U.S. transportation system is at risk from increases in heavy precipitation, coastal flooding, heat, wildfires, and other extreme events, as well as changes to average temperature (*high confidence*). Throughout this century, climate change will continue to pose a risk to U.S. transportation infrastructure, with regional differences (*high confidence*).

Description of evidence base

Global mean sea level has risen since 1900 and is expected to continue to rise.[2] High tide flooding is increasing and is projected to continue increasing.[1] The peak storm surge levels are expected to rise more than the rise in sea level; models show that if the depth of storm flooding today is A and the rise in sea level between now and a future occurrence of an identical storm is B, then the resulting future storm surge depths can be greater than A + B.[52] The U.S. roads and bridges in the coastal floodplain[49] are vulnerable today, as storms are repeatedly causing damage.[50,53,54,138] Sea level rise is also projected to impact ports,[57] airports,[58] and roads.[63,64,65] High tide flooding currently makes some roads impassable due to flooding[60,61] and is very likely to increase transportation disruptions in the future.[61]

In most parts of the United States, heavy precipitation is increasing in frequency and intensity, and more severe precipitation events are anticipated in the future.[25] Inland transportation infrastructure is highly vulnerable to intense rainfall and flooding.[3,25,66,67,69,139] In the western United States, large wildfires have increased and are likely to increase in the future,[70] escalating the vulnerability of transportation infrastructure to severe precipitation events.[71,72]

The frequency of summer heat waves has increased since the 1960s, and average annual temperatures have increased over the past three decades; these temperature changes are projected to continue to increase in the future.[41] Warming temperatures have increased costs[81] and reduced the performance of roads,[80] bridges,[4,5] railways,[4,5,6] and air transport.[3,74,86] Future temperature increases are projected to reduce infrastructure lifetime[78,79,122] and increase road costs.[12] Milder winters will likely lengthen the shipping season in northern inland ports,[87,88] benefit transportation safety,[42,43,44,66,82] and reduce winter maintenance.[4,12,45] In Alaska, however, permafrost thawing will damage roads[46] and increase the cost of roads (Ch. 26: Alaska).

Major uncertainties

Peer-reviewed literature on climate impacts to some assets is limited. Most literature addresses local- or regional-scale issues. Uncertainty in the ranges of climate change projection leads to challenges to quantifying impacts on transportation assets, which have long lifetimes.

Impacts to transportation infrastructure from climate change will depend on many factors, including population growth, economic demands, policy decisions, and technological changes. How these factors, with their potential compounding effects, as well as the impacts of disruptive or transformative technologies (such as automated vehicles or autonomous aerial vehicles), will contribute to transportation performance in the future is poorly understood.

The relationship among increases in large precipitation events and flood-induced infrastructure damage is uncertain because multiple factors (including land use, topography, and even flood control) impact flooding.[140,141,142,143] Hirsch and Ryberg (2012)[144] found limited evidence of increasing global mean carbon dioxide concentrations resulting in increasing flooding in any region of the United States. Archfield et al. (2016)[145] found that flood changes to date are fragmented and that a climate change signal on flood changes was not yet clear.

Description of confidence and likelihood

There is *very high confidence* that sea level rise and increases in flooding during coastal storms and astronomical high tides will lead to damage and service reductions with coastal bridges, roads, rails, and ports.

There is *high confidence* that heavy precipitation events have increased in intensity and frequency since 1901 (with the largest increase seen in the Northeast); this trend is projected to continue.[25] There is *medium confidence* that precipitation increases will lead to surface and rail transit delays in urban areas. There is *medium confidence* that flood-induced damages to roads and bridges will increase.

Rising temperatures and extreme heat (*high confidence*) will damage pavement and increase railway and air transit delays. However, the actual magnitude of those impacts will depend on technological advancements and policy decisions about design and operations.

Key Message 2

Impacts to Urban and Rural Transportation

Extreme events that increasingly impact the transportation network are inducing societal and economic consequences, some of which disproportionately affect vulnerable populations (*high confidence*). In the absence of intervention, future changes in climate will lead to increasing transportation challenges, particularly because of system complexity, aging infrastructure, and dependency across sectors (*high confidence*).

Description of evidence base

The Key Message is largely supported by observation and empirical evidence that is well documented in the gray (non-peer-reviewed) literature and recent government reports. Because this is an important emerging area of research, the peer-reviewed scientific literature is sparse. Hence, much of the supporting materials for this Key Message are descriptions of impacts of recent events provided by news organizations and government summaries.

Many urban locations have experienced disruptive extreme events that have impacted the transportation network and led to societal and economic consequences. Louisiana experienced historic floods in 2016 that disrupted all modes of transportation and caused adverse impacts on major industries and businesses due to the halt of freight movement and employees' inability to get to work.[146] The 2016 floods that affected Texas from March to June resulted in major business disruption due to the loss of a major transportation corridor.[147] In 2017, Hurricane Harvey affected population and freight mobility in Houston, Texas, when 23 ports were closed and over 700 roads were deemed impassable.[148] Consequences of extreme events can be magnified when events are cumulative. The 2017 hurricanes impacting the southern Atlantic and Gulf Coasts and Puerto Rico created rising freight costs because freight carriers had to deal with poor traveling conditions, an unreliable fuel stock, and limited exports for the return trip.[149,150] Low-income populations have been linked to differences in perceived risks associated with an extreme event, in how they respond, and in their ability to evacuate or relocate.[151] Delays in evacuations can potentially lead to significant transportation delays, affecting the timeliness of first responders and evacuations. National- and local-level decision-makers are considering strategies during storm recovery and its aftermath to identify and support vulnerable populations to ensure transportation and access to schools, work, and community services (for example, the 2016 Baton Rouge flood event).

Similar to the urban and suburban scenarios, rural areas across the country have also experienced disruptions and impacts from climate events. Hurricane Irene resulted in the damage or destruction of roads throughout New England, resulting in small towns being isolated throughout the region.[152] Similarly, Hurricane Katrina devastated rural community infrastructure across the Gulf

Coast, which resulted in extended periods of isolation and population movement.[153] Lesser-known events are also causing regular impacts to rural communities, such as flood events in 2014 in Minnesota and in 2017 throughout the Midwest, which impacted towns for months due to damaged road infrastructure.[154,155]

Although flooding events and hurricanes receive significant attention, other weather-based events cause equal or greater impacts to rural areas. Landslide events have isolated rural communities by reducing them to single-road access.[156,157] Extreme heat events combined with drought have resulted in increases in wildfire activity that have impacted rural areas in several regions. The impacts of these wildfire events include damage to infrastructure both within rural communities and to access points to the communities.[158]

As documented, rural communities incur impacts from climate events that are similar to those experienced in urban and suburban communities. However, rural and isolated areas experience the additional concerns of recovering from extreme events with fewer resources and less capacity.[111] This difference often results in rural communities facing extended periods of time with limited access for commercial and residential traffic.

Major uncertainties

Realized societal and economic impacts from transportation disruptions vary by extreme event, depending on the intensity and duration of the storm; pre-storm conditions, including cumulative events; planning mechanisms (such as zoning practices); and so on. In addition, a combination of weather stressors, such as heavy precipitation with notable storm surge, can amplify effects on different assets, compounding the societal and economic consequences. These amplifications are poorly understood but directly affect transportation users. Interdependencies among transportation and other lifeline sectors can also have significant impacts on the degree of consequences experienced. These impacts are also poorly understood.

Description of confidence and likelihood

There is *medium to high confidence* that the urban setting can amplify heat.[159] There is also *medium to high confidence* that transportation networks are impacted by inland and coastal flooding.[70] There is *medium confidence* that socioeconomic conditions are strongly related to a population's resilience to extreme events.[151]

There is *high confidence* that impacts to the transportation network from extreme events are inducing societal and economic consequences, some of which disproportionately affect vulnerable populations (*medium confidence*). In the absence of intervention, projected changes in climate will likely lead to increasing transportation challenges as a result of system complexity, aging infrastructure with hundreds of billions of dollars in rehabilitation backlogs,[13] and dependency across sectors.

Key Message 3

Vulnerability Assessments

> Engineers, planners, and researchers in the transportation field are showing increasing interest and sophistication in understanding the risks that climate hazards pose to transportation assets and services (*very high confidence*). Transportation practitioner efforts demonstrate the connection between advanced assessment and the implementation of adaptive measures, though many communities still face challenges and barriers to action (*high confidence*).

Description of evidence base

Chapter authors reviewed more than 60 recently published vulnerability assessments (details and links available through the online version of Figure 12.3) conducted by or for states and localities. The research approach involved internet searches, consultations with experts, and leveraging existing syntheses and compilations of transportation-related vulnerability assessments. The authors cast a broad net to ensure that as many assessments as possible were captured in the review. The studies were screened for a variety of metrics (for example, method of assessment, hazard type, asset category, vulnerability assessment type, economic analysis, and adaptation actions), and findings were used to inform the conclusions reached in this section.

Major uncertainties

Most of the literature and the practitioner studies cited for Key Message 3 were gray literature, which is not peer-reviewed but serves the purpose of documenting the state of the practice. This section was not an assessment of the science (that is, the validity of individual study results was not assessed) but surveyed how transportation practitioners are assessing and managing climate impacts. The conclusions are not predicated on selection of or relative benefits of specific modeling or technological advances.

Practitioners' motivations underlying changes in the state of the practice were derived from information in the studies and from cited literature. The authors of this section did not survey authors of individual vulnerability studies to determine their situation-specific motivations.

Description of confidence and likelihood

There is *high confidence* regarding the efforts of state and local transportation agencies to understand climate impacts through assessments like those referenced in Figure 12.3. There is *medium confidence* in the reasons for delay in implementing resilience measures and the motivations for vulnerability assessments. There is no consensus on how emerging transportation technologies will develop in the coming years and how this change will affect climate mitigation, adaptation, and resilience.

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Impacts, Risks, and Adaptation in the United States: Fourth National Climate Assessment, Volume II

13 Air Quality

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13 Air Quality

Carr Fire, Shasta County, California, August 2018

Key Message 1

Increasing Risks from Air Pollution

More than 100 million people in the United States live in communities where air pollution exceeds health-based air quality standards. Unless counteracting efforts to improve air quality are implemented, climate change will worsen existing air pollution levels. This worsened air pollution would increase the incidence of adverse respiratory and cardiovascular health effects, including premature death. Increased air pollution would also have other environmental consequences, including reduced visibility and damage to agricultural crops and forests.

Key Message 2

Increasing Impacts of Wildfires

Wildfire smoke degrades air quality, increasing the health risks to tens of millions of people in the United States. More frequent and severe wildfires due to climate change would further diminish air quality, increase incidences of respiratory illness from exposure to wildfire smoke, impair visibility, and disrupt outdoor recreational activities.

Key Message 3

Increases in Airborne Allergen Exposure

The frequency and severity of allergic illnesses, including asthma and hay fever, are likely to increase as a result of a changing climate. Earlier spring arrival, warmer temperatures, changes in precipitation, and higher carbon dioxide concentrations can increase exposure to airborne pollen allergens.

Key Message 4

Co-Benefits of Greenhouse Gas Mitigation

Many emission sources of greenhouse gases also emit air pollutants that harm human health. Controlling these common emission sources would both mitigate climate change and have immediate benefits for air quality and human health. Because methane is both a greenhouse gas and an ozone precursor, reductions of methane emissions have the potential to simultaneously mitigate climate change and improve air quality.

Executive Summary

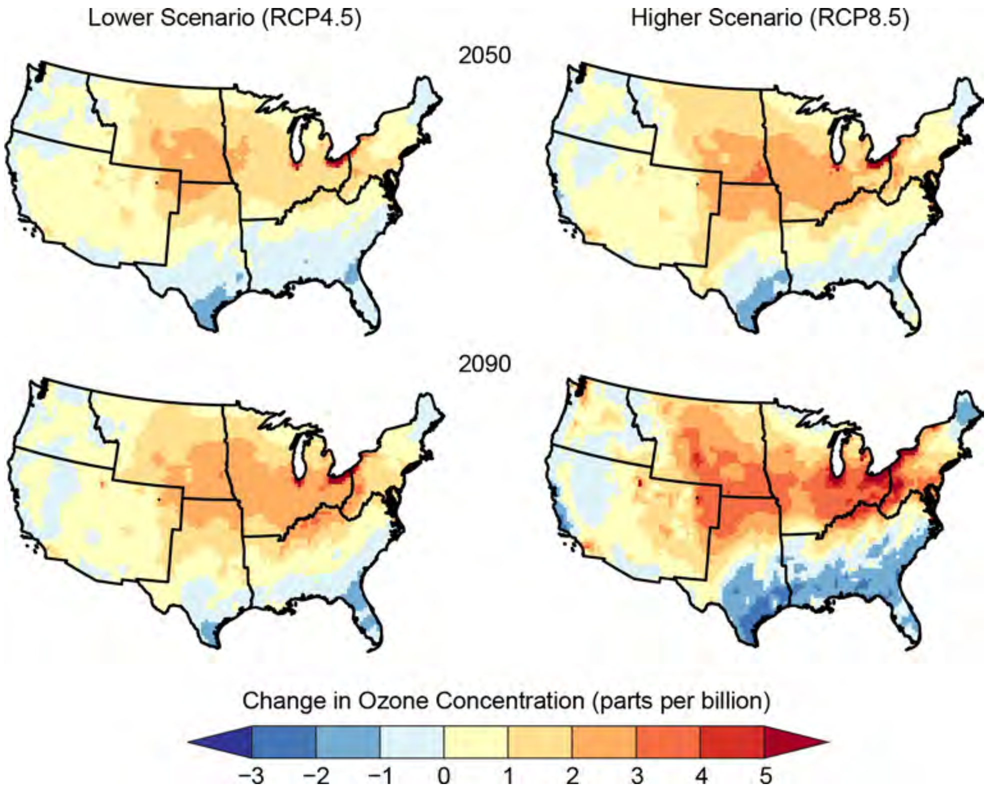
Unless offset by additional emissions reductions of ozone precursor emissions, there is high confidence that climate change will increase ozone levels over most of the United States, particularly over already polluted areas, thereby worsening the detrimental health and environmental effects due to ozone. The climate penalty results from changes in local weather conditions, including temperature and atmospheric circulation patterns, as well as changes in ozone precursor emissions that are influenced by meteorology. Climate change has already had an influence on ozone concentrations over the United States, offsetting some of the expected ozone benefit from reduced precursor emissions. The magnitude of the climate penalty over the United States could be reduced by mitigating climate change.

Climatic changes, including warmer springs, longer summer dry seasons, and drier soils and vegetation, have already lengthened the wildfire season and increased the frequency of large wildfires. Exposure to wildfire smoke increases the risk of respiratory disease, resulting in adverse impacts to human health. Longer fire seasons and increases in the number of large fires would impair both human health and visibility.

Climate change, specifically rising temperatures and increased carbon dioxide (CO_2) concentrations, can influence plant-based allergens, hay fever, and asthma in three ways: by increasing the duration of the pollen season, by increasing the amount of pollen produced by plants, and by altering the degree of allergic reactions to the pollen.

The energy sector, which includes energy production, conversion, and use, accounts for 84% of greenhouse gas (GHG) emissions in the United States as well as 80% of emissions of nitrogen oxides (NO_x) and 96% of sulfur dioxide, the major precursor of sulfate aerosol. In addition to reducing future warming, reductions in GHG emissions often result in co-benefits (other positive effects, such as improved air quality) and possibly some negative effects (disbenefits) (Ch. 29: Mitigation). Specifically, mitigating GHG emissions can lower emissions of particulate matter (PM), ozone and PM precursors, and other hazardous pollutants, reducing the risks to human health from air pollution.

Projected Changes in Summer Season Ozone



The maps show projected changes in summer averages of the maximum daily 8-hour ozone concentration (as compared to the 1995–2005 average). Summertime ozone is projected to change non-uniformly across the United States based on multiyear simulations from the Community Multiscale Air Quality (CMAQ) modeling system. Those changes are amplified under the higher scenario (RCP8.5) compared with the lower scenario (RCP4.5), as well as at 2090 compared with 2050. Data are not available for Alaska, Hawai‘i, U.S.-Affiliated Pacific Islands, and the U.S. Caribbean. *From Figure 13.2 (Source: adapted from EPA 2017[1]).*

State of the Sector

Air quality is important for human health, vegetation, and crops as well as aesthetic considerations (such as visibility) that affect appreciation of the natural beauty of national parks and other outdoor spaces. Many of the processes that determine air quality are affected by weather (Figure 13.1). For example, hot, sunny days can increase ozone levels, while stagnant weather conditions can produce high concentrations of both ozone and particulate matter (PM). Ozone and PM are air pollutants that adversely affect human health and are monitored and regulated with national standards. Temperature, wind patterns, cloud cover, and precipitation, as well as the amounts and types of pollutants emitted into the air from human activities and natural sources, all affect air quality (Figure 13.1). Thus, climate-driven changes in weather, human activity, and natural emissions are all expected to impact future air quality across the United States.

These climate effects on air quality are not expected to occur uniformly at all locations. For example, as discussed in Chapter 2: Climate, precipitation is projected to increase in some regions of the country and decrease in other regions. Regions that experience excessive periods of drought and higher temperatures will have increased frequency of wildfires and more windblown dust from soils. At the same time, changes to temperatures and rainfall affect the types of crops that can be grown (Ch. 10: Ag & Rural) and the length of the growing season, the application of fertilizers and pesticides to crops, and ensuing transport and fate of those chemicals into the air, water, and soil. In the future, climate change is expected to alter the demand for heating and cooling of indoor spaces due to changes in temperatures. The resulting shift in fuel types and amounts used will modify the amount and composition of air pollutants emitted. Climate change can also increase the duration of the pollen season and the amount of pollen at some locations, as well as worsen respiratory health impacts due to pollen exposure. Despite the potential variability in regional impacts of climate change, there is evidence that climate change will increase the risk of unhealthy air quality in the future across the Nation in the absence of further air pollution control efforts (for other impacts of climate change on health, see Ch. 14: Human Health).

Since people spend most of their time inside buildings, indoor air quality is important for human health. Indoor air pollutants may come from interior sources or may be transported into buildings with outdoor air. If there are changes in airborne pollutants of outdoor origin, such as ozone, pollen, mold, and $PM_{2.5}$ (particulate matter less than 2.5 micrometers in diameter), there will be changes in indoor exposures to these contaminants.[2,3]

There is robust evidence from models and observations that climate change is worsening ozone pollution. The net effect of climate change on PM pollution is less certain than for ozone, but increases in smoke from wildfires and windblown dust from regions affected by drought are expected. The complex interactions of natural variability with changes in climate and emissions pose a significant challenge for air quality management. Some approaches to mitigating climate change could result in large near-term co-benefits for air quality.

Pathways by Which Climate Change Will Influence Air Pollution

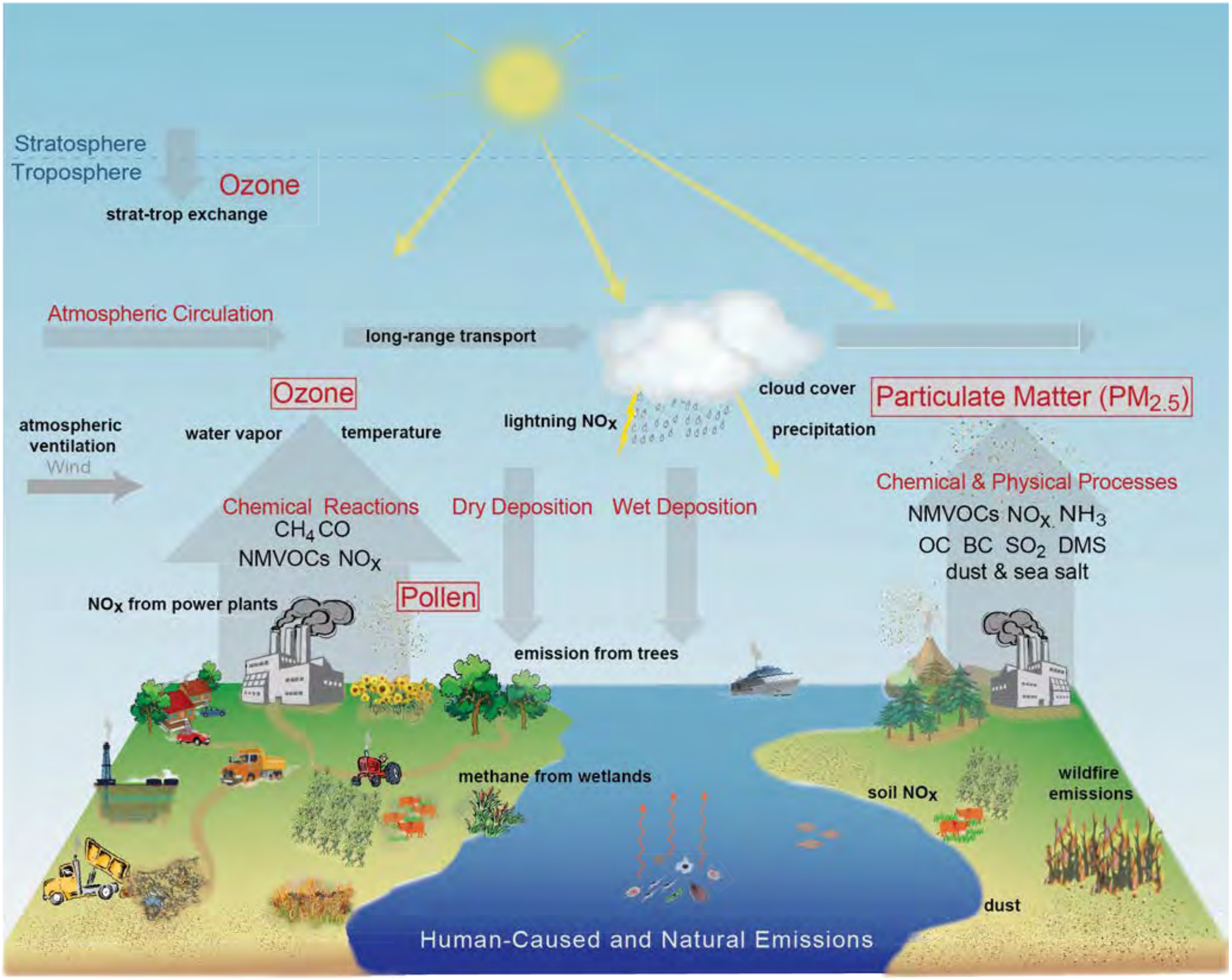


Figure 13.1: Climate change will alter (black bold text) chemical and physical interactions that create, remove, and transport air pollution (red text and gray arrows). Human activities and natural processes release precursors for ground-level ozone (O_3) and particulate matter with a diameter less than 2.5 micrometers ($PM_{2.5}$), including methane (CH_4), carbon monoxide (CO), nitrogen oxides (NO_x), non-methane volatile organic compounds (NMVOCs), sulfur dioxide (SO_2), ammonia (NH_3), organic carbon (OC), black carbon (BC), and dimethyl sulfide (DMS); and direct atmospheric pollutants, including mineral dust, sea salt, pollen, spores, and food particles. Source: adapted from Fiore et al. 2015.[4] Reprinted by permission of the publisher (Taylor & Francis Ltd., http://www.tandfonline.com).

Air Pollution Health Effects

Ground-level ozone and particulate matter are common air pollutants that pose a serious risk to human health and the environment.[5,6] Short- and long-term exposure to these pollutants results in adverse respiratory and cardiovascular effects,[7] including premature deaths,[8] hospital and emergency room visits, aggravated asthma,[3,9] and shortness of breath.[10] Certain population groups, such as the elderly, children, and those with chronic illnesses, are especially susceptible to ozone and PM-related effects.[11,12,13]

A growing body of evidence indicates the harmful effects of short-term (i.e., daily) exposures to ground-level ozone vary with climate conditions, specifically temperature.[14,15,16,17,18] For a given level of ozone, higher temperatures increase the risk of ozone-related premature death.[14,19,20,21] However, the risk of premature death is likely to decrease as the prevalence of air conditioning increases, as is expected to occur with rising temperatures.[22] The extent to which the growing use of air conditioning will offset climate-induced increases in ozone-related premature death is unknown.

Ozone Air Quality

Ozone is not directly emitted but is formed in the atmosphere by reactions between nitrogen oxides (NO_x) and volatile organic compounds (VOCs). Ozone concentrations depend on emissions of these two precursors as well as weather conditions such as temperature, humidity, cloud cover, and winds.[3] These emissions come from a variety of human sources, such as power plants and motor vehicles, and from natural sources, such as forests and wildfires (Figure 13.1). Additionally, ozone concentrations in one region may be influenced by the transport of either precursors or ozone itself from another region.[23,24]

Ozone levels in the United States are often highest in Southern California and the Northeast Corridor as well as around other large cities like Dallas, Houston, Denver, Phoenix, and Chicago,[25] and during extended episodes of extreme heat and sunshine.[26] Ozone air quality in the United States has improved dramatically over the past few decades due to NO_x and VOC emissions control efforts, despite population and economic growth.[27,28,29] Nationally, ozone concentrations have been reduced by 22% over the 1990 to 2016 period.[29] Nonetheless, in 2015 nearly 1 in 3 Americans were exposed to ozone values that exceeded the national standard determined by the U.S. Environmental Protection Agency (EPA) to be protective of human health.[29] Adverse human health impacts associated with exposure to ground-level ozone include premature death, respiratory hospital admissions, cases of aggravated asthma, lost days of school, and reduced productivity among outdoor workers.[30,31,32] Ozone pollution can also damage crops and plant communities, including forests, by reducing photosynthesis.[33]

Due in part to air pollutant regulations driven by the Clean Air Act, NO_x and VOC emissions from human sources should continue to decline over the next few decades.[34] These emissions reductions are designed to reduce ozone concentrations so that polluted areas of the country meet air quality standards. However, climate change will also influence future levels of ozone in the United States by altering weather conditions and impacting emissions from human and natural sources. The prevailing evidence strongly suggests that climate change alone introduces a climate penalty (an increase in air pollution resulting from climate change[35,36]) for ozone over most of the United States from warmer temperatures and increases in natural emissions.[3,4,37,38] This climate penalty will partially counteract the continued reductions in emissions of ozone precursors from human activities.

Particulate Matter

Tiny liquid or solid particles suspended in the atmosphere are known as aerosols or particulate matter (PM). PM includes many different chemical components, such as sulfate, nitrate, organic and black carbon, mineral dust, and sea spray. Unlike ozone, PM can be either directly emitted or formed in the atmosphere. $PM_{2.5}$ refers to atmospheric PM with a diameter less than 2.5 micrometers. These particles are small enough to be inhaled deeply, and exposure to high concentrations can result in serious health impacts, including premature death, nonfatal heart attacks, and adverse birth outcomes.[5,39,40,41] $PM_{2.5}$ concentrations vary greatly with daily weather conditions,[42,43] depending particularly on wind speed (which affects the mixing of pollutants) and precipitation (which removes particles from the air).[4] Concentrations of $PM_{2.5}$ build up during long periods of low wind speeds, and they are reduced when weather fronts move air through a region.[4]

Wildfires not only emit gases that contribute to ozone formation[44,45,46,47,48] but they also are a major source of PM, especially in the western United States during the summer[49,50,51,52,53,54,55] and in the Southeast[48,56] (Ch. 6: Forests; Ch. 19: Southeast, Case Study "Prescribed Fire"; Ch. 24: Northwest; Ch. 25: Southwest). Wildfire smoke can worsen air quality locally,[57] with substantial public health impacts in regions with large populations near heavily forested areas.[56,58,59,60,61] Exposure to wildfire smoke increases the incidence of respiratory illnesses, including asthma, chronic obstructive pulmonary disease, bronchitis, and pneumonia.[62] Smoke can decrease visibility[63] and can be transported hundreds of miles downwind, often crossing national boundaries.[54,64,65,66,67,68,69]

Climate change is expected to impact atmospheric PM concentrations in numerous ways.[38,70] Changing weather patterns, including increased stagnation,[71,72] altered frequency of weather fronts,[73,74] more frequent heavy rain events,[43] changing emissions from vegetation[75,76] and human sources,[77] and increased evaporation of some aerosol components[78] will all affect PM concentrations. In addition, more frequent and longer droughts would lengthen the wildfire season[79,80,81] and result in larger wildfires[82,83] and increased dust emissions in some areas.[84] Projections of regional precipitation changes show considerable variation across models and thus remain highly uncertain.[85] Accurately assessing how $PM_{2.5}$ concentrations will respond to the changing climate is difficult due to these complex and highly spatially variable interactions.

Key Message 1

Increasing Risks from Air Pollution

More than 100 million people in the United States live in communities where air pollution exceeds health-based air quality standards. Unless counteracting efforts to improve air quality are implemented, climate change will worsen existing air pollution levels. This worsened air pollution would increase the incidence of adverse respiratory and cardiovascular health effects, including premature death. Increased air pollution would also have other environmental consequences, including reduced visibility and damage to agricultural crops and forests.

Unless offset by additional reductions of ozone precursor emissions, there is high confidence that climate change will increase ozone levels over most of the United States, particularly over already polluted areas,[3,86] thereby worsening the detrimental health and environmental effects due to ozone. Although competing meteorological effects determine local ozone levels, temperature is often the largest single driver.[87] The climate penalty[35,36] results from changes in local weather conditions, including temperature and atmospheric circulation patterns,[4,88] as well as changes in ozone precursor emissions that are influenced by meteorology.[75,76,77] Climate change has already had an influence on ozone concentrations over the United States, offsetting some of the expected ozone benefit from reduced precursor emissions.[89,90] Assessments of climate change impacts on ozone trends are complicated by year-to-year changes in weather conditions[91] and require multiple years of model information to estimate the potential range of effects.[92] Besides being affected by climate change, future ozone levels in the United States will also be affected greatly by domestic emissions of ozone precursors as well as by international emissions of ozone precursors and global methane levels. Studies suggest that climate change will decrease the sensitivity of regional ozone air quality to intercontinental sources.[93]

$PM_{2.5}$ accounts for most of the health impacts due to air pollution in the United States,[94] and small changes in average concentrations have large implications for public health. Without consideration of climate effects, concentrations of $PM_{2.5}$ in the United States are projected to decline through 2040 due to ongoing emissions control efforts.[34] $PM_{2.5}$ is highly sensitive to weather conditions, including temperature, humidity, wind speed, and rainfall. The effects of climate change on the timing, intensity, duration, and frequency of rainfall are highly uncertain, influencing both the removal of $PM_{2.5}$ from air and the incidence of wildfires and their associated emissions. Accordingly, the net impact of climate-driven weather changes on $PM_{2.5}$ concentrations is less certain than for ozone.[3,4,43,70] However, some studies have indicated that even without considering increased wildfire frequency, climate change will cause a small but important increase in $PM_{2.5}$ over North America.[95,96] The impact of climate change on the $PM_{2.5}$ contribution from intercontinental sources, which depends strongly on projected changes in precipitation, remains highly uncertain.[24]

The health impacts of climate-induced changes in air quality may be reduced by various adaptation measures. For example, as local authorities issue air quality alerts, people may reduce their exposure to air pollution by postponing outdoor activities and staying indoors (for further information on the role of adaptation in reducing climate-related health risks, see Ch. 14: Human Health, KM 3).

The magnitude of the climate penalty over the United States could be reduced by mitigating climate change.[1,90,97] For example, Figure 13.2 shows results from one study[1] projecting the change in summertime ozone resulting from two different future scenarios (RCP8.5 and RCP4.5) (see the Scenario Products section of App. 3 for additional information about these scenarios) at 2050 and 2090, with human emissions of ozone precursors held constant. Due to climate change, ozone is projected to increase over a broad portion of the United States. Mitigating climate change globally (for instance, following RCP4.5 rather than RCP8.5) would reduce the impact on ozone, resulting in fewer adverse health effects, including 500 fewer premature deaths per year due to ozone in 2090.[1]

Projected Changes in Summer Season Ozone

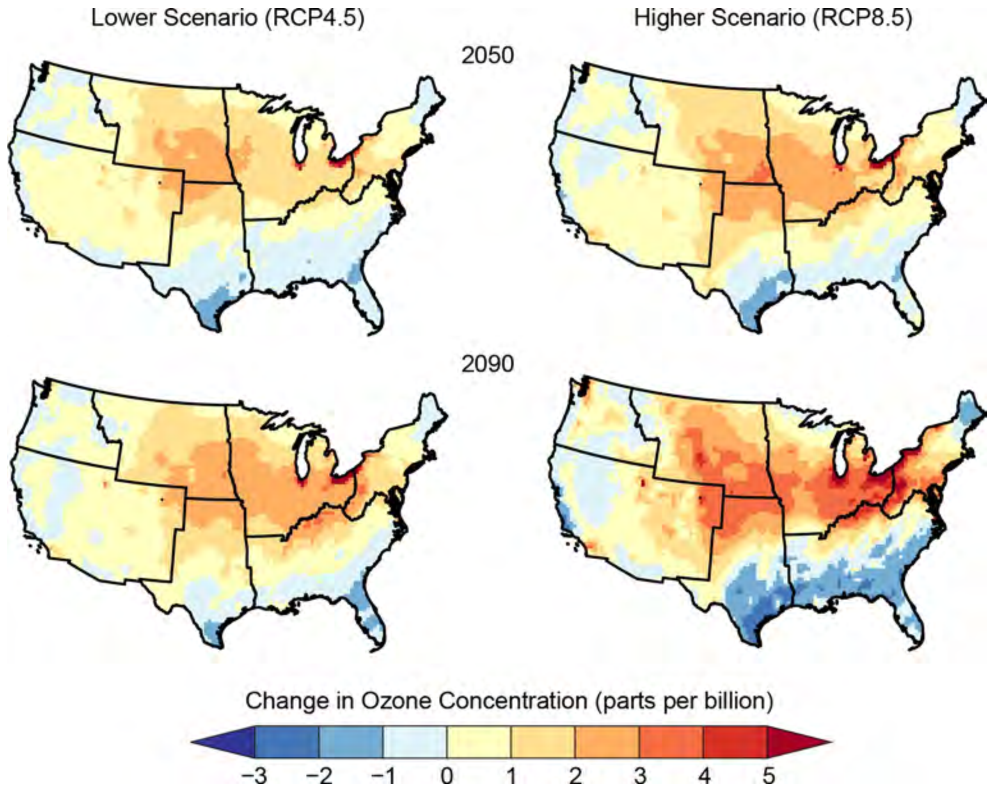


Figure 13.2: The maps show projected changes in summer averages of the maximum daily 8-hour ozone concentration (as compared to the 1995–2005 average). Summertime ozone is projected to change non-uniformly across the United States based on multiyear simulations from the Community Multiscale Air Quality (CMAQ) modeling system. Those changes are amplified under the higher scenario (RCP8.5) compared with the lower scenario (RCP4.5), as well as at 2090 compared with 2050. Data are not available for Alaska, Hawai‘i, U.S.-Affiliated Pacific Islands, and the U.S. Caribbean. Source: adapted from EPA 2017.[1]

Key Message 2

Increasing Impacts of Wildfires

Wildfire smoke degrades air quality, increasing the health risks to tens of millions of people in the United States. More frequent and severe wildfires due to climate change would further diminish air quality, increase incidences of respiratory illness from exposure to wildfire smoke, impair visibility, and disrupt outdoor recreational activities.

Climatic changes, including warmer springs, longer summer dry seasons, and drier soils and vegetation, have already lengthened the wildfire season[79,80,81,98] (Ch. 6: Forests) and increased the frequency of large wildfires.[82,83] Human-caused climate change is estimated to have doubled the area of forest burned in the western United States from 1984 to 2015.[99] Projections indicate that the wildfire frequency and burned area in North America will continue to increase over the 21st century due to climate change.[100,101,102,103,104,105,106]

Wildfires and prescribed fires contribute to ozone formation[44,107] and are major sources of PM, together comprising about 40% of directly emitted $PM_{2.5}$ in the United States in 2011.[34] Exposure to wildfire smoke increases the risk of respiratory disease and mortality.[56,60,62] Longer fire seasons and increases in the number of large fires would impair both human health[108] and visibility.[54,63] Wildfires are projected to become the principal driver of summertime

$PM_{2.5}$ concentrations, offsetting even large reductions in emissions of $PM_{2.5}$ precursors.[54,109]

Opportunities for outdoor recreational activities are also vulnerable to changes in the frequency and intensity of wildfires due to climate change. Climate change-induced increases in wildfire smoke events are likely to reduce the amount and quality of time spent in outdoor activities (Ch. 22: N. Great Plains, KM 3; Ch. 24: Northwest, KM 4). More accurate forecasting of smoke events may mitigate some of the negative effects through changes in timing of outdoor activities.

Forests are actively managed, and the frequency and severity of wildfire occurrence in the future will not be determined solely by climate factors. Humans affect fire activity in many ways, including increasing ignitions and conducting controlled burns and fire suppression.[110,111] Forest management decisions may outweigh the impacts of climate change on both forest ecosystems and air quality.[112]

Key Message 3

Increases in Airborne Allergen Exposure

The frequency and severity of allergic illnesses, including asthma and hay fever, are likely to increase as a result of a changing climate. Earlier spring arrival, warmer temperatures, changes in precipitation, and higher carbon dioxide concentrations can increase exposure to airborne pollen allergens.

Climate change, specifically rising temperatures and increased CO_2 concentrations, can influence plant-based allergens, hay fever, and asthma in three ways: by increasing the duration of the pollen season, by increasing the amount of pollen produced by plants, and by altering the degree of allergic reactions to pollen.

Seasonally, airborne allergen (aeroallergen) exposure in the United States begins with the release of tree pollen in the spring. Between the 1950s and the early 2000s, warming winters and earlier arrival of springs have resulted in earlier flowering of oak trees.[113] Projected increases in CO_2 induce earlier and greater seasonal pollen production in pine trees[114] and oak trees.[115] For summer pollen producers, such as weeds and grasses, the effect of warming temperatures on earlier flowering is less evident. However, the allergen content of timothy grass pollen increases with concurrent increases in ozone and CO_2.[116] For common ragweed, the primary fall aeroallergen, greenhouse studies simulating increased temperature and CO_2 concentrations resulted in earlier flowering, greater floral numbers, increased pollen production, and enhanced allergen content of the pollen.[117,118,119,120] Regional and continental studies indicate that ragweed growth and pollen production increase with urban-induced increases in temperature and CO_2. Ragweed pollen season exposure varies as a function of latitude and delayed autumnal frosts in North America.[119,121] In addition to pollen, aeroallergens are also generated by molds. Plants are often affected, since they can serve as hosts for fungi. For example, projected end-of-century CO_2 concentrations would substantially increase the number of allergenic spores produced from timothy grass.[122]

Although warming temperatures and rising CO_2 levels clearly increase aeroallergen prevalence, the link between exposure and health impacts is less well established. However, hay fever prevalence has been associated with exposure to annual and seasonal extreme heat events.[123] Furthermore, climate-induced changes in oak pollen are projected to increase the number of asthma-related emergency department visits in the Northeast, Southwest, and Midwest.[115]

Key Message 4

Co-Benefits of Greenhouse Gas Mitigation

Many emission sources of greenhouse gases also emit air pollutants that harm human health. Controlling these common emission sources would both mitigate climate change and have immediate benefits for air quality and human health. Because methane is both a greenhouse gas and an ozone precursor, reductions of methane emissions have the potential to simultaneously mitigate climate change and improve air quality.

The energy sector, which includes energy production, conversion, and use, accounts for 84% of greenhouse gas (GHG) emissions[124] as well as 80% of emissions of NO_x and 96% of sulfur dioxide, the major precursor of sulfate aerosol.[125] In addition to reducing future warming, reductions in GHG emissions often result in co-benefits (other positive effects, such as improved air quality) and possibly some negative effects (disbenefits) (Ch. 29: Mitigation). Specifically, mitigating GHGs can lower emissions of PM, ozone and PM precursors, and other hazardous pollutants, reducing the risks to human health from air pollution.[97,126,127,128,129,130] However, the magnitude of air quality co-benefits depends on a number of factors. Areas with higher levels of air pollution have more potential for air quality co-benefits compared to areas where emission controls have been enacted and air pollution levels have been reduced.[131] Different approaches to GHG mitigation yield different reductions, or in some cases, increases in ozone and PM precursors.[132] For example, diesel vehicles emit less GHGs than gasoline-powered vehicles, but without correctly operating pollution-control devices, diesel vehicles emit more particles and ozone precursors and thus contribute more to air quality human health risks.[133]

In addition to co-benefits from sources that emit multiple pollutants, mitigating individual GHGs could yield co-benefits. For example, methane is both a GHG and a slowly reactive ozone precursor that contributes to global background surface ozone concentrations. Some monitoring stations in remote parts of the western United States have recorded rising ozone concentrations, resulting in part from increased global methane levels.[90] The magnitude of the human health benefit of lowering ozone levels via methane mitigation is substantial and is similar in value to the climate change benefits.[134,135] Additionally, PM influences climate on local to global scales by affecting the radiation balance of the Earth,[23,136] so controlling emissions of PM and its precursors would not only yield direct human health benefits via reduced exposure but also avoid or minimize local meteorological conditions that lead to a buildup of pollutants.[137]

Acknowledgments

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Traceable Accounts

Process Description

Due to limited resources and requirements imposed by the Federal Advisory Committee Act, the decision was made that this chapter would be developed using an all-federal author team. The author team was selected based on expertise in climate change impacts on air quality; several of the chapter authors were authors of the "Air Quality Impacts" chapter of the U.S. Global Change Research Program's (USGCRP) Climate and Health Assessment.[3] This chapter was developed through technical discussions of relevant evidence and expert deliberation by the report authors via weekly teleconferences and email exchanges. The authors considered inputs and comments submitted by the public; the National Academies of Sciences, Engineering, and Medicine; and federal agencies.

Key Message 1

Increasing Risks from Air Pollution

More than 100 million people in the United States live in communities where air pollution exceeds health-based air quality standards. Unless counteracting efforts to improve air quality are implemented, climate change will worsen existing air pollution levels (*likely*, *high confidence*). This worsened air pollution would increase the incidence of adverse respiratory and cardiovascular health effects, including premature death (*high confidence*). Increased air pollution would also have other environmental consequences, including reduced visibility and damage to agricultural crops and forests (*likely*, *very high confidence*).

Description of evidence base

It is well established that air pollutants pose a serious risk to human health and the environment.[5,6] Short- and long-term exposure to pollutants such as ozone or $PM_{2.5}$ results in premature deaths,[8] hospital and emergency room visits, aggravated asthma,[3,9] and shortness of breath.[10] Numerous air quality modeling studies have assessed the potential impacts of a changing climate on future ozone and particulate matter levels in the United States.[4,37,38,70,86] These studies examine simulations conducted with a broad ensemble of global and regional climate models under various potential climate scenarios. For ozone, these model assessments consistently project higher future levels commensurate with warmer climates, independent of varying individual model assumptions. This model consensus strengthens confidence in the projected signal. Additionally, well-established data analyses have shown a strong positive correlation between temperature and ozone at many locations in the United States.[87,89] Although competing meteorological effects determine local ozone levels, temperature is often the single largest meteorological driver. This present-day signal also bolsters confidence in the conclusion that warmer climates will be associated with higher ozone. There are also modeling and observational studies that demonstrate that ozone precursor emissions from natural[75] and human sources[77] increase with temperature. In aggregate, the consistency in the ozone response to past and projected future climate across a large volume of analyses provides high confidence that ozone air pollution will likely be worsened in a warmer climate. For particulate matter, the model assessments exhibit greater variability in terms of future concentration differences projected to result from meteorological changes in a warmer climate.[3,4,43,70] The reduced certainty in the response of $PM_{2.5}$ concentrations (particulate matter, or PM, less than 2.5 micrometers in diameter) to changing meteorological drivers is the result of the multiple pathways toward $PM_{2.5}$ formation and the variable influence of meteorological factors on each of those different pathways.[5] Most of these model assessments have not considered the impact of changes in PM from changes in wildfires or windblown dust because they are difficult to quantify. Studies that have included projections of future wildfire incidences have concluded that climate-driven increases in wildfire activity are *likely,* with wildfires becoming an increasingly important source of $PM_{2.5}$[63,108,109] and degrading visibility.[54] Finally, there is ample observational evidence that decreasing ozone and particulate precursor emissions would reduce pollutant levels.[28,29]

Major uncertainties

Model simulations of future air quality indicate that climate warming generally increases ground-level ozone across the United States (see Figure 13.2), but results differ spatially and in the magnitude of the projected signal.[90,138,139,140,141] Because meteorological influences on ozone formation can vary to some degree by location (for example, wind direction may be paramount in locations affected primarily by ozone transport), a few areas may experience lower ozone levels.[4] Future ozone levels over the United States will depend not only on the severity of the climate change impacts on meteorology favorable for ozone accumulation but also on any measures to reduce ozone precursor emissions, introducing further uncertainty. Even larger uncertainties exist with respect to the climate impacts on $PM_{2.5}$, where the future concentrations will depend on changes in a suite of meteorological factors, which in some cases (for example, precipitation) are more difficult to quantify.

Description of confidence and likelihood

There is *high confidence* that rising temperatures will *likely* increase future ozone levels in many parts of the United States in response to climate change. There is greater uncertainty that a warmer climate will increase future $PM_{2.5}$ levels over the United States. Ultimately, the actual ozone and $PM_{2.5}$ changes between the present and the future at any given location will depend on the local climate impacts on meteorology and pollutant emission controls in that region. There is *very high confidence* that reducing ozone precursor emissions and $PM_{2.5}$ precursors and/or direct emissions will *likely* lead to improved air quality in the future, thus mitigating adverse climate effects.

Key Message 2

Increasing Impacts of Wildfires

Wildfire smoke degrades air quality, increasing the health risks to tens of millions of people in the United States. More frequent and severe wildfires due to climate change would further diminish air quality, increase incidences of respiratory illness from exposure to wildfire smoke, impair visibility, and disrupt outdoor recreational activities (*very likely*, *high confidence*).

Description of evidence base

Wildfire smoke worsens air quality through its direct emissions to the atmosphere as well as through chemical reactions of those pollutants with sunlight and other pollutants. Exposure to wildfire smoke increases the risk of exacerbating respiratory illnesses in tens of millions of people in vulnerable population groups across the United States.[62] Several studies have indicated that climate change has already led to longer wildfire seasons,[79] increased frequency of large wildfires,[82,83] and increased area of forest burned.[99] Additional studies project that climate change will cause wildfire frequency and burned area in North America to increase over the 21st century.[81,100,101,102,103,104,105,106] Increased emissions from wildfires may offset the benefits of large reductions in emissions of $PM_{2.5}$ precursors.[54,109] There is a broad and consistent evidence base leading to a high confidence conclusion that the increasing impacts of wildfire are very likely. Increases in wildfire smoke events due to climate change would reduce opportunities for outdoor recreational activities (Ch. 22: N. Great Plains, KM 3; Ch. 24: Northwest, KM 4).

Major uncertainties

Humans affect fire activity in many ways, including increasing ignitions as well as conducting controlled burns and fire suppression activities.[110,111] The frequency and severity of wildfire occurrence in the future will be largely determined by forest management practices and climate adaptation measures, which are very uncertain. Housing development practices and changes in the urban–forest interface are also important factors for future wildfire occurrence and for the extent to which associated smoke emissions impair air quality and result in adverse health effects. The composition of the pollutants contained in wildfire smoke and their chemical reactions are highly dependent on a variety of environmental factors, so projecting and quantifying the effects of wildfire smoke on specific pollutants can be particularly challenging. Exposure to wildfire smoke may also increase the risk of cardiovascular illness, but additional data are required to quantify this risk.[62] More accurate forecasting of wildfire smoke events may mitigate health impacts and reduced opportunities for outdoor recreational activities through changes in timing of those activities.

Description of confidence and likelihood

There is *high confidence* that rising temperatures and earlier spring snowmelt will *very likely* result in lengthening the wildfire season in portions of the United States, leading to an increased frequency of wildfires and associated smoke. There is *very high confidence* that increasing exposure to wildfire smoke, which contains particulate matter, will increase adverse health impacts. It is *likely* that smoke from wildfires will reduce visibility and disrupt outdoor recreational activities.

Key Message 3

Increases in Airborne Allergen Exposure

The frequency and severity of allergic illnesses, including asthma and hay fever, are likely to increase as a result of a changing climate. Earlier spring arrival, warmer temperatures, changes in precipitation, and higher carbon dioxide concentrations can increase exposure to airborne pollen allergens. (*Likely*, *High Confidence*)

Description of evidence base

Considerable evidence supports the conclusion that climate change and rising levels of CO_2 affect key aspects of aeroallergen biology, including the production, temporal distribution, and potential allergenicity of aeroallergens.[142,143,144,145,146] This evidence includes historical trends indicating that climate change has altered seasonal exposure times for allergenic pollen.[113] These changes in exposure times are associated with rising CO_2 levels, higher temperatures, changes in precipitation (which can extend the start or duration of pollen release times), and the amount of pollen released, the allergenicity of the pollen, and the spatial distribution of that pollen.[117,118,119,147]

Specific changes in weather patterns or extremes are also likely to contribute to the exacerbation of allergy symptoms. For example, thunderstorms can induce spikes in aeroallergen concentrations and increase the incidence and severity of asthma and other allergic disease.[148,149] However, the specific mechanism for intensification of weather and allergic disease is not entirely understood.

Overall, climate change and rising CO_2 levels are likely to increase exposure to aeroallergens and contribute to the severity and prevalence of allergic disease, including asthma.[115] There is consistent and compelling evidence that exposure to aeroallergens poses a significant health risk in regard to the occurrence of asthma, hay fever, sinusitis, conjunctivitis, hives, and anaphylaxis.[150,151,152,153] Finally, there is evidence that synergies between aeroallergens and air pollution, especially particulate matter, may increase health risks for individuals who are simultaneously exposed.[154,155,156]

Major uncertainties

While specific climate- and/or CO_2-induced links to aeroallergen biology are evident, allergic diseases develop in response to complex and multiple interactions, including genetic and non-genetic factors, a developing immune system, environmental exposures (such as ambient air pollution or weather conditions), and socioeconomic and demographic factors. Overall, the role of these factors in eliciting a health response has not been entirely elucidated. However, recent evidence suggests that climate change and aeroallergens are having a discernible impact on public health.[123,157]

There are a number of areas where additional information is needed, including regional variation in climate and aeroallergen production; specific links between aeroallergens and related diseases, particularly asthma; the need for standardized approaches to determine exposure times and pollen concentration; and uncertainty regarding the role of CO_2 on allergenicity.

Description of confidence and likelihood

The scientific literature shows that there is *high confidence* that changes in climate, including rising temperatures and altered precipitation patterns as well as rising levels of atmospheric CO_2, will increase the concentration, allergenicity, season length, and spatial distribution of a number of aeroallergens. These changes in aeroallergen exposure are, in turn, *likely* to impact allergic disease.

Key Message 4

Co-Benefits of Greenhouse Gas Mitigation

Many emission sources of greenhouse gases also emit air pollutants that harm human health. Controlling these common emission sources would both mitigate climate change and have immediate benefits for air quality and human health. Because methane is both a greenhouse gas and an ozone precursor, reductions of methane emissions have the potential to simultaneously mitigate climate change and improve air quality. (*Very Likely*, *Very High Confidence*)

Description of evidence base

Decades of experience in air quality management have resulted in a detailed accounting of the largest emission sources of greenhouse gases (GHGs) and precursors of ozone and PM. The cost and effectiveness of emission control technologies for the largest emissions sources are well understood. By combining these emission and control technology data with energy system modeling tools, the potential to achieve benefits to air quality while mitigating GHG emissions under a range of scenarios has been quantified in numerous studies.

Major uncertainties

A wide range of values have been reported for the magnitude of air quality co-benefits. Much of this variability can be attributed to differences in the mix of co-benefits included in the analysis and the time period under consideration. The largest sources of uncertainty are the cost paths of different energy technologies over time and the extent to which policy choices impact the evolution of these costs and the availability of different energy technologies.

Description of confidence and likelihood

There is *very high confidence* that emissions of ozone and PM precursors could be reduced by reducing combustion sources of CO_2. Reducing emissions of ozone and PM precursors would be *very likely* to reduce ozone and PM pollution, which would *very likely* result in fewer adverse health effects from air pollution. There is *very high confidence* that controlling methane emissions would also reduce ozone formation rates, which would also *very likely* lead to lower ozone levels.

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Impacts, Risks, and Adaptation in the United States: Fourth National Climate Assessment, Volume II

14 Human Health

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14 Human Health

Algal bloom in Lake Erie in the summer of 2015

Key Message 1

Climate Change Affects the Health of All Americans

The health and well-being of Americans are already affected by climate change, with the adverse health consequences projected to worsen with additional climate change. Climate change affects human health by altering exposures to heat waves, floods, droughts, and other extreme events; vector-, food- and waterborne infectious diseases; changes in the quality and safety of air, food, and water; and stresses to mental health and well-being.

Key Message 2

Exposure and Resilience Vary Across Populations and Communities

People and communities are differentially exposed to hazards and disproportionately affected by climate-related health risks. Populations experiencing greater health risks include children, older adults, low-income communities, and some communities of color.

Key Message 3

Adaptation Reduces Risks and Improves Health

Proactive adaptation policies and programs reduce the risks and impacts from climate-sensitive health outcomes and from disruptions in healthcare services. Additional benefits to health arise from explicitly accounting for climate change risks in infrastructure planning and urban design.

Key Message 4

Reducing Greenhouse Gas Emissions Results in Health and Economic Benefits

Reducing greenhouse gas emissions would benefit the health of Americans in the near and long term. By the end of this century, thousands of American lives could be saved and hundreds of billions of dollars in health-related economic benefits gained each year under a pathway of lower greenhouse gas emissions.

Executive Summary

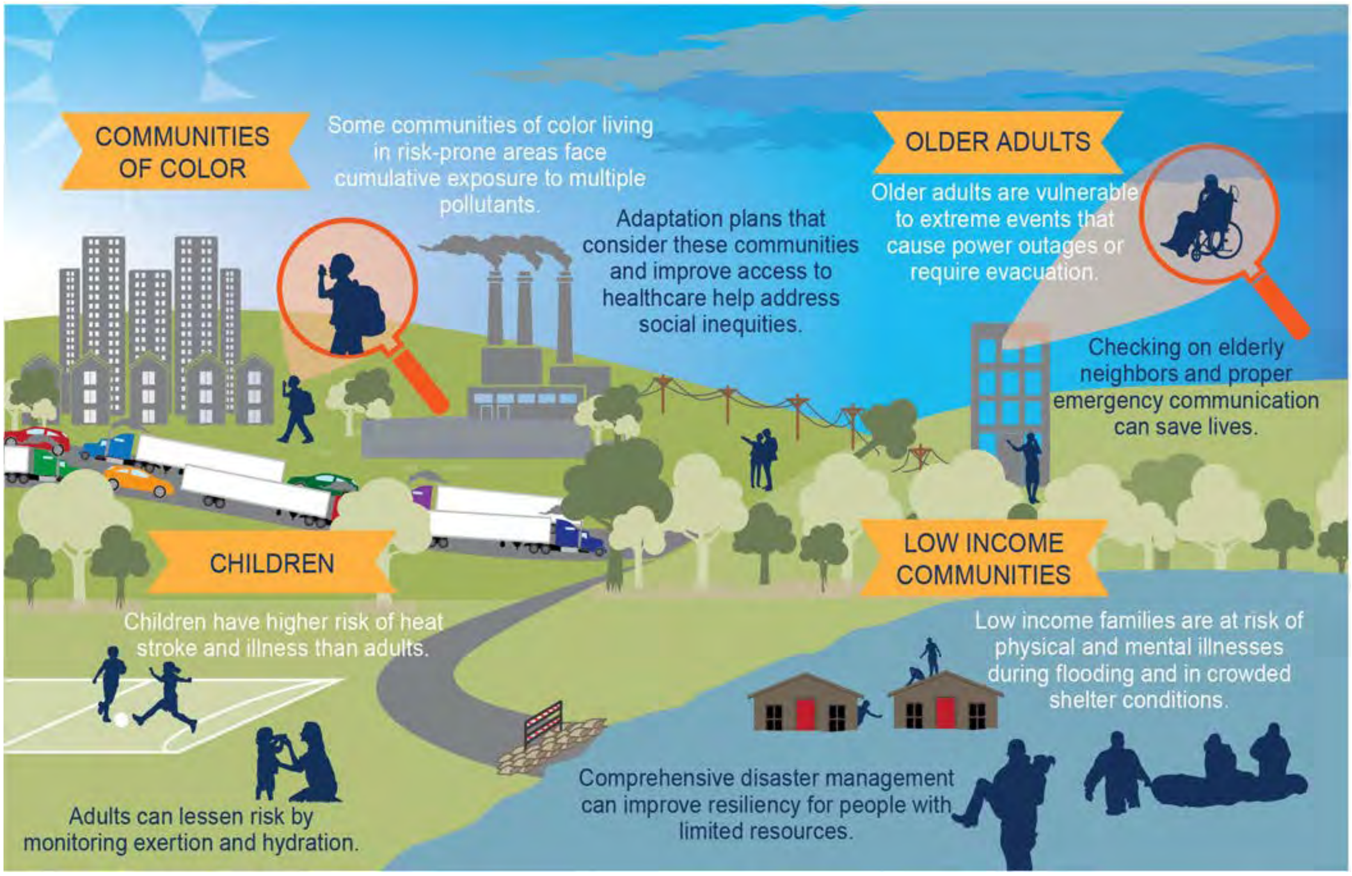
Climate-related changes in weather patterns and associated changes in air, water, food, and the environment are affecting the health and well-being of the American people, causing injuries, illnesses, and death. Increasing temperatures, increases in the frequency and intensity of heat waves (since the 1960s), changes in precipitation patterns (especially increases in heavy precipitation), and sea level rise can affect our health through multiple pathways. Changes in weather and climate can degrade air and water quality; affect the geographic range, seasonality, and intensity of transmission of infectious diseases through food, water, and disease-carrying vectors (such as mosquitoes and ticks); and increase stresses that affect mental health and well-being.

Changing weather patterns also interact with demographic and socioeconomic factors, as well as underlying health trends, to influence the extent of the consequences of climate change for individuals and communities. While all Americans are at risk of experiencing adverse climate-related health outcomes, some populations are disproportionately vulnerable.

The risks of climate change for human health are expected to increase in the future, with the extent of the resulting impacts dependent on the effectiveness of adaptation efforts and on the magnitude and pattern of future climate change. Individuals, communities, public health departments, health-related organizations and facilities, and others are taking action to reduce health vulnerability to current climate change and to increase resilience to the risks projected in coming decades.

The health benefits of reducing greenhouse gas emissions could result in economic benefits of hundreds of billions of dollars each year by the end of the century. Annual health impacts and health-related costs are projected to be approximately 50% lower under a lower scenario (RCP4.5) compared to a higher scenario (RCP8.5). These estimates would be even larger if they included the benefits of health outcomes that are difficult to quantify, such as avoided mental health impacts or long-term physical health impacts.

Vulnerable Populations



Some communities of color living in risk-prone areas face cumulative exposure to multiple pollutants.

Adaptation plans that consider these communities and improve access to healthcare help address social inequities.

Older adults are vulnerable to extreme events that cause power outages or require evacuation.

Checking on elderly neighbors and proper emergency communication can save lives.

Children have higher risk of heat stroke and illness than adults.

Adults can lessen risk by monitoring exertion and hydration.

Low income families are at risk of physical and mental illnesses during flooding and in crowded shelter conditions.

Comprehensive disaster management can improve resiliency for people with limited resources.

Examples of populations at higher risk of exposure to adverse climate-related health threats are shown along with adaptation measures that can help address disproportionate impacts. When considering the full range of threats from climate change as well as other environmental exposures, these groups are among the most exposed, most sensitive, and have the least individual and community resources to prepare for and respond to health threats. White text indicates the risks faced by those communities, while dark text indicates actions that can be taken to reduce those risks. *From Figure 14.2 (Source: EPA).*

A comprehensive assessment of the impacts of climate change on human health in the United States concluded that climate change exacerbates existing climate-sensitive health threats and creates new challenges, exposing more people in more places to hazardous weather and climate conditions.[1] This chapter builds on that assessment and considers the extent to which modifying current, or implementing new, health system responses could prepare for and manage these risks. Please see Chapter 13: Air Quality for a discussion of the health impacts associated with air quality, including ozone, wildfires, and aeroallergens.

Key Message 1

Climate Change Affects the Health of All Americans

The health and well-being of Americans are already affected by climate change, with the adverse health consequences projected to worsen with additional climate change. Climate change affects human health by altering exposures to heat waves, floods, droughts, and other extreme events; vector-, food- and waterborne infectious diseases; changes in the quality and safety of air, food, and water; and stresses to mental health and well-being.

Climate Change and Health

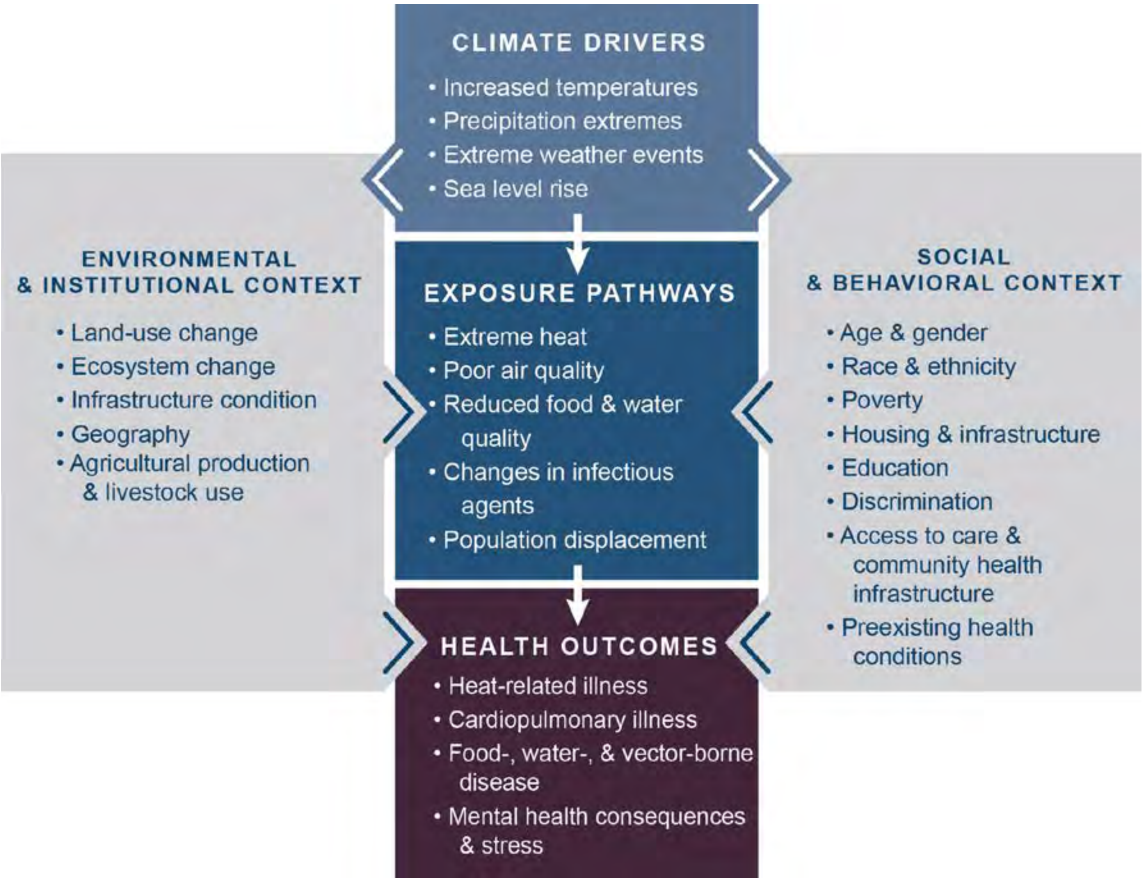


Figure 14.1: This conceptual diagram illustrates the exposure pathways by which climate change could affect human health. Exposure pathways exist within the context of other factors that positively or negatively influence health outcomes (gray side boxes). Key factors that influence vulnerability for individuals are shown in the right box and include social determinants of health and behavioral choices. Key factors that influence vulnerability at larger scales, such as natural and built environments, governance and management, and institutions, are shown in the left box. The extent to which climate change could alter the burden of disease in any location at any point in time will depend not just on the magnitude of local climate change but also on individual and population vulnerability, exposure to changing weather patterns, and capacity to manage risks, which may also be affected by climate change. Source: Balbus et al. 2016.[2]

The first paragraph in each of the following sections summarizes findings of the 2016 U.S. Climate and Health Assessment,[1] and the remainder of each section assesses findings from newly published research.

Extreme Events

More frequent and/or more intense extreme events, including drought, wildfires, heavy rainfall, floods, storms, and storm surge, are expected to adversely affect population health.[3] These events can exacerbate underlying medical conditions, increase stress, and lead to adverse mental health effects.[4] Further, extreme weather and climate events can disrupt critical public health, healthcare, and related systems in ways that can adversely affect health long after the event.[3]

Recent research improves identification of vulnerable population groups during and after an extreme event,[5] including their geographic location and needs (e.g. Bathi and Das 2016, Gotanda et al. 2015, Greenstein et al. 2016[6,7,8]). For example, the 2017 hurricane season highlighted the unique vulnerabilities of populations residing in Puerto Rico, the U.S. Virgin Islands, and other Caribbean islands (Ch. 20: U.S. Caribbean, Box 20.1).[9]

Temperature Extremes

High temperatures in the summer are conclusively linked to an increased risk of a range of illnesses and death, particularly among older adults, pregnant women, and children.[18] People living in urban areas may experience higher ambient temperatures because of the additional heat associated with urban heat islands, exacerbating heat-related risks.[19] With continued warming, increases in heat-related deaths are projected to outweigh reductions in cold-related deaths in most regions.[18]

Analyses of hospital admissions, emergency room visits, or emergency medical services calls show that hot days are associated with an increase in heat-related illnesses,[20,21] including cardiovascular and respiratory complications,[22]

Box 14.1: Health Impacts of Drought and Periods of Unusually Dry Months

In late 2015, California was in the fourth year of its most severe drought since becoming a state in 1850, with 63 emergency proclamations declared in cities, counties, tribal governments, and special districts.[10,11] Households in two drought-stricken counties (Tulare and Mariposa) reported a range of drought-related health impacts, including increased dust leading to allergies, asthma, and other respiratory issues and acute stress and diminished peace of mind.[10] These health effects were not evenly distributed, with more negative physical and mental health impacts reported when drought negatively affected household property and finances.

Drier conditions can increase reproduction of a fungus found in soils, potentially leading to the disease coccidioidomycosis, or Valley fever.[3,12] Coccidioidomycosis can cause persistent flu-like symptoms, with over 40% of cases hospitalized and 75% of patients unable to perform their normal daily activities for weeks, months, or longer. Higher numbers of cases in Arizona and California are associated with periods of drier conditions as measured by lower soil moisture in the previous winter and spring.[13]

Overall, the impacts of drought on hospital admissions and deaths depend on drought severity and the history of droughts in a region.[14] Complex relationships between drought and its associated economic consequences, particularly the interactions among factors that affect vulnerability, protective factors, and coping mechanisms, can increase mood disorders, domestic violence, and suicide.[15,16,17] renal failure,[23] electrolyte imbalance, kidney stones,[24] negative impacts on fetal health,[25] and preterm birth.[26] Risks vary across regions (Ch. 18: Northeast, Box 18.3).[27] Health risks may be higher earlier in the summer season when populations are less accustomed to experiencing elevated temperatures, and different outcomes are observed at different levels of high temperature.[28,29] See Chapter 13: Air Quality for a discussion of the associations between temperature, air quality, and adverse health outcomes.

Vector-Borne Diseases

Climate change is expected to alter the geographic range, seasonal distribution, and abundance of disease vectors, exposing more people in North America to ticks that carry Lyme disease or other bacterial and viral agents, and to mosquitoes that transmit West Nile, chikungunya, dengue, and Zika viruses.[30,31,32] Changing weather patterns interact with other factors, including how pathogens adapt and change, changing ecosystems and land use, demographics, human behavior, and the status of public health infrastructure and management.[33,34]

El Niño events and other episodes of variable weather patterns may indicate the extent to which the risk of infectious disease transmission could increase with additional climate change.[33,35,36]

Increased temperatures and more frequent and intense extreme precipitation events can create conditions that favor the movement of vector-borne diseases into new geographic regions (e.g., Belova et al. 2017, Monaghan et al. 2016, Ogden and Lindsay 2016[31,37,38]). At the same time, very high temperatures may reduce transmission risk for some diseases.[39,40] Economic development also may substantially reduce transmission risk by reducing contacts with vector populations.[41] In the absence of adaptation, exposure to the mosquito *Aedes aegypti*, which can transmit dengue, Zika, chikungunya, and yellow fever viruses, is projected to increase by the end of the century due to climatic, demographic, and socioeconomic changes, with some of the largest increases projected to occur in North America.[31,32] Similarly, changes in temperature may influence the distribution and abundance of tick species that transmit common pathogens.[38,42,43]

Box 14.2: Transboundary Transmission of Infectious Diseases

Outbreaks occurring in other countries can impact U.S. populations and military personnel living abroad and can sometimes affect the United States. For example, the 2015-2016 El Niño, one of the strongest on record,[44] may have contributed to the 2014-2016 Zika epidemic in the Americas.[31,45,46,47,48] Warmer conditions may have facilitated expansion of the geographic range of mosquito populations and increased their capacity to transmit Zika virus.[40] Zika virus can cause a wide range of symptoms, including fever, rash, and headaches, as well as birth defects. The outbreak began in South America and spread to areas with mosquitoes capable of transmitting the virus, including Puerto Rico, the U.S. Virgin Islands, Florida, and Texas.

Water-Related Illnesses and Death

Increasing water temperatures associated with climate change are projected to alter the seasonality of growth and the geographic range of harmful algae and coastal pathogens, and runoff from more frequent and intense rainfall is projected to increasingly compromise recreational waters and sources of drinking water through increased introductions of pathogens and toxic algal blooms.[49,50,51,52,53,54]

Projected increases in extreme precipitation and flooding, combined with inadequate water and sewer infrastructure, can contribute to viral and bacterial contamination from combined sewage overflows and a lack of access to potable drinking water, increasing exposure to pathogens that lead to gastrointestinal illness.[55,56,57,58,59] The relationship between precipitation and temperature-driven transmission of waterborne diseases is complex and site-specific, with, for example, some areas finding increased numbers of cases associated with excessive rainfall and others finding stronger associations with drought.[60,61,62,63,64,65] Heavy rainfall, flooding, and high temperatures have been linked to increases in diarrheal disease[62,64,66,67] and can increase other bacterial and parasitic infections such as leptospirosis and cryptosporidiosis.[65,68] Increases in air temperatures and heat waves are expected to increase temperature-sensitive marine pathogens such as *Vibrio*.[60,69,70,71]

Food Safety and Nutrition

Climate change, including rising temperatures and changes in weather extremes, is projected to adversely affect food security by altering exposures to certain pathogens and toxins (for example, *Salmonella*, *Campylobacter*, *Vibrio parahaemolyticus* in raw oysters, and mycotoxigenic fungi).[72]

Climate change, including changes in some extreme weather and climate events, can adversely affect global and U.S. food security by, for example, threatening food safety,[73,74,75] disrupting food availability, decreasing access to food, and increasing food prices.[76,77,78,79,80,81,82] Food quality also is expected to be affected by rising CO_2 concentrations that decrease dietary iron,[83] zinc,[84] protein,[85] and other macro- and micronutrients in crops[86,87,88] and seafood.[89,90] Projected changes in carbon dioxide concentrations and climate change could diminish expected gains in global nutrition; however, any impact on human health will depend on the many other drivers of global food security and factors such as food chain management, human behavior, and food safety governance.[91,92,93,94]

Mental Health

Mental health consequences, ranging from minimal stress and distress symptoms to clinical disorders, such as anxiety, depression, post-traumatic stress, and suicidality, can result from exposures to short-lived or prolonged climate- or weather-related events and their health consequences.[4] These mental health impacts can interact with other health, social, and environmental stressors to diminish an individual's well-being. Some groups are more vulnerable than others, including the elderly, pregnant women, people with preexisting mental illness, the economically disadvantaged, tribal and Indigenous communities, and first responders.[4]

Individuals whose households experienced a flood or risk of flood report higher levels of depression and anxiety, and these impacts can persist several years after the event.[95,96,97,98] Disasters present a heavy burden on the mental health of children when there is forced displacement from their home or a loss of family and community stability.[99] Increased use of alcohol and tobacco are common following disasters as well as droughts.[15,16,100,101] Higher temperatures can lead to an increase in aggressive behaviors, including homicide.[102,103] Social cohesion, good coping skills, and preemptive disaster planning are examples of adaptive measures that can help reduce the risk of prolonged psychological impacts.[102,104,105]

Key Message 2

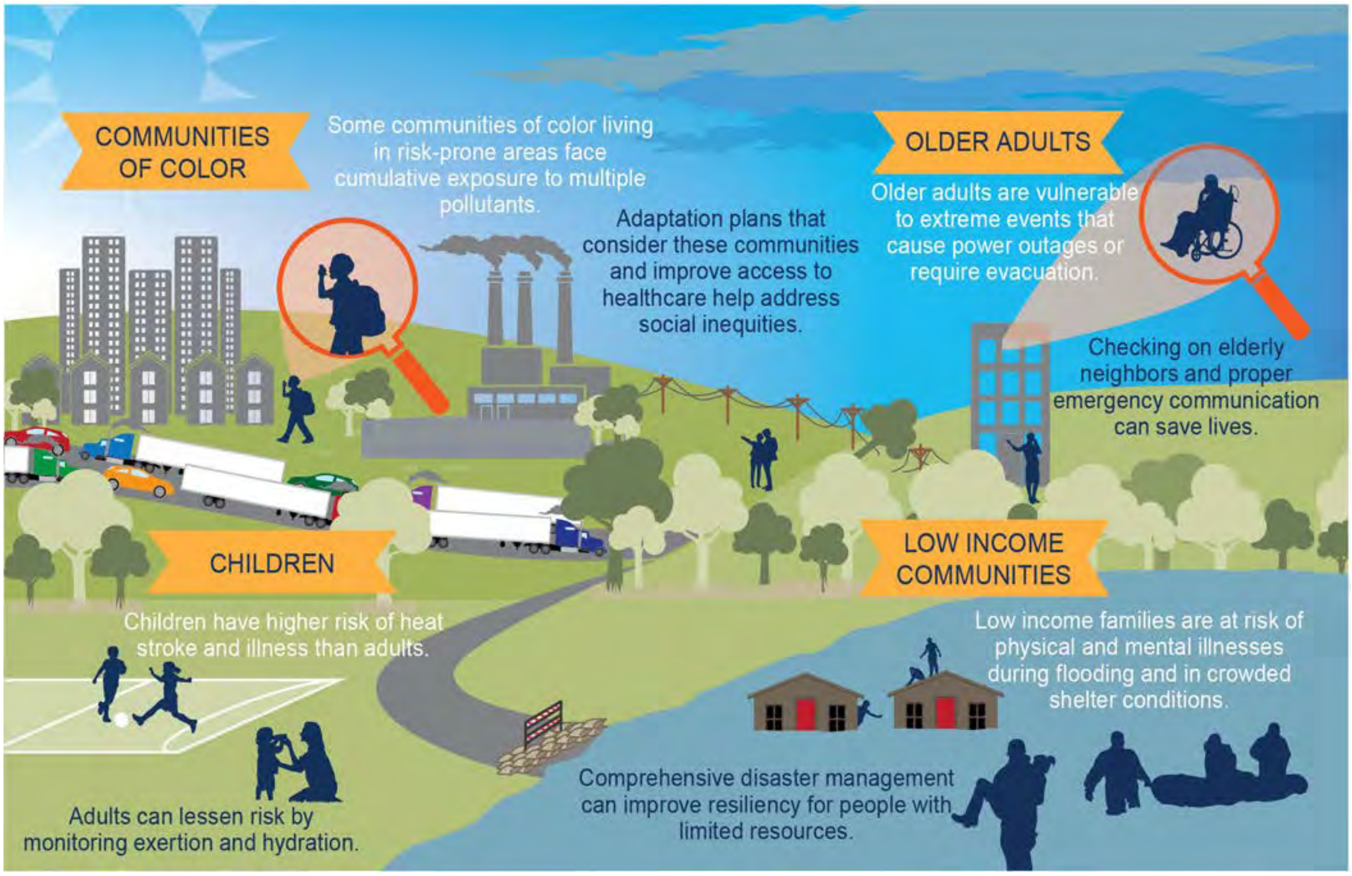
Exposure and Resilience Vary Across Populations and Communities

People and communities are differentially exposed to hazards and disproportionately affected by climate-related health risks. Populations experiencing greater health risks include children, older adults, low-income communities, and some communities of color.

The health impacts of climate change are not felt equally, and some populations are at higher risk than others.[106] Low-income communities and some communities of color are often already overburdened with poor environmental conditions and are disproportionately affected by, and less resilient to, the health impacts of climate change.[106,107,108,109,110] The health risks of climate change are expected to compound existing health issues in Native American and Alaska Native communities, in part due to the loss of traditional foods and practices, the mental stress from permanent community displacement, increased injuries from lack of permafrost, storm damage and flooding, smoke inhalation, damage to water and sanitation systems, decreased food security, and new infectious diseases (Ch. 15: Tribes; Ch. 26: Alaska).[111,112]

Across all climate risks, children, older adults, low-income communities, some communities of color, and those experiencing discrimination are disproportionately affected by extreme weather and climate events, partially because they are often excluded in planning processes.[113] Other populations might experience increased climate risks due to a combination of exposure and sensitivity, such as outdoor workers, communities disproportionately burdened by poor environmental quality, and some communities in the rural Southeastern United States (Ch. 19: Southeast).[114,115,116]

Vulnerable Populations



Some communities of color living in risk-prone areas face cumulative exposure to multiple pollutants.

Adaptation plans that consider these communities and improve access to healthcare help address social inequities.

Older adults are vulnerable to extreme events that cause power outages or require evacuation.

Checking on elderly neighbors and proper emergency communication can save lives.

Children have higher risk of heat stroke and illness than adults.

Adults can lessen risk by monitoring exertion and hydration.

Low income families are at risk of physical and mental illnesses during flooding and in crowded shelter conditions.

Comprehensive disaster management can improve resiliency for people with limited resources.

Figure 14.2: Examples of populations at higher risk of exposure to adverse climate-related health threats are shown along with adaptation measures that can help address disproportionate impacts. When considering the full range of threats from climate change as well as other environmental exposures, these groups are among the most exposed, most sensitive, and have the least individual and community resources to prepare for and respond to health threats. White text indicates the risks faced by those communities, while dark text indicates actions that can be taken to reduce those risks. Source: EPA.

Additional populations with increased health and social vulnerability typically have less access to information, resources, institutions, and other factors to prepare for and avoid the health risks of climate change. Some of these communities include poor people in high-income regions, minority groups, women, pregnant women, those experiencing discrimination, children under five, persons with physical and mental illness, persons with physical and cognitive disabilities, the homeless, those living alone, Indigenous people, people displaced because of weather and climate, the socially isolated, poorly planned communities, the disenfranchised, those with less access to healthcare, the uninsured and underinsured, those living in inadequate housing, and those with limited financial resources to rebound from disasters.[107,109,117,118] Figure 14.2 depicts some of the populations vulnerable to weather, climate, and climate change.

Building Resilient Communities

Projections of climate change-related changes in the incidence of adverse health outcomes, associated treatment costs, and health disparities can promote understanding of the ethical and human rights dimensions of climate change, including the disproportionate share of climate-related risk experienced by socially marginalized and poor populations. Such projections can also highlight options to increase population resilience.[119,120,121] The ability of a community to anticipate, plan for, and reduce impacts is enhanced when these efforts build on other environmental and social programs directed at sustainably and equitably addressing human needs.[122] Resilience is enhanced by community-driven planning processes where residents of vulnerable and impacted communities define for themselves the complex climate challenges they face and the climate solutions most relevant to their unique vulnerabilities.[110,123,124,125] A flood-related disaster in central Appalachia in spring 2013 highlighted how community-based coping strategies related to faith and spirituality, cultural values and heritage, and social support can enhance resilience post-disaster.[126]

Communities in Louisiana and New Jersey, for example, are already experiencing a host of negative environmental exposures coupled with extreme coastal and inland flooding. Language-appropriate educational campaigns can highlight the effectiveness of ecological protective measures (such as restoring marshes and dunes to prevent or reduce surge flooding) for increasing resilience. Resilience also can be built by creating institutional readiness, recognizing the importance of resident mobility (geographic movements at various scales such as commuting, migration, and evacuation), acknowledging the importance and support of social networks (such as family, church, and community), and facilitating adaptation to changing conditions.[127,128]

Key Message 3

Adaptation Reduces Risks and Improves Health

Proactive adaptation policies and programs reduce the risks and impacts from climate-sensitive health outcomes and from disruptions in healthcare services. Additional benefits to health arise from explicitly accounting for climate change risks in infrastructure planning and urban design.

Adapting to the Health Risks of Climate Change

Individuals, communities, public health departments, healthcare facilities, organizations, and others are taking action to reduce health and social vulnerabilities to current climate change and to increase resilience to the risks projected in coming decades.[129]

Examples of state-level adaptation actions include conducting vulnerability and adaptation assessments, developing comprehensive response plans (for example, extreme heat),[110,130] climate-proofing healthcare infrastructure, and implementing integrated surveillance of climate-sensitive infectious disease (for example, Lyme disease). Incorporating short-term to seasonal forecasts into public health programs and activities can protect population health today and under a warming climate.[129] Over decades or longer, emergency preparedness and disaster risk reduction planning can benefit from incorporating climate projections to ensure communities are prepared for changing weather patterns.[131]

Local efforts include altering urban design (for example, by using cool roofs, tree shades, and green walkways) and improving water management (for example, via desalination plants or watershed protection). These can provide health and social justice benefits, elicit neighborhood participation, and increase resilience for specific populations, such as outdoor workers.[107,132,133]

Adaptation options at multiple scales are needed to prepare for and manage health risks in a changing climate. For example, options to manage heat-related mortality include individual acclimatization (the process of adjusting to higher temperatures) as well as protective measures, such as heat wave early warnings,[134] air conditioning at home, cooling shelters,[135] green space in the neighborhood,[136,137] and resilient power grids to avoid power outages during extreme weather events.[138]

Early warning and response systems can protect population health now and provide a basis for more effective adaptation to future climate.[139,140,141] Improvements in forecasting weather and climate conditions and in environmental observation systems, in combination with social factors, can provide information on when and where changing weather patterns could result in increasing numbers of cases of, for example, heat stress or an infectious disease.[31,45,142,143,144] Such early warning systems can provide more time to pre-position resources and implement control programs, thereby preventing adverse health outcomes. For example, to help communities prepare for extreme heat, federal agencies are partnering with local entities to bring together stakeholders across the fields of public health, meteorology, emergency management, and policy to develop useful information systems that can prevent heat-related illnesses and deaths.[145] Adaptation efforts outside the health sector can have health benefits when, for example, infrastructure planning is designed to cool ambient temperatures and attenuate storm water runoff[146,147] and when interagency planning initiatives involve transportation, ecosystem management, urban planning, and water management.[148] Adaptation measures developed and deployed in other sectors can harm population health if they are developed and implemented without taking health into consideration.

Box 14.3: Healthcare

The U.S. healthcare sector is a significant contributor to climate change, accounting for about 10% of total U.S. greenhouse gas emissions.[149] Healthcare facilities are also a critical component of communities' emergency response system and resilience to climate change. Measures within healthcare institutions that decrease greenhouse gas emissions could significantly reduce U.S. emissions, reduce operating costs, and contribute to greater resilience of healthcare infrastructure. For example, U.S. hospitals could save roughly $15 billion over 10 years by adopting basic energy efficiency and waste-reduction measures (cumulative; no discount rate reported).[150] Combined heat and power systems can enhance hospitals' resilience in the face of interruptions to the power grid while reducing costs and emissions in normal operations.[151]

Box 14.3: Healthcare, continued

Hospitals at Risk from Storm Surge by Hurricanes

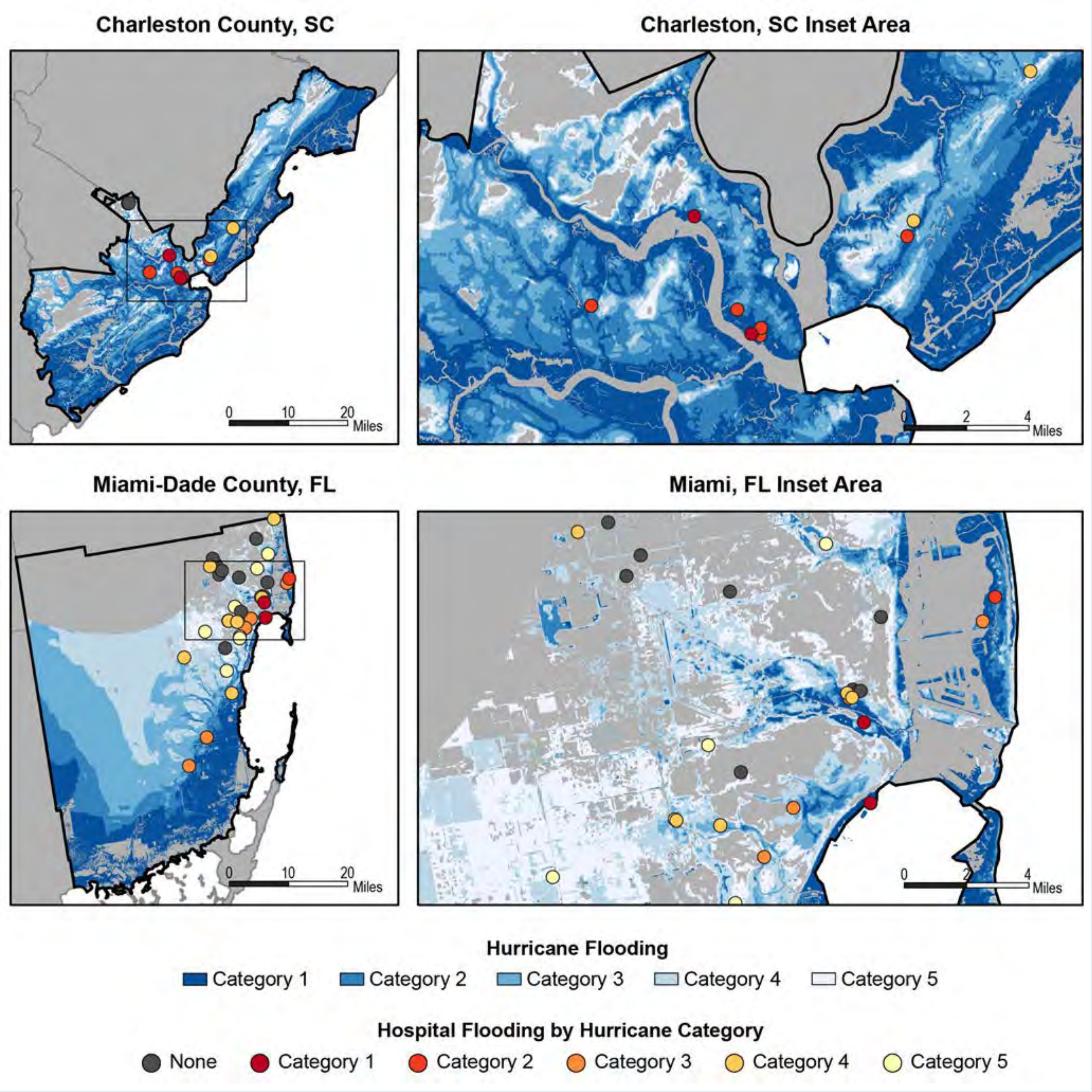


Figure 14.3: These maps show the locations of hospitals in (top) Charleston County, South Carolina, and (bottom) Miami-Dade County, Florida, with respect to storm surge inundation for different categories of hurricanes making landfall at high tide. Colors indicate the lowest category hurricane affecting a given location, with darker blue shading indicating areas with the greatest susceptibility to flooding and darker red dots indicating the most vulnerable hospitals. Four of the 38 (11%) hospitals in Miami-Dade County face possible storm surge inundation following a Category 2 hurricane; this could increase to 26 (68%) following a Category 5 hurricane. Charleston hospitals are more exposed to inundation risks. Seven of the 11 (64%) hospitals in Charleston County face possible storm surge inundation following a Category 2; this could increase to 9 (82%) following a Category 4. The impacts of a storm surge will depend on the effectiveness of resilience measures, such as flood walls, deployed by the facilities. Data from National Hurricane Center 2018[152] and the Department of Homeland Security 2018.[153]

Box 14.3: Healthcare, *continued*

In addition, healthcare facilities may benefit from modifications to prepare for potential consequences of climate change. For example, Nicklaus Children's Hospital, formerly Miami Children's, invested $11.3 million in a range of technology retrofits, including a hurricane-resistant shell, to withstand Category 4 hurricanes for uninterrupted, specialized medical care services.[151] The hospital was able to operate uninterrupted during Hurricane Irma and provided shelter for spouses and families of storm-duty staff and some storm evacuees. Assessment of climate change related risks to healthcare facilities and services can inform healthcare sector disaster preparedness efforts. For example, analyses in Los Angeles County suggest that preparing for increased wildfire risk should be a priority for area hospitals.[154]

Key Message 4

Reducing Greenhouse Gas Emissions Results in Health and Economic Benefits

Reducing greenhouse gas emissions would benefit the health of Americans in the near and long term. By the end of this century, thousands of American lives could be saved and hundreds of billions of dollars in health-related economic benefits gained each year under a pathway of lower greenhouse gas emissions.

Reducing greenhouse gas emissions (Ch. 29: Mitigation) would benefit the health of Americans in the near and long term.[1,155] Adverse health effects attributed to climate change have many potential economic and social costs, including medical expenses, caregiving services, or lost productivity, as well as costs that are harder to quantify, such as those associated with pain, suffering, inconvenience, or reduced enjoyment of leisure activities.[156] These health burdens are typically borne by the affected individual as well as family, friends, employers, communities, and insurance or assistance programs.

Under a lower scenario (RCP4.5) by the end of this century, thousands of lives could be saved and hundreds of billions of dollars of health-related costs could be avoided compared to a higher scenario (RCP8.5).[157] Annual health impacts (including from temperature extremes, poor air quality, and vector-borne diseases) and health-related costs are projected to be approximately 50% less under a lower scenario (RCP4.5) than under a higher scenario (RCP8.5) (methods are summarized in Traceable Accounts) (see also Ch. 13: Air Quality).[37,157,158,159,160,161,162,163,164,165,166,167] The projected lives saved and economic benefits are likely to underestimate the true value because they do not include benefits of impacts that are difficult to quantify, such as mental health or long-term health impacts (see the Scenario Products Section in App. 3 for more on scenarios).

Temperature-Related Mortality

The projected increase in the annual number of heat wave days is substantially reduced under a lower scenario (RCP4.5) compared to a higher scenario (RCP8.5), reducing heat wave intensities[161,168] and resulting in fewer high-mortality heat waves[162,168] without considering adaptation (Figure 14.4). In 49 large cities in the United States, changes in extreme hot and extreme cold temperatures are projected to result in more than 9,000 additional premature deaths per year under a higher scenario by the end of the century, although this number would be lower if considering acclimatization or other adaptations (for example, increased use of air conditioning). Under a lower

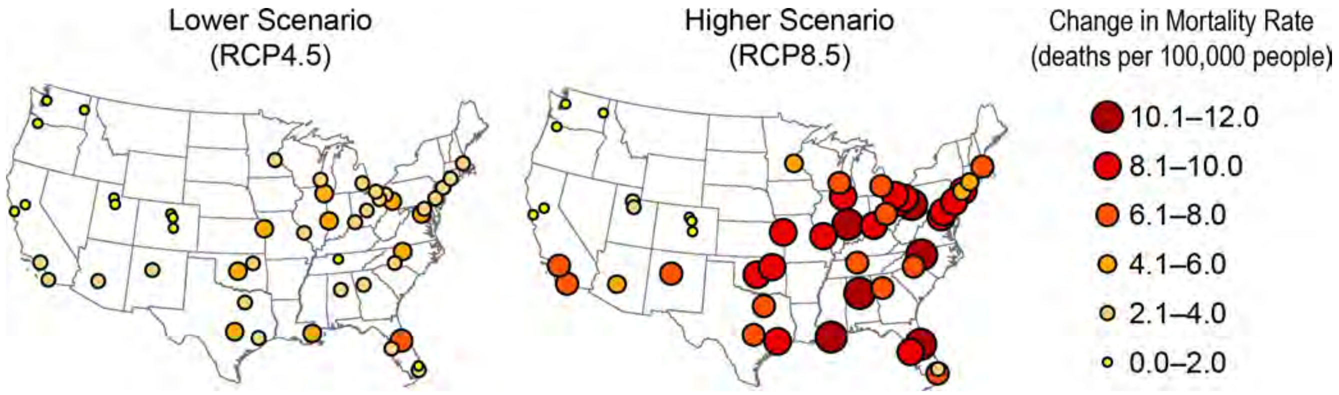

Projected Change in Annual Extreme Temperature Mortality

Figure 14.4: The maps show estimated changes in annual net mortality due to extremely hot and cold days in 49 U.S. cities for 2080–2099 as compared to 1989–2000. Across these cities, the change in mortality is projected to be an additional 9,300 deaths each year under a higher scenario (RCP8.5) and 3,900 deaths each year under a lower scenario (RCP4.5). Assuming a future in which the human health response to extreme temperatures in all 49 cities was equal to that of Dallas today (for example, as a result of availability of air conditioning or physiological adaptation) results in an approximate 50% reduction in these mortality estimates. For example, in Atlanta, an additional 349 people are projected to die from extreme temperatures each year by the end of century under RCP8.5. Assuming residents of Atlanta in 2090 have the adaptive capacity of Dallas residents today, this number is reduced to 128 additional deaths per year. Cities without circles should not be interpreted as having no extreme temperature impact. Data not available for the U.S. Caribbean, Alaska, or Hawai‘i & U.S.-Affiliated Pacific Islands regions. Source: adapted from EPA 2017.[157]

scenario, more than half of these deaths could be avoided each year. Annual damages associated with the additional extreme temperature-related deaths in 2090 were projected to be $140 billion (in 2015 dollars) under a higher scenario (RCP8.5) and $60 billion under a lower scenario (RCP4.5).[157]

Labor Productivity

Under a higher scenario (RCP8.5), almost two billion labor hours are projected to be lost annually by 2090 from the impacts of temperature extremes, costing an estimated $160 billion in lost wages (in 2015 dollars) (Ch. 1: Overview, Figure 1.21).[157,167,169] States within the Southeast and Southern Great Plains regions are projected to experience higher impacts, with labor productivity in jobs with greater exposure to heat projected to decline by 3% (Ch. 19: Southeast).[164,170] Some counties in Texas and Florida are projected to experience more than 6% losses in annual labor hours by the end of the century.[157,160]

Infectious Diseases

Annual national cases of West Nile neuroinvasive disease are projected to more than double by 2050 due to increasing temperatures, among other factors,[30,171] resulting in approximately $1 billion per year in hospitalization costs and premature deaths under a higher scenario (RCP8.5; in 2015 dollars).[37] In this same scenario, an additional 3,300 cases and $3.3 billion in costs (in 2015 dollars) are projected each year by the end of the century. Approximately half of these cases and costs would be avoided under a lower scenario (RCP4.5).[37,157]

Water Quality

By the end of the century, warming under a higher scenario (RCP8.5) is projected to increase the length of time recreational waters have concentrations of harmful algal blooms (cyanobacteria) above the recommended public health threshold by one month annually; these bacteria can produce a range of toxins that can cause gastrointestinal illness, neurological disorders, and other illnesses.[157,165] The increase in the number of days where recreational waters pose this health risk is almost halved under a lower scenario (RCP4.5).

Acknowledgments

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Opening Image Credit

Algal bloom: NOAA Great Lakes Environmental Research Laboratory.

Traceable Accounts

Process Description

The chapter evaluated the scientific evidence of the health risks of climate change, focusing primarily on the literature published since the cutoff date (approximately fall 2015) of the U.S. Climate and Health Assessment.[1] A comprehensive literature search was performed by federal contractors in December 2016 for studies published since January 1, 2014, using PubMed, Scopus, and Web of Science. An Excel file containing 2,477 peer-reviewed studies was provided to the author team for it to consider in this assessment. In addition to the literature review, the authors considered recommended studies submitted in comments by the public, the National Academies of Sciences, Engineering, and Medicine, and federal agencies. The focus of the literature was on health risks in the United States, with limited citations from other countries providing insights into risks Americans are or will likely face with climate change. A full description of the search strategy can be found at https://www.niehs.nih.gov/CCHH_Search_Strategy_NCA4_508.pdf. The chapter authors were chosen based on their expertise in the health risks of climate change. Teleconferences were held with interested researchers and practitioners in climate change and health and with authors in other chapters of this Fourth National Climate Assessment (NCA4).

The U.S. Climate and Health Assessment[1] did not consider adaptation or mitigation, including economic costs and benefits, so the literature cited includes research from earlier years where additional information was relevant to this assessment.

For NCA4, Air Quality was added as a report chapter. Therefore, while Key Messages in this Health chapter include consideration of threats to human health from worsened air quality, the assessment of these risks and impacts are covered in Chapter 13: Air Quality. Similarly, co-benefits of reducing greenhouse gas emissions are covered in the Air Quality chapter.

Key Message 1

Climate Change Affects the Health of All Americans

The health and well-being of Americans are already affected by climate change (*very high confidence*), with the adverse health consequences projected to worsen with additional climate change (*likely*, *high confidence*). Climate change affects human health by altering exposures to heat waves, floods, droughts, and other extreme events; vector-, food- and waterborne infectious diseases; changes in the quality and safety of air, food, and water; and stresses to mental health and well-being.

Description of evidence base

Multiple lines of evidence demonstrate statistically significant associations between temperature, precipitation, and other variables and adverse climate-sensitive health outcomes, indicating sensitivity to weather patterns.[1] These lines of evidence also demonstrate that vulnerability varies across sub-populations and geographic areas; populations with higher vulnerability include poor people in high-income regions, minority groups, women, children, the disabled, those living alone, those with poor health status, Indigenous people, older adults, outdoor workers, people displaced because of weather and climate, low-income residents that lack a social network, poorly planned communities, communities disproportionately burdened by poor environmental quality, the disenfranchised, those with less access to healthcare, and those with limited financial resources to rebound from disasters.[108,109,110,111,118,172] Recent research confirms projections that the magnitude and pattern of risks are expected to increase as climate change continues across the century.[173]

Major uncertainties

The role of non-climate factors, including socioeconomic conditions, population characteristics, and human behavior, as well as health sector policies and practices, will continue to make it challenging to attribute injuries, illnesses, and deaths to climate change. Inadequate consideration of these factors creates uncertainties in projections of the magnitude and pattern of health risks over coming decades. Certainty is higher in near-term projections where there is greater understanding of future trends.

Description of confidence and likelihood

There is *very high confidence* that climate change is affecting the health of Americans. There is *high confidence* that climate-related health risks, without additional adaptation and mitigation, will *likely* increase with additional climate change.

Key Message 2

Exposure and Resilience Vary Across Populations and Communities

People and communities are differentially exposed to hazards and disproportionately affected by climate-related health risks (*high confidence*). Populations experiencing greater health risks include children, older adults, low-income communities, and some communities of color (*high confidence*).

Description of evidence base

Multiple lines of evidence demonstrate that low-income communities and some communities of color are experiencing higher rates of exposure to adverse environmental conditions and social conditions that can reduce their resilience to the impacts of climate change.[106,107,108,109,110] Populations with increased health and social vulnerability typically have less access to information, resources, institutions, and other factors to prepare for and avoid the health risks of climate change.[107,132,133] Across all climate-related health risks, children, older adults, low-income communities, and some communities of color are disproportionately impacted. There is high agreement among experts but fewer analyses demonstrating that other populations with increased vulnerability include outdoor workers, communities disproportionately burdened by poor environmental quality, communities in the rural southeastern United States, women, pregnant women, those experiencing gender discrimination, persons with chronic physical and mental illness, persons with various disabilities (such as those affecting mobility, long-term health, sensory perception, cognition), the homeless, those living alone, Indigenous people, people displaced because of weather and climate, low-income residents who lack a social network, poorly planned communities, the disenfranchised, those with less access to healthcare, the uninsured and underinsured, those living in inadequate housing, and those with limited financial resources to rebound from disasters.[106,107,108,110,118]

Adaptation can increase the climate resilience of populations when the process of developing and implementing policies and measures includes understanding the ethical and human rights dimensions of climate change, meeting human needs in a sustainable and equitable way, and engaging with representatives of the most impacted communities to assess the challenges they face and to define the climate solutions.[124,125]

Major uncertainties

The role of non-climate factors, including socioeconomic conditions, discrimination (racial and ethnic, gender, persons with disabilities), psychosocial stressors, and the continued challenge to measure the cumulative effects of past, present, and future environmental exposures on certain people and communities will continue to make it challenging to attribute injuries, illnesses, and deaths to climate change. While there is no universal framework for building more resilient communities that can address the unique situations across the United States, factors integral to community resilience include the importance of social networks, the value of including community voice in the planning and execution of solutions, and the co-benefits of institutional readiness to address the physical, health, and social needs of impacted communities. These remain hard to quantify.[127,128]

Description of confidence and likelihood

There is *high confidence* that climate change is disproportionately affecting the health of children, older adults, low-income communities, communities of color, tribal and Indigenous communities, and many other distinct populations. And there is *high confidence* that some of the most vulnerable populations experience greater barriers to accessing resources, information, and tools to build resilience.

Key Message 3

Adaptation Reduces Risks and Improves Health

Proactive adaptation policies and programs reduce the risks and impacts from climate-sensitive health outcomes and from disruptions in healthcare services (*medium confidence*). Additional benefits to health arise from explicitly accounting for climate change risks in infrastructure planning and urban design (*low confidence*).

Description of evidence base

Health adaptation is taking place from local to national scales.[129,148,174] Because most of the health risks of climate change are also current public health problems, strengthening standard health system policies and programs, such as monitoring and surveillance, are expected to be effective in the short term in addressing the additional health risks of climate change. Modifications to explicitly incorporate climate change are important to ensure effectiveness as the climate continues to change. Incorporating environmentally friendly practices into healthcare and infrastructure can promote resilience.[151]

Major uncertainties

Overall, while there is considerable evidence of the effectiveness of public health programs,[110,129,130] the effectiveness of policies and programs to reduce *future* burdens of climate-sensitive health outcomes in a changing climate can only be determined over coming decades. The relatively short time period of implementing health adaptation programs means uncertainties remain about how to best incorporate climate change into existing policies and programs to manage climate-sensitive health outcomes and about which interventions will likely be most effective as the climate continues to change.[174,175] For example, heat wave early warning and response systems save lives, but it is not clear which components most effectively contribute to morbidity and mortality reduction.

Description of confidence and likelihood

There is *medium confidence* that with sufficient human and financial resources, adaptation policies and programs can reduce the current burden of climate-sensitive health outcomes.[110,151,176,177] There is *low confidence* that the incorporation of health risks into infrastructure and urban planning and design will likely decrease climate-sensitive health impacts.

Key Message 4

Reducing Greenhouse Gas Emissions Results in Health and Economic Benefits

Reducing greenhouse gas emissions would benefit the health of Americans in the near and long term (*high confidence*). By the end of this century, thousands of American lives could be saved and hundreds of billions of dollars in health-related economic benefits gained each year under a pathway of lower greenhouse gas emissions (*likely*, *medium confidence*).

Description of evidence base

Benefits of mitigation associated with air quality, including co-benefits of reducing greenhouse gas emissions, can be found in Chapter 13: Air Quality. This Key Message is consistent with and inclusive of those findings.

Multiple individual lines of evidence across several health topic areas demonstrate significant benefits of greenhouse gas emission reductions, with health impacts and health-related costs reduced by approximately half under RCP4.5 compared to RCP8.5 by the end of the century, based on comprehensive multisector quantitative analyses of economic impacts projected under consistent scenarios (Ch. 13: Air Quality).[37,157,158,159,160,161,162,163,164,165,166,167] The economic benefits of greenhouse gas emissions reductions to the health sector could be on the order of hundreds of billions of dollars annually by the end of the century.

Heat: Greenhouse gas emission reductions under RCP4.5 could substantially reduce the annual number of heat wave days (for example, by 21 in the Northwest and by 43 in the Southeast by the end of the century);[161] the number of high-mortality heat waves;[162,168] and heat wave intensities.[161,168] The EPA (2017)[157] estimated city-specific relationships between daily deaths (from all causes) and extreme temperatures based on historical observations that were combined with the projections of extremely hot and cold days (average of three years centered on 2050 and 2090) using city-specific extreme temperature thresholds to project future deaths from extreme heat and cold under RCP8.5 and RCP4.5 in five global climate models (GCMs). In 49 large U.S. cities, changes in extreme temperatures are projected to result in over 9,000 premature deaths per year under RCP8.5 by the end of the century without adaptation ($140 billion each year); under RCP4.5, more than half these deaths could be avoided annually ($60 billion each year).[157]

Labor productivity: Hsiang et al. (2017)[167] and the EPA (2017)[157] estimated the number of labor hours from changes in extreme temperatures using dose–response functions for the relationship between temperature and labor from Graff Zivin and Neidell (2014).[169] Under RCP8.5, almost 2 billion labor hours are projected to be lost annually by 2090 from the impacts of extreme heat and cold, costing an estimated $160 billion in lost wages. The Southeast[164,170] and Southern Plains are projected to experience high impacts, with labor productivity in high-risk sectors projected to decline by 3%. Some counties in Texas and Florida are projected to experience more than 6% losses in annual labor hours by the end of the century.[157,160]

Vector-borne disease: Belova et al. (2017)[37] and the EPA (2017)[157] define health impact functions from regional associations between temperatures and the probability of above-average West Nile neuroinvasive disease (WNND) incidence to estimate county-level expected WNND incidence rates for a 1995 reference period (1986–2005) and two future years (2050: 2040–2059 and 2090: 2080–2099) using temperature data from five GCMs. Annual national cases of WNND are projected to more than double by 2050 due to increasing temperatures, resulting in approximately $1 billion per year in hospitalization costs and premature deaths. In 2090, an additional 3,300 annual cases are projected under RCP8.5, with $3.3 billion per year in costs. Greenhouse gas emission reductions under RCP4.5 could avoid approximately half these cases and costs.

Water quality: Chapra et al. (2017)[165] and the EPA (2017)[157] evaluate the biophysical impacts of climate change on the occurrence of cyanobacterial harmful algal blooms in the contiguous United States using models that project rainfall runoff, water demand, water resources systems, water quality, and algal growth. In 2090, warming under RCP8.5 is projected to increase the length of time that recreational waters have concentrations of harmful algal blooms (cyanobacteria) above the recommended public health threshold by one month annually; greenhouse gas emissions under RCP4.5 could reduce this by two weeks.

Food safety and nutrition: There is limited evidence quantifying specific health outcomes or economic impacts of reduced food safety and nutrition.

Major uncertainties

While projections consistently indicate that changes in climate are expected to have negative health consequences, quantifying specific health outcomes (for example, number of cases, number of premature deaths) remains challenging, as noted in Key Message 1. Economic estimates only partially capture and monetize impacts across each health topic area, which means that damage costs are likely to be an undervaluation of the actual health impacts that would occur under any given scenario. Economic estimates in this chapter do not include costs to the healthcare system.

Description of confidence and likelihood

There is a *high confidence* that a reduction in greenhouse gas emissions would benefit the health of Americans. There is *medium confidence* that reduced greenhouse gas emissions under RCP4.5

compared to RCP8.5 will *likely* reduce lost labor hours by almost half and avoid thousands of premature deaths and illnesses projected each year from climate impacts on extreme heat, ozone and aeroallergen levels (Ch. 13: Air Quality), and West Nile neuroinvasive disease. There is *medium confidence* that the economic benefits of greenhouse gas emissions reductions in the health sector could *likely* be on the order of hundreds of billions of dollars each year by the end of the century. Including avoided or reduced benefits of risks that are difficult to quantify, such as mental health or long-term health consequences, would increase these estimates.

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15 Tribes and Indigenous Peoples

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15 Tribes and Indigenous Peoples

Wind River Indian Reservation students collect seeds for a land restoration project.

Key Message 1

Indigenous Livelihoods and Economies at Risk

Climate change threatens Indigenous peoples' livelihoods and economies, including agriculture, hunting and gathering, fishing, forestry, energy, recreation, and tourism enterprises. Indigenous peoples' economies rely on, but face institutional barriers to, their self-determined management of water, land, other natural resources, and infrastructure that will be impacted increasingly by changes in climate.

Key Message 2

Physical, Mental, and Indigenous Values-Based Health at Risk

Indigenous health is based on interconnected social and ecological systems that are being disrupted by a changing climate. As these changes continue, the health of individuals and communities will be uniquely challenged by climate impacts to lands, waters, foods, and other plant and animal species. These impacts threaten sites, practices, and relationships with cultural, spiritual, or ceremonial importance that are foundational to Indigenous peoples' cultural heritages, identities, and physical and mental health.

Key Message 3

Adaptation, Disaster Management, Displacement, and Community-Led Relocations

Many Indigenous peoples have been proactively identifying and addressing climate impacts; however, institutional barriers exist in the United States that severely limit their adaptive capacities. These barriers include limited access to traditional territory and resources and the limitations of existing policies, programs, and funding mechanisms in accounting for the unique conditions of Indigenous communities. Successful adaptation in Indigenous contexts relies on use of Indigenous knowledge, resilient and robust social systems and protocols, a commitment to principles of self-determination, and proactive efforts on the part of federal, state, and local governments to alleviate institutional barriers.

Executive Summary

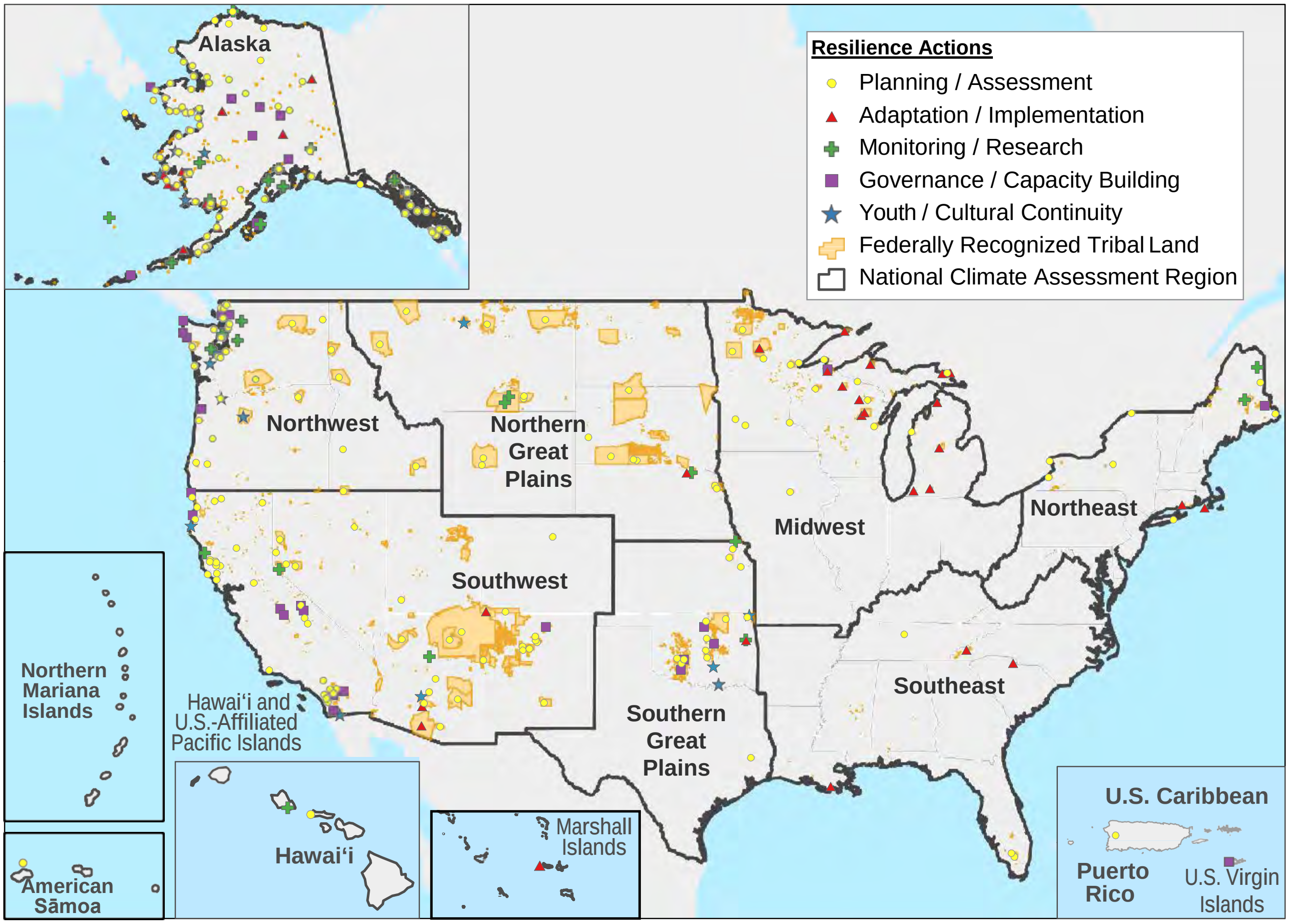
Indigenous peoples in the United States are diverse and distinct political and cultural groups and populations. Though they may be affected by climate change in ways that are similar to others in the United States, Indigenous peoples can also be affected uniquely and disproportionately. Many Indigenous peoples have lived in particular areas for hundreds if not thousands of years. Indigenous peoples' histories and shared experience engender distinct knowledge about climate change impacts and strategies for adaptation. Indigenous peoples' traditional knowledge systems can play a role in advancing understanding of climate change and in developing more comprehensive climate adaptation strategies.

Observed and projected changes of increased wildfire, diminished snowpack, pervasive drought, flooding, ocean acidification, and sea level rise threaten the viability of Indigenous peoples' traditional subsistence and commercial activities that include agriculture, hunting and gathering, fisheries, forestry, energy, recreation, and tourism enterprises. Despite institutional barriers to tribal self-determination stemming from federal trust authority over tribal trust lands, a number of tribes have adaptation plans that include a focus on subsistence and commercial economic activities. Some tribes are also pursuing climate mitigation actions through the development of renewable energy on tribal lands.

Climate impacts to lands, waters, foods, and other plant and animal species threaten cultural heritage sites and practices that sustain intra- and intergenerational relationships built on sharing traditional knowledges, food, and ceremonial or cultural objects. This weakens place-based cultural identities, may worsen historical trauma still experienced by many Indigenous peoples in the United States, and adversely affects mental health and Indigenous values-based understandings of health.

Throughout the United States, climate-related disasters are causing Indigenous communities to consider or actively pursue relocation as an adaptation strategy. Challenges to Indigenous actions to address disaster management and recovery, displacement, and relocation in the face of climate change include economic, social, political, and legal considerations that severely constrain their abilities to respond to rapid ecological shifts and complicate action toward safe and self-determined futures for these communities.

Indigenous Peoples' Climate Initiatives and Plans



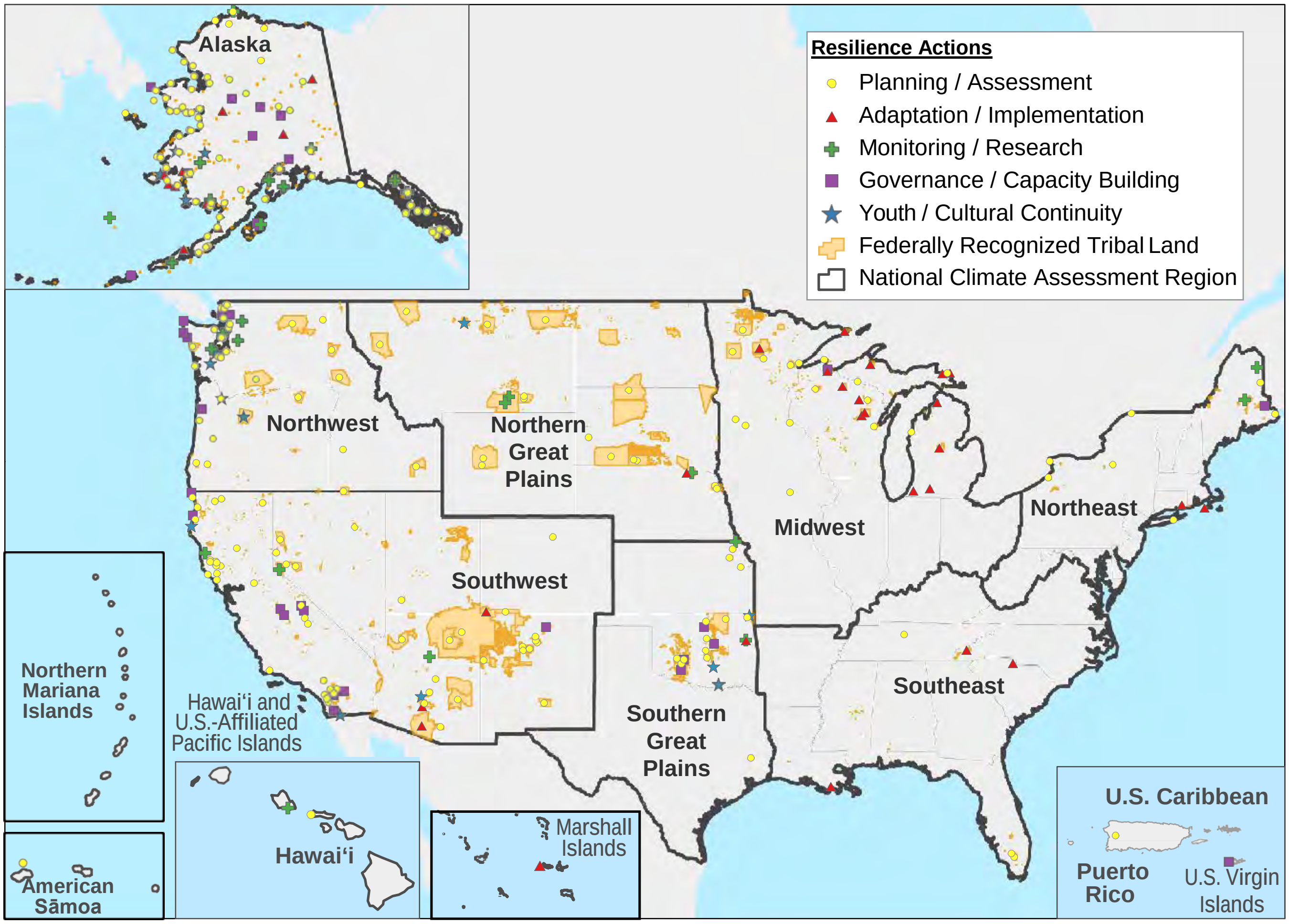
Many Indigenous peoples are taking steps to adapt to climate change impacts. Search the online version of this map by activity type, region, and sector to find more information and links to each project: https://biamaps.doi.gov/nca/. To provide feedback and add new projects for inclusion in the database, see: https://www.bia.gov/bia/ots/tribal-resilience-program/nca/. Thus far, tribal entities in the Northwest have the highest concentration of climate activities (Ch. 24: Northwest). For other case studies of selected tribal adaptation activities, see both the Institute for Tribal Environmental Professionals' Tribal Profiles,[1] and Tribal Case Studies within the U.S. Climate Resilience Toolkit.[2,3] *From Figure 15.1 (Source: Bureau of Indian Affairs).*

State of the Sector

Indigenous peoples in the United States are diverse and distinct political and cultural groups and populations. Though they may be affected by climate change in ways that are similar to others in the United States, Indigenous peoples can also be affected uniquely and disproportionately. Many Indigenous peoples have lived in particular areas for hundreds if not thousands of years, and their cultures, spiritual practices, and economies have evolved to be adaptive to local seasonal and interannual environmental changes.[4] Thus, Indigenous knowledge systems differ from those of non-Indigenous peoples who colonized and settled the United States, and they engender distinct knowledge about climate change impacts and strategies for adaptation.[4,5,6] Indigenous knowledges, accumulated over generations through direct contact with the environment, broadly refer to Indigenous peoples' systems of observing, monitoring, researching, recording, communicating, and learning and their social adaptive capacity to adjust to or prepare for changes. One of these knowledge systems that is often referred to in the context of climate change is traditional ecological knowledge, which primarily focuses on the relationships between humans, plants, animals, natural phenomena, and the landscape.

A growing number of tribal governments and intertribal organizations are developing climate adaptation plans, with some in the early stages of implementation. Many Indigenous peoples support their own technical staff who study and manage broad sectoral programs and issues, which now include climate change adaptation planning and implementation. To this end, Indigenous peoples regularly collaborate with climate scientists and other professionals working in academic, governmental, and nongovernmental organizations, especially in the use of downscaled (local-scale) climate information and tools that have become more available in recent years. While not comprehensive, Figure 15.1 identifies over 800 activities across all regions featured in this report that Indigenous peoples and their partners have undertaken in the last decade. This map catalogues several broad types of adaptation projects: planning and assessment, adaptation and implementation, monitoring and research, governance and capacity building, and youth engagement and cultural continuity. Collectively, these activities span many sectors and all regions of the country. Projects are primarily planning related and include adaptation planning, vulnerability assessments, and professional development to increase the skills and capacity of tribal staff and management.

These actions in response to climate change occur in a broader context in which Indigenous peoples today, including federally and non-federally recognized tribes, are continuing to seek and exercise self-determination to define their own political status and to freely pursue economic, social, and cultural development. Limits to Indigenous self-determined action can intensify vulnerability to climate change in many cases. In the 19th century, the United States established a trust responsibility to federally recognized tribes, which is a legal and fiduciary obligation to honor their treaty rights and support tribal self-determination. The trust responsibility is meant to include financial support and the provision of essential services, such as education, health, public safety, and environmental protection. However, trust responsibility also authorizes the U.S. Government to manage tribal lands and the revenues generated from these lands. This can limit self-determination in cases where the U.S. Government's management of tribes' trust assets lacks accountability or does not adequately fulfill the federal policy requirement of consultation with tribes on a sovereign government-to-government basis.



Indigenous Peoples' Climate Initiatives and Plans

Figure 15.1: Many Indigenous peoples are taking steps to adapt to climate change impacts. Search the online version of this map by activity type, region, and sector to find more information and links to each project: https://biamaps.doi.gov/nca/. To provide feedback and add new projects for inclusion in the database, see: https://www.bia.gov/bia/ots/tribal-resilience-program/nca/. Thus far, tribal entities in the Northwest have the highest concentration of climate activities (Ch. 24: Northwest). For other case studies of tribal adaptation activities, see both the Institute for Tribal Environmental Professionals' Tribal Profiles,[1] and Tribal Case Studies within the U.S. Climate Resilience Toolkit.[2,3] Source: Bureau of Indian Affairs.

Non-federally recognized tribes, Native Hawaiians, and other Indigenous peoples also have rights to self-determination to protect their traditional knowledges, cultures, and ancestral lands, while developing their economies and providing community services; but they do so without reservation lands, treaty rights, and federal provision of essential services, among other rights, authorities, and capacities to which federally recognized tribes can appeal.

This chapter expands on the Indigenous Peoples chapter from the Third National Climate Assessment[7] and on Indigenous contributions to earlier assessments, with a focus on three major themes as expressed in the Key Messages that were not discussed in previous assessments in as much detail. This chapter recognizes that Indigenous communities of the United States represent diverse cultures, histories, governments, and environments and that their individual experiences with climate change will differ. In addition, this chapter attempts to provide more information than previous assessments about Indigenous issues in the Pacific Islands and the Caribbean regions, although in some cases, especially for the Caribbean, the literature is sparse. Thus, uniform, national-scale quantitative metrics of risk across this broad spectrum of conditions are not available. Nevertheless, Indigenous peoples and their partners are building comprehensive understandings of local climate change risks and taking steps to adapt to these threats.

Key Message 1

Indigenous Livelihoods and Economies at Risk

Climate change threatens Indigenous peoples' livelihoods and economies, including agriculture, hunting and gathering, fishing, forestry, energy, recreation, and tourism enterprises. Indigenous peoples' economies rely on, but face institutional barriers to, their self-determined management of water, land, other natural resources, and infrastructure that will be impacted increasingly by changes in climate.

While the lands, waters, and other natural resources of Indigenous peoples hold sacred cultural significance, they also play a principal role in ensuring the viability of these communities' economies and livelihoods.[5,8] Tribal trust lands provide habitat for more than 525 species listed under the Endangered Species Act, and more than 13,000 miles of rivers and 997,000 lakes are located on federally recognized tribal lands.[9] For many tribes, despite this endowment of natural resources, median household income is only 69% of the national average median income.[10] Challenges to economic development for federally recognized tribes are in part related to institutional barriers to tribal self-determination stemming from federal trust authority over tribal trust lands.[8,11] Due to past federal polices, including the Dawes Act (1887) and Indian Reorganization Act (1934), most reservation lands today constitute a checkerboard pattern of trust and fee-simple (private) land ownership, highly fractionated government trust lands with many owners, and trust lands subject to ongoing federal oversight in resource management decisions.[12,13,14,15] These issues are complicated further when multiple or overlapping federal, state, or local government jurisdictions are involved.[16]

Historical and ongoing federal oversight of natural resource management on tribal lands can, in some cases, hinder growth in tribal and individual natural resource-based business enterprises, because tribes lack the autonomy to determine their own property rights and related institutions.[17,18] Similar critiques of historic and contemporary U.S. policy have been identified in studies of Indigenous climate change adaptation.[19,20] Non-federally recognized tribes lack legal status to qualify for federal funding and economic development support, though some are eligible for state support.[21] Funding limitations are often identified as a barrier to the planning or implementation of climate adaptation or mitigation actions,[22] which suggests that increased economic revenues could create opportunities for tribes to choose to pursue climate actions.

Many Indigenous peoples continue to express their cultural relationships with ancestral lands through traditional subsistence economies. Such economies rely on local natural resources for personal use (such as food, shelter, fuel, clothing, tools, transportation, and arts and crafts) and for trade, barter, or sharing. Climate change threatens these delicately balanced subsistence networks by, for example, changing the patterns of seasonal timing and availability of culturally important species in traditional hunting, gathering, and fishing areas[4,5,7,22,23,24,25,26,27,28,29,30,31,32] Each of the Fourth National Climate Assessment's regional chapters includes at least one example of climate impacts or adaptation related to Indigenous subsistence species or practices.

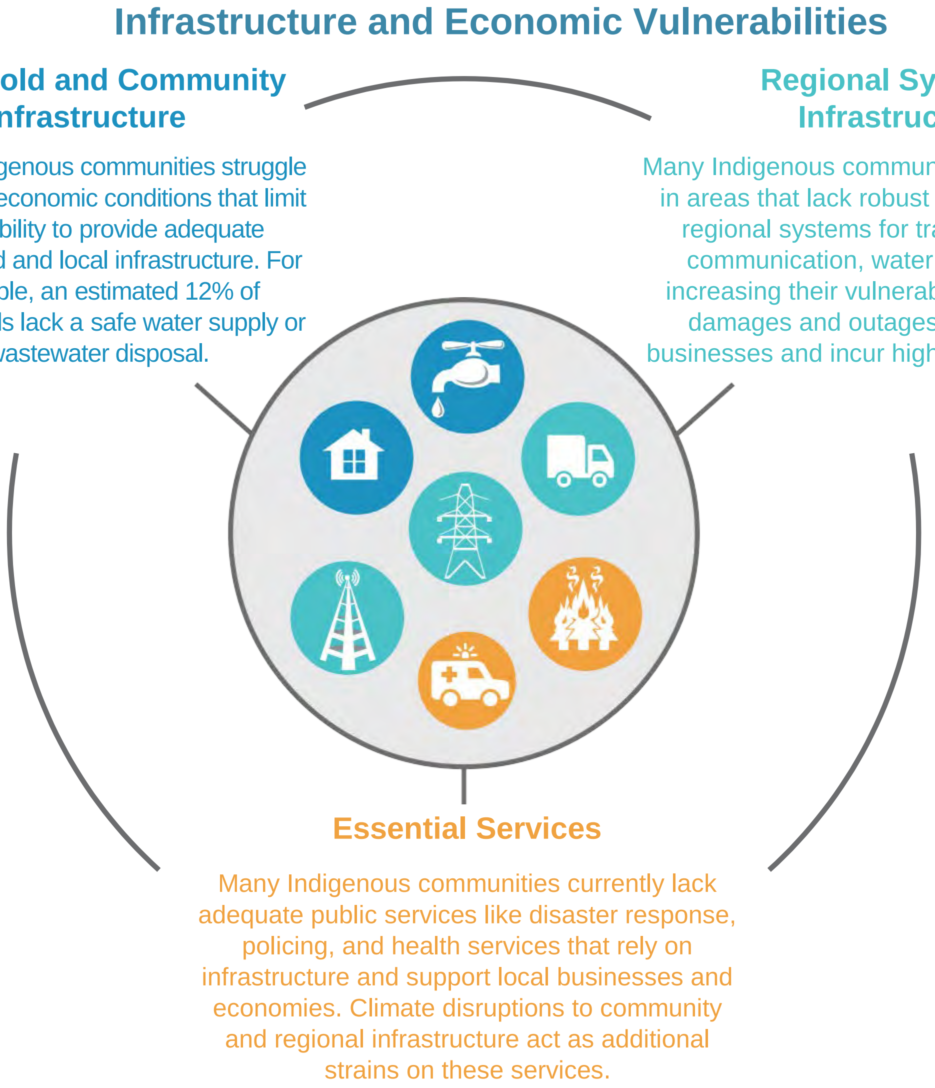
Most Indigenous peoples across all regions of the United States pursue a mix of traditional subsistence and commercial sector activities that include agriculture, hunting and gathering, fisheries, forestry, energy, recreation, and tourism enterprises.[5,22,33,34,35] Observed and projected changes of increased wildfire, diminished snowpack, pervasive drought, flooding, ocean acidification, and sea level rise (Ch. 2: Climate) threaten the viability of each of these enterprises.[22,29,33,36,37,38,39,40,41,42,43,44,45,46,47,48,49,50,51,52] Tribal casino properties, for example, often include water-dependent recreational amenities that, due to pervasive drought, are impacted by changes to local water regimes,[53] and some tribes account for this in their adaptation plans, such as the Confederated Salish and Kootenai Tribes[54] and the Lummi Nation.[55] In addition, Indigenous agriculture is already being adversely affected by changing patterns of flooding, drought, dust storms, and rising temperatures, with future projections varying by region but indicating increased soil erosion and irrigation water demand and decreased crop quality and animal herd sizes (Ch. 25: Southwest, KM 4 and 6).[22,41,52,56,57,58] Some tribes include consideration of subsistence and commercial economic resources in their adaptation plans. For example, the 1854 Treaty Authority Adaptation Plan,[59] which includes the Bois Forte, Fond du Lac, and Grand Portage Tribes, provides detailed adaptation strategies customized to protect and sustain walleye, sturgeon, moose, and wild rice, among others (Ch. 21: Midwest). Similarly, the Confederated Tribes of the Umatilla Indian Reservation[60] have identified climate risks to salmon, elk, deer, roots, and huckleberry habitat (Ch. 24: Northwest, KM2).

Federal and state legal frameworks and regulatory actions can compound physical climate change stressors on Indigenous peoples' subsistence economies and act as a barrier to climate change adaptation. For example, federal and state fish and wildlife regulations, such as endangered species listings, are meant to respond to species population declines that can be exacerbated by climate change (Ch. 7: Ecosystems), but they can further stress Indigenous subsistence economies that have traditionally relied on those species.[61,62,63] Such regulatory actions taken without the input of Indigenous peoples can limit traditional sources of income, such as arts and crafts that are part of Indigenous economies. For example, some Alaska Natives utilize skins, furs, and walrus tusks to support local subsistence economies and to produce clothing and crafts that support local tourism.[64,65]

Members of the Oglala Lakota Nation plant climate-resilient tree species on the Pine Ridge Indian Reservation in South Dakota. Photo credit: © Alex Basaraba (www.alexbasaraba.com).

Another recognized barrier to economic self-determination and climate adaptation for federally recognized tribes with resource constraints is the costly and lengthy process to quantify, secure, and use appropriated water rights.[7,41,53,66,67,68] This is particularly the case in the arid western United States, where the majority of reservation land acreage is located and where prior appropriation doctrine is the primary mechanism for allocating scarce water resources.[66] As water becomes more scarce and regional demands increase, the quantification of water rights is viewed by many as necessary to design and plan adaptation strategies that secure water for various uses: cultural, municipal, recreational, agricultural, fisheries, and aquatic resources, among others.[4,19,58,66,67,69,70,71] To date, approximately 30 reservations have engaged in water rights settlements,[72] and while research shows that water rights quantification can positively affect tribal economies, additional analysis is necessary to better understand these effects.[66]

Infrastructure and linked systems that support Indigenous economies and livelihoods are at risk from more frequent or intense heavy downpours, floods, heat waves, wildfires, and droughts, as well as higher sea levels and storm surges.[19,49,73] As shown in Figure 15.2, Indigenous peoples are vulnerable to infrastructure disruptions that can occur at the level of an individual household (for example, housing and sanitary water supply); within larger regional, integrated systems (such as for power, transportation, and telecommunication) (Ch. 17: Complex Systems); or within human systems that rely on such infrastructure to provide other essential services (such as emergency medical response). This vulnerability is partly due to long-standing, unmet infrastructure needs and deferred maintenance challenges.[74] For example, many Indigenous communities lack sufficient water delivery and treatment facilities and the operating capital needed to maintain and/or improve those facilities.[41,75,76]



Infrastructure and Economic Vulnerabilities

Household and Community Infrastructure

Many Indigenous communities struggle with poor economic conditions that limit their ability to provide adequate household and local infrastructure. For example, an estimated 12% of households lack a safe water supply or wastewater disposal.

Regional Systems Infrastructure

Many Indigenous communities are located in areas that lack robust and redundant regional systems for transportation, communication, water, and power, increasing their vulnerability to system damages and outages that disrupt businesses and incur high costs to repair.

Essential Services

Many Indigenous communities currently lack adequate public services like disaster response, policing, and health services that rely on infrastructure and support local businesses and economies. Climate disruptions to community and regional infrastructure act as additional strains on these services.

Figure 15.2: Communities' economic potential and livelihoods rely on infrastructure and the essential services it delivers, and many tribes and Indigenous communities already face acute infrastructure challenges that make them highly vulnerable to climate impacts.[22] Indigenous peoples along the coasts and in the islands, the Southwest, and Alaska have experienced the most extensive infrastructure-related impacts thus far (Ch. 8: Coastal; Ch. 20: U.S. Caribbean; Ch. 25: Southwest; Ch. 26: Alaska; Ch. 27: Hawai'i & Pacific Islands). Source: USGCRP.

Indigenous peoples also have unmet needs and challenges in the energy sector. The evolution of the federal trust doctrine, and its associated timely and costly regulatory oversight of resource use on tribal trust lands, challenges federally recognized tribes' ability to secure outside investments in energy and related infrastructure development (Ch. 4: Energy, KM 3; Ch. 29: Mitigation).[77,78] In addition, non-tribal entities operate the majority of energy development on tribal land, reducing opportunities for tribal workforce development and capacity building for self-directing future energy projects.[79] Still, energy development, particularly renewable energy, that is implemented in accordance with Indigenous values holds promise as a source of revenue, employment, and economic self-determination.[22,80] While not all Indigenous communities support energy development due to concerns about cultural and environmental impacts, there are a number of examples of growing interest in renewable energy.[79] The Pueblo of Jemez, for example, has developed the Nation's first utility-scale solar project on tribal lands, and other tribes view renewable energy as a key strategy for climate mitigation.[22] Tribes have also identified small-scale distributed electricity generation systems and energy efficiency as supporting their climate adaptation goals through increased energy independence.[22,79]

Key Message 2

Physical, Mental, and Indigenous Values-Based Health at Risk

Indigenous health is based on interconnected social and ecological systems that are being disrupted by a changing climate. As these changes continue, the health of individuals and communities will be uniquely challenged by climate impacts to lands, waters, foods, and other plant and animal species. These impacts threaten sites, practices, and relationships with cultural, spiritual, or ceremonial importance that are foundational to Indigenous peoples' cultural heritages, identities, and physical and mental health.

Physical health risks and impacts to Indigenous peoples are the same as those faced by the general U.S. population (Ch. 14: Human Health); however, certain factors, known as the social determinants of health, are unique and contribute to the increased vulnerability of Indigenous peoples to adverse and potentially severe or fatal health outcomes (Box 15.1). Conventional Western science approaches to measuring and analyzing Indigenous health, adaptive capacity, health disparities, and environmental justice issues typically do not capture many of the key elements of health and resilience that are important to Indigenous populations.[81,82,83,84,85,86] These elements emphasize non-physiological aspects of health, which include concepts related to community connection, natural resources security, cultural use, education and knowledge, self-determination and autonomy, and resilience.[83,84] For example, the Swinomish Indian Tribal Community has used shellfish beds and shoreline armoring as indicators to evaluate health in the context of a changing climate.[81]

Box 15.1: Social Determinants of Indigenous Health

A number of health risks are higher among Indigenous populations due in part to historic and contemporary social, political, and economic factors that can affect conditions of daily life and limit resources and opportunities for leading a healthy life.[87] Many Indigenous peoples still experience historical trauma associated with colonization, removal from their homelands, and loss of their traditional ways of life, and this has been identified as a contributor to contemporary physical and mental health impacts.[88,89] Other factors include institutional racism, living and working circumstances that increase exposure to health threats, and limited access to healthcare services.[87,89] Though local trends may differ across the country, in general, Indigenous peoples have disproportionately higher rates of asthma,[90] cardiovascular disease,[91,92,93,94] Alzheimer's disease or dementia,[95,96] diabetes,[97] and obesity.[93] These health disparities have direct linkages to increased vulnerability to climate change impacts, including changes in the pollen season and allergenicity, air quality, and extreme weather events (Ch. 14: Human Health).[98] For example, diabetes prevalence within federally recognized tribes is about twice that of the general U.S. population.[97] People with diabetes are more sensitive to extreme heat and air pollution, and physical health impacts can also influence mental health.[9]

Indigenous peoples have a unique and interconnected relationship with the natural environment that is integral to their place-based social, cultural, and spiritual identity; intangible cultural heritage (traditions or living expressions transmitted and inherited through generations); and subsistence practices and livelihoods.[61,82,87,99,100] Climate change impacts to ecosystems (Ch. 7: Ecosystems) alter the relationships between humans and animals, between individuals, and within and between communities; these relationships are central to Indigenous physical, mental, and spiritual health.[82,86,101,102] This alteration in relationships occurs when individuals, families, and communities (within and between generations) are less able or not able to share traditional knowledges about the natural environment (such as where and when to harvest or hunt), food, and ceremonial or cultural objects, among other things, because the knowledge is no longer accurate or traditional foodstuffs and species are less available due to climate change. For many Indigenous peoples, the act of sharing is fundamental to these intra- and intergenerational relationships, sustains cultural practices and shared identity, and underpins subsistence practices.[44,103] A projected health-related consequence of reduced or lost access to the knowledge, experiences, and relationships built on sharing is increased food insecurity for households reliant on subsistence practices.[61] For example, in Alaska, changes in sea ice coverage and thickness and the timing of ice formation (Ch. 9: Oceans; Ch. 26: Alaska) can lead to decreased access to hunting and fishing areas, which can mean people are unable to access food sources (that is, loss of cultural use.[81] This can then result in lost opportunity for the social components of these activities, including reduced community connection (e.g., Donatuto et al. 2014[81]),less food and knowledge sharing, and diminished relationship building.[44,61]

Communities that rely on the natural environment for sustenance and livelihoods are at increased risk for adverse mental health outcomes related to climate change.[104] Many Indigenous communities share a focus on relationships between people and wildlife and on a respect for natural resources.[29,81,105] Climate impacts to lands, waters, foods, and other plant and animal species undermine these relationships, affect place-based cultural heritages and identities, and may worsen the historical trauma still experienced by many Indigenous peoples.[86,101,102] For example, in

Arctic Indigenous communities, changing wildlife and vegetation patterns are disrupting traditional and subsistence practices and have been associated with increased rates of mood and anxiety disorders; strong emotional responses; and loss of connections to homeland, social networks, and self-worth.[82,101] Additionally, climate impacts that degrade water quality can adversely affect sacred water sources and aquatic species on which subsistence livelihoods and associated relationships are based, increasing the risk of mental health impacts in addition to the well-studied physical health concerns.[53,71] Damage to cultural heritage sites from climate change can affect mental health through impacts to cultural, economic, and social relationships.[106] Media imagery and reports or stories of climate risks and vulnerability also lead to psychological trauma or increased anger, anxiety, depression, fear, and stress.[107] These impacts can intensify existing social stressors, such as loss of jobs and social connections, loss of social support, and family distress.[101,104]

Climate change adaptation measures can reduce physiological vulnerability to health risks; to date, most observational evidence comes from behavioral and public health responses to extreme heat.[108,109,110,111] Organizations including the National Indian Health Board and the Alaska Native Tribal Health Consortium have ongoing efforts to increase Indigenous adaptive capacity specifically for health. Some tribes have climate vulnerability assessments that acknowledge the role of traditional subsistence species, or First Foods, as an essential aspect of health and tribal resilience; for example, the Yurok Tribe assesses the role of salmon in community health,[112] and the Confederated Tribes of the Umatilla Indian Reservation[60] discuss climate risks to salmon, elk, deer, roots, and huckleberry habitat (Ch. 24: Northwest, KM 2). In the Republic of the Marshall Islands, a community-led planning process known as Reimaanlok incorporates traditional knowledge and facilitates local self-determination to support shared goals of climate adaptation, natural resource management, and community health.[85]

Key Message 3

Adaptation, Disaster Management, Displacement, and Community-Led Relocations

Many Indigenous peoples have been proactively identifying and addressing climate impacts; however, institutional barriers exist in the United States that severely limit their adaptive capacities. These barriers include limited access to traditional territory and resources and the limitations of existing policies, programs, and funding mechanisms in accounting for the unique conditions of Indigenous communities. Successful adaptation in Indigenous contexts relies on use of Indigenous knowledge, resilient and robust social systems and protocols, a commitment to principles of self-determination, and proactive efforts on the part of federal, state, and local governments to alleviate institutional barriers.

Indigenous peoples have a long and rich history of adaptation to climate variability[1,71,113,114] that is rooted in their dynamic relationships to the natural environment.[115] However, the ability of Indigenous peoples to anticipate and respond to climate change is affected by economic, social, political, and legal considerations that severely constrain their abilities to consider and respond to rapid ecological shifts. Despite the many examples of Indigenous peoples undertaking climate vulnerability assessments and adaptation planning (see Figure 15.1 for links to information on current adaptation efforts), as the pace of ecological changes increases with climate change, and sociopolitical obstacles to implementing responses continue to exist, there are challenges and barriers to adaptation.[116,117]

Incorporating Indigenous Knowledges in Adaptation

Indigenous knowledge systems can play a role in advancing understanding of climate change and in developing more comprehensive climate adaptation strategies,[6,7,118] in part because they focus on understanding relationships of interdependency and involve multigenerational knowledge of ecosystem phenology (the study of cyclic and seasonal natural phenomena)[6,119,120] and ecological shifts.[25,121] For example, Inupiat residents in Alaska have identified cyclical patterns of coastal erosion, and their understanding of how quickly and in which direction wind and wave energy reaches the coast can help communities prone to flooding.[122] Indigenous adaptation planning, including considerations of issues such as flooding and water rights, benefits from a greater focus on participatory planning in natural resource management.[19,22,123,124,125,126] This planning incorporates local knowledge and values from conception through implementation[127,128,129] in ways that ensure the protection of Indigenous knowledges and Indigenous peoples' rights not to share sensitive information.[22] In this way, traditional ways of knowing are contributing to sustainable land management practices under changing environmental conditions.[130,131,132,133] For example, the Wabanaki Nations of Maine work closely with local researchers, foresters, and landowners as part of the Cooperative Emerald Ash Borer Project to precisely catalogue and map the decline of the native black ash deciduous trees on which these communities rely for economic, cultural, and spiritual practices. The cooperative leverages Indigenous knowledge of environmental history as it relates to the invasive emerald ash borer beetle.[131] Additionally, the Nez Perce Tribe employs Indigenous knowledges as part of an initiative to enhance local salmon populations that have been in decline (Ch. 24: Northwest, KM 2). For more on Indigenous knowledges, see the regional chapters in this assessment.

Limited Access to Traditional Territory and Decision-Making

Historically in North America, Indigenous peoples occupied vast amounts of land and had access to a wide range of natural resources. Under these conditions, high mobility provided a robust response to changing environmental conditions,[122] but such options today are limited or nonexistent. Multiple considerations, such as whether tribes have corporate status, federal recognition, reservation lands, off-reservation resource rights, specified water rights, access to Ceded Territories and traditional resources, among many others, affect how Indigenous communities develop and implement climate adaptation efforts.[22] Specifically, limitations on the abilities of tribal individuals, communities, businesses, and governing bodies to manage land, participate in policymaking, and access various resources can act as barriers to climate adaptation efforts. Federally recognized tribes have access to a distinct array of resources, programs, and legal authorities, yet they still face numerous limitations in their abilities to implement adaptive strategies. For example, when ecosystems or species' habitats or migration routes shift due to changes in climate, tribes' rights to gather, hunt, trap, and fish within recognized areas are constrained by reservation or other legally defined borders, making adaptation more challenging.[22,40,48,134] This is also the case when federal or state regulations fail to prioritize Indigenous peoples' access to traditional resources. Tribes with noncontiguous reservation lands can be negatively impacted by non-tribal landowners who do not support climate adaptation efforts, and many Indigenous peoples lacking federal recognition often lack the autonomy, funding, and governmental support to address climate change.[31,48,135,136] Because of these and other considerations, decisions regarding natural resource use are often made without appropriate consultation and collaboration with Indigenous peoples,[19] a process that further inhibits local adaptive capacity.

Disaster Management

As in many communities, Indigenous peoples are experiencing climate change impacts from more frequent and severe weather events, including drought, heat waves, hurricanes, torrential downpours, and flooding (Ch. 2: Climate).[137] In recent years, the Federal Government has made amendments to disaster recovery laws that provide more autonomy to tribes in managing disaster recovery, including the Sandy Recovery Improvement Act of 2013, which grants tribes the authority to request a disaster declaration and assistance from the President, instead of relying on state authorities.[138] However, many tribes continue to face hurdles to disaster management and disaster risk reduction planning. A study of tribes' participation in the federally run and subsidized National Flood Insurance Program finds that, as of 2012, only 7% of tribal communities were participating in the program due to lack of information, limited local government capacity, and limited land jurisdiction.[139]

Risk management and feasible adaptation options are also limited by fundamental issues with federal disaster funding that can be especially prohibitive for tribes. Federal programs are designed to offer extensive emergency relief after disasters have occurred, but they have only limited funding for hazard mitigation or preparation for long-term environmental change.[140] Most slow-onset disasters, such as erosion, are absent from the Federal Government's primary disaster recovery legislation, the Stafford Act, making it particularly challenging to prepare for changing coastlines.[141,142] Additionally, the low population and rural contexts of many Indigenous communities limit the score they can receive in state and federal cost–benefit analyses, which also severely limits funding for disaster risk reduction.[140,143,144]

Displacement and Relocation

Many Indigenous peoples are now facing relocation due to climate-related disasters, more frequent coastal and riverine flooding, loss of land due to erosion, permafrost thawing, or compromised livelihoods caused by ecological shifts linked to climate change.[7,122,145,146,147] Throughout the 18th, 19th, and 20th centuries, Indigenous peoples were removed in large numbers from their homelands by settler colonial governments, leading, in many cases, to death, diaspora, and socioeconomic struggles. The historical context of forced relocations of Indigenous peoples emphasizes the need for relocation frameworks that protect self-determination.[120,144,146,148]

In various regions of the United States, communities of Indigenous peoples are considering relocation or actively pursuing relocation as an adaptation strategy, including communities in Alaska, the Southeast, the Pacific Islands, and the Pacific Northwest (Figure 15.3) (Ch. 19: Southeast; Ch. 24: Northwest; Ch. 26: Alaska; Ch. 27: Hawaiʻi & Pacific Islands). The complex barriers to adapting to these extreme circumstances continue to be the lack of statutes and regulations, legal authority, and governance structures that enable federal, state, and local actors to coordinate funding priorities and regulations.[7] For example, many tribal communities facing slow-onset disasters, as described above, fail to qualify for relocation funds because they have not been declared federal disaster areas. Also, because

Isle de Jean Charles, LA, and Kivalina, AK

Figure 15.3: These photos show aerial views of (left) Isle de Jean Charles, Louisiana, and (right) Kivalina, Alaska. As projections of sea level rise and coastal inundation are realized, many impacted communities are confronting political, ecological, and existential questions about how to adapt. Photo credits: (left) Ronald Stine; (right) ShoreZone (CC BY 3.0).

there is no single, comprehensive federal program to assist tribes with relocation efforts, tribes must rely on project-specific funding streams that are not designed for relocation initiatives and that often have conflicting requirements and priorities.[147] These barriers are even more challenging when tribes lack federal recognition.[146,149] Additionally, there is no clear platform through which communities can connect non-Indigenous scientific information with their own knowledge systems to inform local decision-making processes as to whether adaptation is best achieved through relocation or by protecting in place through capital investments such as flood management infrastructure.[150,151] Finally, even if relocation is agreed on and logistically feasible, the challenges associated with maintaining community and cultural continuity often undermine the objective of the adaptation strategy, and models for mitigating the impacts of relocation on cultural institutions are rare and difficult to replicate.[152]

Community Planning

Figure 15.4: Some tribal communities at risk of displacement from climate change are actively planning whole-community relocation strategies. As part of the resettlement of the tribal community of Isle de Jean Charles, residents are working with the Lowlander Center (a local, nongovernmental organization), the State of Louisiana, and others to finalize a plan that reflects the physical, sociocultural, and economic needs of the community. Photo credit: Louisiana Office of Community Development.

In the past few years, solutions have emerged to better address the need for community-driven relocations, but even these have proven more complex for tribal communities than originally expected. The state-recognized Isle de Jean Charles Band of Biloxi-Chitimacha-Choctaw of Louisiana, in partnership with the Lowlander Center (Figure 15.4), developed a community resettlement plan that was selected in 2016, in conjunction with the State of Louisiana's application to the National Disaster Resilience Competition, to receive funding from the U.S. Department of Housing and Urban Development. Due to restrictions on the funding included within the legislation and the tribe's lack of federal recognition, the state is managing the resettlement of the entire island community, which limits tribal authority over relocation plans. This arrangement exemplifies one way in which tribes are limited in deploying adaptation strategies when using funds that are not specifically designed to meet the unique needs of tribal communities (Ch. 19: Southeast). Though promising, this solution, to date, is a pilot program through a one-time competitive funding opportunity, and there is no planned ongoing support for other community-led resettlements. Outside of this pilot program, the most promising funding options for facilitating relocations away from changing coastlines are voluntary buyout programs offered by some local, state, and federal entities, but new research suggests that these are particularly ill-suited to tribes because of their focus on individual households, instead of community-wide relocations.[153] Central organizing institutions, such as the Denali Commission that is assessing relocation challenges for communities in rural Alaska, may help provide structure for joint state, federal, and tribal partnerships for pursuing safe, timely, and culturally appropriate relocation. More research would be required to properly assess whether these and other solutions would facilitate action toward safe and self-determined futures for these communities.

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Opening Image Credit

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Traceable Accounts

Process Description

The report authors developed this chapter through technical discussions of relevant evidence and expert deliberation via several meetings, teleconferences, and email exchanges between the spring of 2016 and June 2017. The authors considered inputs and comments submitted by the public in response to the U.S. Global Change Research Program's (USGCRP) Federal Register Notices, as well as public input provided through regional engagement workshops and engagement webinars. The author team also considered comments provided by experts within federal agencies through a formal interagency review process.

Additional efforts to solicit input for the chapter were undertaken in 2016–2017. The Bureau of Indian Affairs (BIA) worked with partners, the College of Menominee Nation, and the Salish Kootenai College to develop and execute an outreach plan for the chapter. This included awarding mini-grants for community meetings in the fall of 2016 and attending and presenting at tribally focused meetings such as the American Indian Higher Education Consortium 2016 Student Conference (March 2016), the Annual National Conference of the Native American Fish and Wildlife Society (May 2016), the National Tribal Forum on Air Quality (May 2016), the workshops of Rising Voices (2016, 2017), the Native Waters on Arid Lands Tribal Summit (November 2017), the BIA Tribal Providers Conference in Alaska (November 2017), and the Tribes & First Nations Summit (December 2017), among others. Additionally, through these tribal partners, the BIA provided 28 travel scholarships to interested tribal partners to attend and comment on the initial draft content of all regional chapters at the USGCRP's regional engagement workshops. Additional avenues to communicate during these formal open-comment periods included multiple webinars, website notices on the BIA Tribal Resilience Program page, and email notices through BIA and partner email lists. In particular, the BIA solicited comments from multiple tribal partners on the completeness of the online interactive version of the map in Figure 15.1. Chapter authors and collaborators also presented at interactive forums with tribal representatives, such as the National Adaptation Forum (2017), and in various webinars to extend awareness of formal requests for comment opportunities through the USGCRP and partners, such as the Pacific Northwest Tribal Climate Change Network. The feedback and reports from these activities were used to ensure that the Key Messages and supporting text included the most prominent topics and themes.

Key Message 1

Indigenous Livelihoods and Economies at Risk

Climate change threatens Indigenous peoples' livelihoods and economies, including agriculture, hunting and gathering, fishing, forestry, energy, recreation, and tourism enterprises (*very high confidence*). Indigenous peoples' economies rely on, but face institutional barriers to, their self-determined management of water, land, other natural resources, and infrastructure (*high confidence*) that will be impacted increasingly by changes in climate (*likely*, *high confidence*).

Description of evidence base

Multiple studies of Indigenous peoples in the United States provide consistent and high-quality evidence that climate change is both a current and future threat to Indigenous livelihoods and economies. The climate impacts on traditional subsistence economies and hunting and gathering activities have been extensively documented and consistently provide qualitative observational evidence of impacts.[4,5,7,22,23,24,25,26,27,28,29,31,32,44] There is also very robust documentation of observed adverse climate change related impacts to Indigenous commercial sector activities in agriculture, fishing, forestry, and energy,[22,29,33,36,37,39,40,41,42,43,44,45,46,47,48,49,73,154] as well as recreation, tourism, and gaming.[5,50,51,52,53] These sectors form the basis of most Indigenous economies in the United States.

Multiple studies also consistently identify funding constraints as barriers to the economic development of federally and non-federally recognized tribes,[21,22] as well as barriers that limit self-determination stemming from historical and ongoing federal oversight of natural resources on tribal trust lands,[8,11,17,18] including energy resources.[77,78] Multiple qualitative studies provide consistent and high-quality evidence of current vulnerabilities and challenges related to infrastructure and linked systems that support Indigenous economies and livelihoods.[19,22,49,73,74,76] Despite these challenges, there is consistent and high-quality evidence supporting the finding that energy development, particularly renewable energy, that is implemented in accordance with Indigenous values holds promise as a source of revenue, employment, economic self-determination, and climate mitigation and adaptation for Indigenous communities.[22,79,80]

The studies cited above consistently conclude that these impacts on livelihoods and economies will increase under future projections of climate change. However, methods for making these determinations vary, and quantitative or modeling results that are specific to Indigenous peoples in the United States are limited.

Major uncertainties

As with all prospective studies, there is some uncertainty inherent in modeled projections of future changes, including both global climate system models and economic sector models. In addition, none of the cited studies explicitly modeled the effects of climate adaptation actions in the relevant economic sectors and the extent to which such actions may reduce Indigenous vulnerabilities.

The literature currently lacks studies that attempt to quantify and/or monetize climate impacts on Indigenous economies or economic activities. Instead, the studies cited above in the “Descrip- tion of evidence base” section are qualitative analyses. The chapter references Chapter 29: Mitiga- tion for some quantitative studies about climate impacts to U.S. economic sectors, but these are not specifically about Indigenous economies. Quantitative national studies of climate impacts may have general applicability to Indigenous peoples, but their overall utility in quantifying impacts to Indigenous peoples may be limited, because there is uncertainty regarding the extent to which appropriate extrapolations can be made between Indigenous and non-Indigenous contexts.

Other uncertainties include characterizing future impacts and vulnerabilities in a shifting policy landscape, when vulnerabilities can be either exacerbated or alleviated in part by policy changes, such as the quantification and adjudication of federal reserved water rights and the development of policies that promote or inhibit the development of adaptation and mitigation strategies (for example, the development of water rights for instream flow purposes).[19]

Description of confidence and likelihood

Given the amount of robust and consistent studies in the literature, the authors have *very high confidence* that Indigenous peoples' subsistence and commercial livelihoods and economies, including agriculture, hunting and gathering, fishing, forestry, recreation, tourism, and energy, face current threats from climate impacts to water, land, and other natural resources, as well as infrastructure and related human systems and services. The authors have *high confidence* in the available evidence indicating that it is *likely* that future climate change will increase impacts to water, land, other natural resources, and infrastructure that support Indigenous people's livelihoods and economies. The authors have *high confidence* that Indigenous peoples' economies depend on, but face institutional barriers to, their self-determined management of water, land, other natural resources, and infrastructure, stemming from funding constraints and the complexities of federal oversight of trust resources.

Key Message 2

Physical, Mental, and Indigenous Values-Based Health at Risk

Indigenous health is based on interconnected social and ecological systems that are being disrupted by a changing climate (*high confidence*). As these changes continue, the health of individuals and communities will be uniquely challenged by climate impacts to lands, waters, foods, and other plant and animal species (*likely*, *high confidence*). These impacts threaten sites, practices, and relationships with cultural, spiritual, or ceremonial importance that are foundational to Indigenous peoples' cultural heritages, identities, and physical and mental health (*high confidence*).

Description of evidence base

Multiple epidemiological studies provide consistent and high-quality evidence that Indigenous peoples face health disparities according to conventional Western science approaches to assessing health risk; in general, Indigenous peoples have disproportionately higher rates of asthma,[90] cardiovascular disease,[91,92,93,94] Alzheimer's disease or dementia,[95,96] diabetes,[97] and obesity.[93] There is also robust qualitative evidence that various social determinants of health affect Indigenous health disparities, including historical trauma,[88,89] institutional racism, living and working circumstances that increase exposure to health threats, and limited access to healthcare services.[87,89] A recent peer-reviewed scientific assessment of health concluded that these health disparities have direct linkages to increased vulnerability to climate change impacts from changes in the pollen season and allergenicity, air quality, and extreme weather events.[98]

Additionally, a number of qualitative studies consistently find that Indigenous health, adaptive capacity, and health disparities/environmental justice issues typically do not capture many of the key elements of health and resilience that are important to Indigenous populations, which include concepts related to community connection, natural resources security, cultural use, education and knowledge, self-determination, and autonomy.[81,82,83,84,85,86] Available qualitative evidence consistently identifies Indigenous peoples as having a unique and interconnected relationship with the natural environment and wildlife that is integral to their place-based social, cultural, and spiritual identity; intangible cultural heritage (traditions or living expressions transmitted and inherited through generations); and subsistence practices and livelihoods that foster intra- and intergenerational knowledge sharing and relationships.[29,44,61,81,82,86,87,99,100,101,102,103,105] Climate impacts to lands, waters, foods, and other plant and animal species undermine these relationships, affect place-based cultural heritages and identities (including through damage to cultural heritage sites), may worsen historical trauma still experienced by many Indigenous peoples, and ultimately result in adverse mental health impacts.[86,101,102,106] There is robust documentation of observed adverse climate change related impacts on culture and food security,[44,61,99,103] physical health,[98] and mental health.[71,101,102,104,107]

The studies consistently conclude that these adverse impacts to culture,[61,155] food security,[61,99] and overall human health[98,99,101,102] will continue under future projections of climate change, though methods for making these determinations vary, and there are limited quantitative or modeling results that are specific to Indigenous peoples in the United States.

There is consistent evidence from behavioral and public health research showing that responses to extreme heat serve as examples of climate change adaptation.[108,109,110,111] There are also multiple examples of tribal health vulnerability assessments that acknowledge the role of traditional subsistence species, or First Foods, as an essential aspect of health and tribal resilience.[60,112] One example from the Republic of the Marshall Islands illustrates a community-led planning process that incorporates traditional knowledge, facilitates local self-determination, and supports climate adaptation, natural resource management, and community health goals.[85]

Major uncertainties

The literature currently lacks national-scale studies that quantify and/or monetize climate impacts on Indigenous health, either through traditional Western science health metrics or Indigenous values-based metrics and indicators of health. There are quantitative studies of specific health-relevant topics, such as climate impacts to air quality (Ch. 13: Air Quality) or extreme heat (Ch. 29: Mitigation), but health impact models have not to date been used to model Indigenous population-specific climate impacts. Quantitative national studies of climate impacts may have general applicability to Indigenous peoples, but their overall utility in quantifying impacts to Indigenous peoples may be limited, because there is uncertainty regarding the extent to which appropriate extrapolations can be made between Indigenous and non-Indigenous contexts. In addition, none of the studies explicitly modeled the effects of climate adaptation actions and the extent to which such actions may reduce Indigenous vulnerabilities or projected future impacts.

Other uncertainties include characterizing future impacts and vulnerabilities in a shifting policy landscape, in which vulnerabilities can be either exacerbated or alleviated in part by policy or programmatic changes, such as a recognition of the non-physiological aspects of Indigenous health.

Description of confidence and likelihood

Based on available evidence, the authors have *high confidence* that Indigenous health is based on interconnected social and ecological systems that are being disrupted by a changing climate. The authors have *high confidence* in the available evidence indicating that it is *likely* that future climate change will increase impacts to lands, waters, foods, and other plant and animal species and that Indigenous health will be uniquely challenged by these impacts. The authors have *high confidence*, based on the quality of available evidence, that the lands, waters, foods, and other natural resources and species are foundational to Indigenous peoples' cultural heritages, identities, and physical and mental health due to their essential role in maintaining Indigenous peoples' sites, practices, and relationships with cultural, spiritual, or ceremonial importance.

Key Message 3

Adaptation, Disaster Management, Displacement, and Community-Led Relocations

Many Indigenous peoples have been proactively identifying and addressing climate impacts; however, institutional barriers exist in the United States that severely limit their adaptive capacities (*very high confidence*). These barriers include limited access to traditional territory and resources and the limitations of existing policies, programs, and funding mechanisms in accounting for the unique conditions of Indigenous communities. Successful adaptation in Indigenous contexts relies on use of Indigenous knowledge, resilient and robust social systems and protocols, a commitment to principles of self-determination, and proactive efforts on the part of federal, state, and local governments to alleviate institutional barriers (*high confidence*).

Description of evidence base

There is robust documentation of ongoing Indigenous adaptation to climate variability and change.[1,71,113,114,116,117] There is also a very strong evidence base with multiple sources, consistent results, and high consensus that Indigenous peoples face obstacles to adaptation, including:

- a limited capacity to implement adaptation strategies,[19,139,150,151]
- limited access to traditional territory and resources,[6,22,31,48,134,135,136,139,146,149] and
- limitations of existing policies, programs, and funding mechanisms.[6,7,31,135,136,139,140,142,143,144,146,147,149,150,151]

There are many studies that provide evidence with medium consensus that effective participatory planning processes for environmental decision-making (such as for sustainable land management or climate adaptation) are guided by Indigenous knowledge and resilient and robust social systems and protocols).[6,7,118,119,120,127,128,129,131,132,133] In addition, some studies draw conclusions regarding the principles of self-determination in adaptation or relocation planning and decision processes.[144,146,148]

Major uncertainties

Adaptation is still in its infancy in most Indigenous (and non-Indigenous) communities in the United States, so there have not been enough projects implemented all the way to completion to be able to observe results and draw conclusions regarding the efficacy of any particular adaptation process or approach. Extrapolations can be made, however, from other relevant and closely related environmental decision-making processes, such as for land or water resource management.

Description of confidence and likelihood

Based on the quality of available evidence, the authors have *very high confidence* that Indigenous peoples are proactively identifying and addressing climate impacts but that many face various obstacles limiting their implementation of adaptation practices. There is *high confidence* that successful adaptation in Indigenous contexts leverages Indigenous knowledge, robust social systems and protocols, and a commitment to Indigenous self-determination.

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16 Climate Effects on U.S. International Interests

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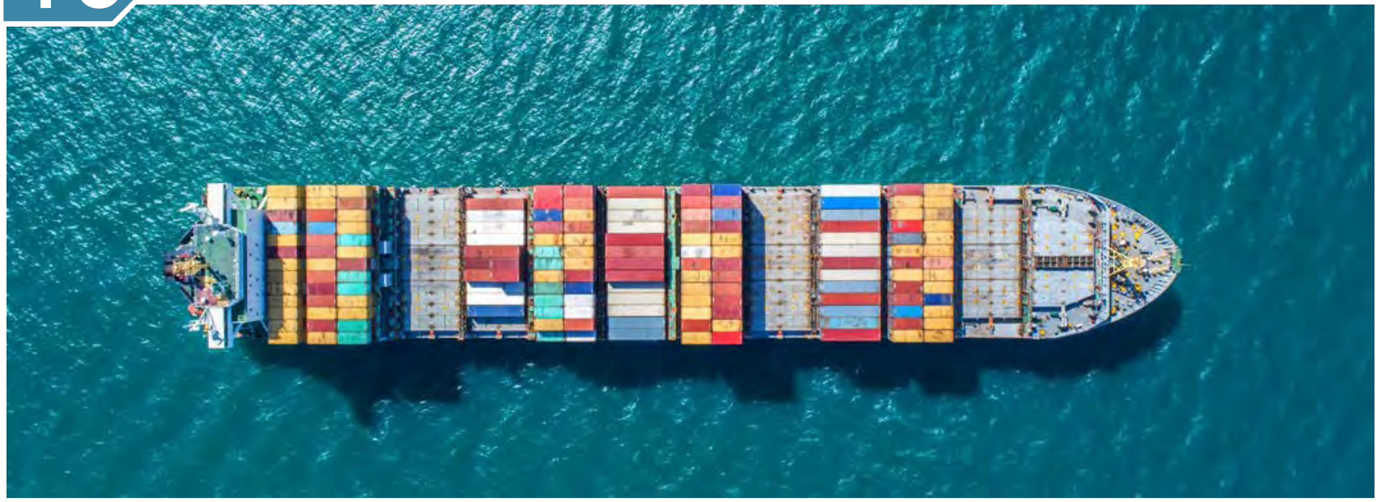
16 Climate Effects on U.S. International Interests



Container ship bringing goods to port

Key Message 1

Economics and Trade

The impacts of climate change, variability, and extreme events outside the United States are affecting and are virtually certain to increasingly affect U.S. trade and economy, including import and export prices and businesses with overseas operations and supply chains.

Key Message 2

International Development and Humanitarian Assistance

The impacts of climate change, variability, and extreme events can slow or reverse social and economic progress in developing countries, thus undermining international aid and investments made by the United States and increasing the need for humanitarian assistance and disaster relief. The United States provides technical and financial support to help developing countries better anticipate and address the impacts of climate change, variability, and extreme events.

Key Message 3

Climate and National Security

Climate change, variability, and extreme events, in conjunction with other factors, can exacerbate conflict, which has implications for U.S. national security. Climate impacts already affect U.S. military infrastructure, and the U.S. military is incorporating climate risks in its planning.

Key Message 4

Transboundary Resources

Shared resources along U.S. land and maritime borders provide direct benefits to Americans and are vulnerable to impacts from a changing climate, variability, and extremes. Multinational frameworks that manage shared resources are increasingly incorporating climate risk in their transboundary decision-making processes.

Executive Summary

U.S. international interests, such as economics and trade, international development and humanitarian assistance, national security, and transboundary resources, are affected by impacts from climate change, variability, and extreme events. Long-term changes in climate could lead to large-scale shifts in the global availability and prices of a wide array of agricultural, energy, and other goods, with corresponding impacts on the U.S. economy. Some U.S.-led businesses are already working to reduce their exposure to risks posed by a changing climate.

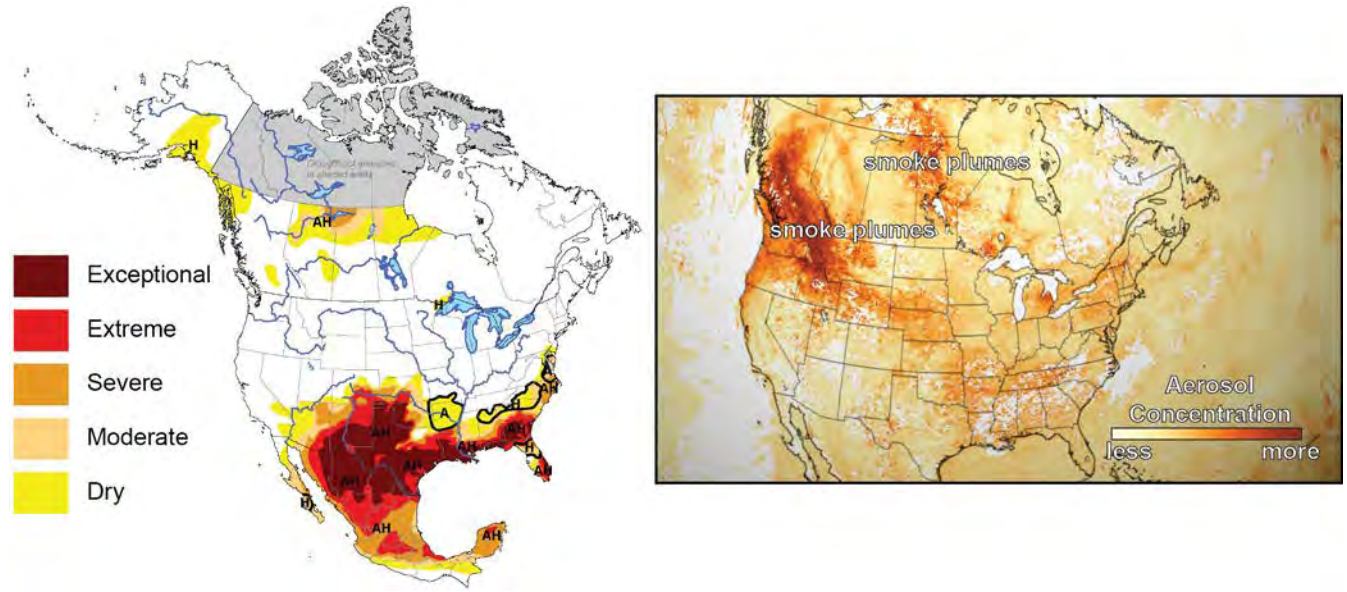
U.S. investments in international development are sensitive to climate-related impacts and will likely be undermined by more frequent and intense extreme events, such as droughts, floods, and tropical cyclones. These events can impede development efforts and result in greater demand for U.S. humanitarian assistance and disaster relief. In response, the U.S. government has funded adaptation programs that seek to reduce vulnerability to climate impacts in critical sectors.

Climate change, variability, and extreme events increase risks to national security through direct impacts on U.S. military infrastructure and, more broadly, through the relationship between climate-related stress on societies and conflict. Direct linkages between climate and conflict are unclear, but climate variability has been shown to affect conflict through intermediate processes, including resource competition, commodity price shocks, and food insecurity. The U.S. military is working to fully understand these threats and to incorporate projected climate changes into long-term planning.

The impacts of changing weather and climate patterns across U.S. international borders affect those living in the United States. The changes pose new challenges for the management of shared and transboundary resources. Many bilateral agreements and public–private partnerships are incorporating climate risk and adaptive management into their near- and long-term strategies.

U.S. cooperation with international and other national scientific organizations improves access to global information and strategic partnerships, which better positions the Nation to observe, understand, assess, and respond to the impacts associated with climate change, variability, and extremes on national interests both within and outside of U.S. borders.

Transboundary Climate-Related Impacts



Shown here are examples of climate-related impacts spanning U.S. national borders. (left) The North American Drought Monitor map for June 2011 shows drought conditions along the U.S.–Mexico border. Darker colors indicate greater intensity of drought (the letters A and H indicate agricultural and hydrological drought, respectively). (right) Smoke from Canadian wildfires in 2017 was detected by satellite sensors built to detect aerosols in the atmosphere. The darker orange areas indicate higher concentrations of smoke and hazy conditions moving south from British Columbia to the United States. *From Figure 16.4 (Sources: [left] adapted from NOAA 2018,[114] [right] adapted from NOAA 2018[115]).*

Introduction

The global impacts of climate (climate change, variability, and extreme events) are already having important implications for societies and ecosystems around the world and are projected to continue to do so into the future.[1,2,3] There are specific U.S. interests that can be affected by climate-related impacts outside of U.S. borders, such as climate variability (for example, El Niño/La Niña events), climate extremes (for example, floods resulting from extreme precipitation), and long-term changes (for example, sea level rise). These interests include economics and trade (Key Message 1), international development and humanitarian assistance (Key Message 2), national security (Key Message 3), and transboundary resources (Key Message 4). While these four topics are addressed separately, they can also affect each other. For example, climate-related disasters in developing countries not only have significant local and regional socioeconomic impacts, but they can also set back U.S. development investments, increase the need for U.S. humanitarian assistance, and affect U.S. trade and national security. U.S. citizens have long been concerned about the welfare of those living beyond U.S. borders and their vulnerability to the global impacts of climate.[4,5]

Key Message 1

Economics and Trade

> The impacts of climate change, variability, and extreme events outside the United States are affecting and are virtually certain to increasingly affect U.S. trade and economy, including import and export prices and businesses with overseas operations and supply chains.

The impacts of climate change, variability, and extremes that occur outside the United States can directly affect the U.S. economy and trade through impacts on U.S.-owned, provided, or consumed services, infrastructure, and resources in other countries.[6,7,8,9] Additionally, impacts on foreign-owned infrastructure, services, and resources can have indirect impacts on U.S. trade and businesses that rely on those assets and services, such as impacts on overseas energy and water utilities in places where U.S. international businesses are located. These foreign impacts are in addition to the impacts that climate change, variability, and extreme events within U.S. borders have on the U.S. economy and trade,[10,11] as described elsewhere in the report (for example, Ch. 7: Ecosystems, KM 3).

In addition to local impacts on U.S.-owned assets abroad, climate change is expected to lead to large-scale shifts in the availability and prices of a wide array of agricultural,[12,13] energy,[14,15] and other goods, with corresponding impacts on the U.S. economy. These impacts occur on a wide range of timescales, ranging from months to multiple decades. For example, the prices of agricultural and mining commodities and manufactured goods are affected by year-to-year and decadal climate variations in the availability of irrigation water for agriculture or hydroelectric power.[16,17,18,19] International price changes affect U.S. businesses abroad, as well as U.S. exports and imports. An example is the damaging effect that a series of short-term climate extremes in 2010 and 2011 had on global wheat production. These extremes included drought in Russia, Ukraine, and the United States and damaging precipitation in Australia. A corresponding reduction in wheat production, in combination with high demand, low stocks, trade policies, and other factors, contributed to a spike in global wheat prices.[20] This benefitted U.S. wheat exports while increasing the cost of flour and bread in the United States.[21] This example highlights the complex interactions that often arise through major impacts of overseas climate change, variability, or extremes on U.S. interests (see Key Message 3 for a discussion of some of the security implications from the 2010–2011 drought).[22] Where these impacts increase global market prices, U.S. purchasers and consumers tend to be harmed, whereas U.S. producers tend to benefit. The opposite is generally true for impacts that drive prices down.

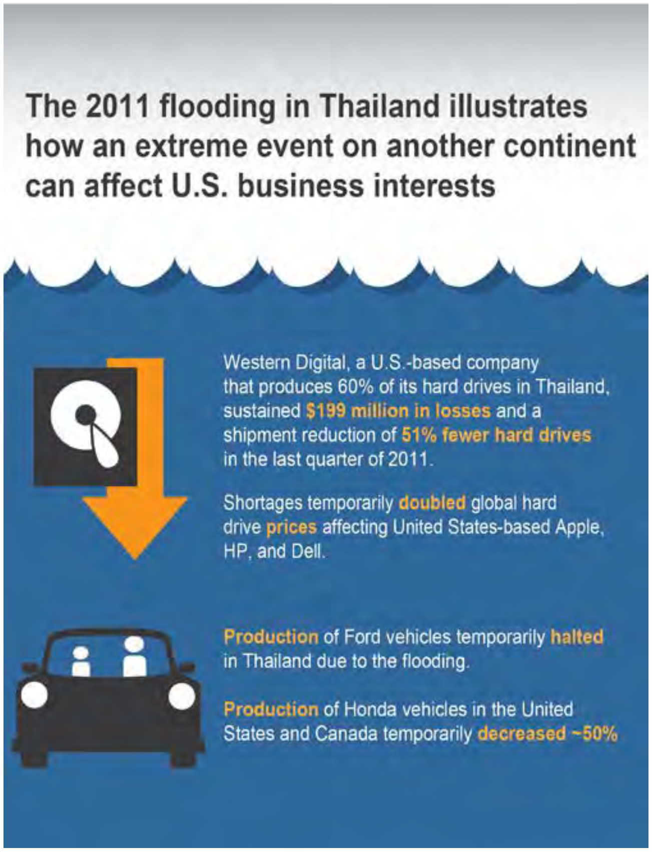
Overseas climate variability, extremes, and change can disrupt U.S. economic interests through impacts to overseas supply chains via impacts to international manufacturing, storage, and transportation infrastructure (road, rail, shipping, and air; Figure 16.1).[23,24,25] At the same time, climate change is creating new transport opportunities, such as the potential summertime availability of trans-Arctic commercial shipping in the next few decades due to a reduction in ice cover caused by warmer temperatures,[26,27,28] though the infrastructure to support this transportation pathway and its safety has not yet been developed (Ch. 26: Alaska, KM 5).

Climate risks are being increasingly recognized and reported by businesses. The Financial Stability Board's Task Force on Climate-related Financial Disclosures (TCFD 2017[29]) has encouraged businesses to report those risks, with hundreds of businesses currently enlisted as partners in the TCFD effort. Some U.S.-led businesses are working to reduce their climate risks abroad. One way they are doing this is through partnerships with environmental groups. For example, Starbucks and Conservation International[30] have partnered to strengthen the capacity of coffee farmers and supply chains to manage climate risks,[31] while Coca-Cola and the World Wildlife Fund are working together to protect foreign watersheds that Coca-Cola uses for water supply.[32] Coca-Cola increased its company-wide water efficiency from 2004 to 2012 by 21.4%, which avoided approximately $600 million in costs and tended to increase resilience in the face of water shortages.[33] As noted in the next section (Key Message 2), U.S. government actions are helping to promote climate resilience of infrastructure services[34,35] and other factors that have the potential to create more stable conditions for American businesses operating in developing countries, as well as promoting the welfare of those countries.

Global trade can promote resilience to climate change by shifting production of goods and services to areas with more favorable climates and away from those with less favorable climates.[36,37,38] However, these shifts will generally have associated costs and may have a harmful effect on communities where production is decreased.

Few studies exist that quantify the impact of climate change on U.S. corporations and the effectiveness of adaptation actions to reduce those impacts.[39]

Impact of 2011 Thailand Flooding on U.S. Business Interests



The 2011 flooding in Thailand illustrates how an extreme event on another continent can affect U.S. business interests

Western Digital, a U.S.-based company that produces 60% of its hard drives in Thailand, sustained **$199 million in losses** and a shipment reduction of **51% fewer hard drives** in the last quarter of 2011.

Shortages temporarily **doubled** global hard drive **prices** affecting United States-based Apple, HP, and Dell.

Production of Ford vehicles temporarily **halted** in Thailand due to the flooding.

Production of Honda vehicles in the United States and Canada temporarily **decreased ~50%**

Figure 16.1: Severe flooding in Thailand in 2011 created significant disruptions of local business operations and global supply chains, resulting in a range of impacts to U.S. business interests. Source: ICF.

Key Message 2

International Development and Humanitarian Assistance

The impacts of climate change, variability, and extreme events can slow or reverse social and economic progress in developing countries, thus undermining international aid and investments made by the United States and increasing the need for humanitarian assistance and disaster relief. The United States provides technical and financial support to help developing countries better anticipate and address the impacts of climate change, variability, and extreme events.

U.S. development assistance helps save lives, reduce poverty, and strengthen democratic governance; it also helps societies emerge from humanitarian crises.[40,41] Given their structures and levels of development, the economies and societies of developing countries are generally at greater relative risk from the impacts of climate variability, change, and extremes than are those of developed countries.[1] In addition to causing suffering in developing countries, these impacts threaten to undermine U.S. investments in development and may necessitate additional humanitarian assistance (and possibly military assistance or intervention; see Key Message 3) in response to more frequent and severe natural disasters (such as flooding).

U.S. international development assistance programs, implemented either directly by U.S. government agencies (such as the U.S. Agency for International Development [USAID] and the Millennium Challenge Corporation [MCC]) or indirectly through multilateral institutions (such as the World Bank and United Nations agencies), invest in critical sectors such as agriculture, water and sanitation, health, and infrastructure. These sectors, and the U.S. investments in them, are sensitive to natural variations in climate and extremes and are vulnerable to adverse impacts of climate change.[1,34,42]

The U.S. government systematically identifies climate risks and seeks to reduce the vulnerability of its international development investments. For example, the MCC amended its Environmental Guidelines in June 2012 to formally adopt the International Finance Corporation’s Performance Standards on Environmental and Social Sustainability, which includes provisions on climate risk management.[43,44] In addition, USAID has its own climate risk management guidelines.[45] For more than a decade, the U.S. government has also funded adaptation programs that seek to reduce vulnerability to climate impacts in these critical sectors.

Developing countries are often highly vulnerable to climate extremes, which can set back development and increase the need for disaster response and recovery assistance. For example, in 1998, Hurricane Mitch devastated Honduras and Nicaragua, killing thousands of people and causing widespread damage to property and infrastructure.[46] USAID and the U.S. Department of Defense (DoD) jointly responded with an immediate relief effort. USAID also reoriented many of its programs to focus on longer-term recovery.[47] Climate change is likely to increase the demand for U.S. humanitarian assistance of this kind, given the expected increase in the severity of extreme events like tropical cyclones and droughts.[1,48,49]

Many developing countries depend heavily on agriculture as a major source of jobs and a large percentage of their gross domestic product (GDP). Drought can have impacts on food production and security at multiple scales. At the national level, the loss of food and income and the need to help farmers through bad years can set back development. At the household level, drought can wipe out crops and financial assets and leave families vulnerable to starvation.

The United States works at several levels to help countries anticipate drought and to provide farmers with tools to manage risks to their crops and finances. For example, the United States invests in early warning systems in developing countries such as the Famine Early Warning Systems Network (FEWS NET), a joint effort by multiple U.S. agencies created after a devastating drought in Ethiopia in 1984. Currently, FEWS NET works with governments and international partners in 34 countries (Figure 16.2).[50] In 2015, FEWS NET warned that Ethiopia was facing its worst drought in 60 years and projected that as many as 15 million people would face acute food insecurity. Before the drought and food crisis materialized, USAID mobilized an emergency aid program and provided 680,000 metric tons of food to more than 4 million people.[51]

U.S. investments in making Ethiopian agriculture more climate resilient also helped individual farmers cope with the 2015 drought. A financial risk management program enables farmers to buy “weather index” insurance, which links payouts to certain indicators of extreme weather, such as drought. The insurance program uses information from FEWS NET and coordinates with Ethiopian partners as well as global reinsurance companies. More than 25,000 Ethiopian farmers who purchased this type of insurance received payouts during the drought, helping them to pay off debts, feed their families, and care for livestock.[52,53] Similar index insurance products are being developed through public–private partnerships across Africa, Asia, and Latin America.

Investments by the United States towards enhancing national capacity to produce and use climate information in decision-making, also known as climate services, help countries manage their own risks and build resilience. For instance, the United States collaborated with Jamaica’s meteorological service and agriculture ministry to develop a seasonal drought forecast tailored to the needs of Jamaican farmers. Jamaican agriculture was severely affected by drought in 2014.[54] Crop production losses were 57% nationally and close to 75% among farmers identifying climate risks as a major concern. However, farmers who used the drought forecast fully were able to cut their losses nearly in half that year compared to farmers who did not use or did not have access to the forecast.[55]

Climate-resilience investments are being made to assist other key economic sectors in developing countries, including some that are expected to have benefits over longer time frames. For instance, in the Philippines, the United States has supported six cities and provinces to consider climate impacts in the provision of water supply and wastewater treatment services. The project is improving the design, management, and maintenance of long-lived infrastructure, as well as local planning and governance.[56] It assisted one water-scarce city, Zamboanga City, in developing the country’s first-ever urban water demand management plan.[57]

Famine Early Warning Systems Network

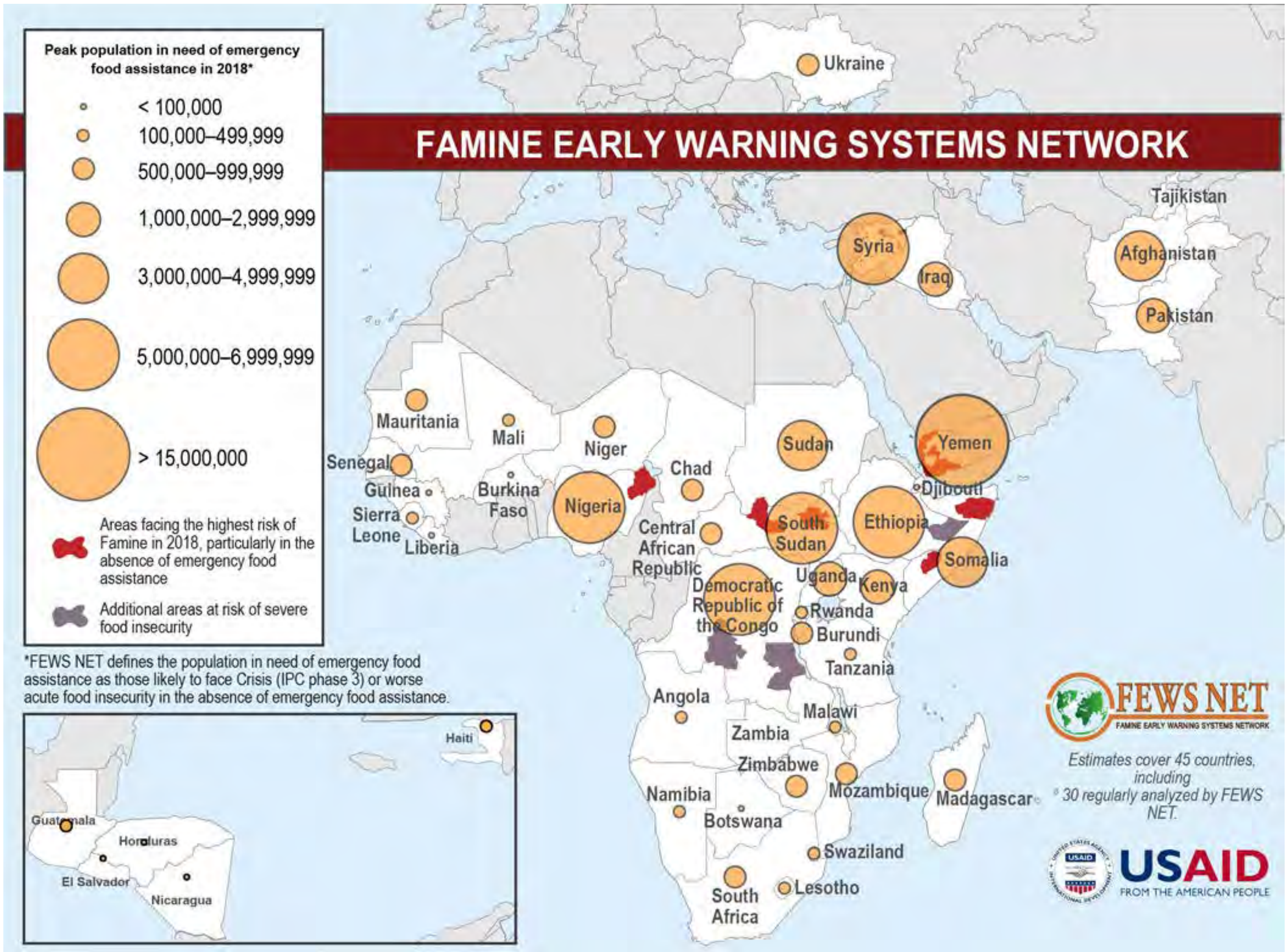


Figure 16.2: The Famine Early Warning Systems Network involves a collaboration between U.S. government agencies, other national government ministries, and international partners to collect data and produce analyses of conditions in food-insecure regions and countries. The analyses integrate information on climate, agricultural production, prices, trade, nutrition, and other societal factors to develop scenarios of food security around the world 6 to 12 months in advance. This map shows projections of peak populations in need of emergency food assistance in 2018. Source: adapted from USAID 2018.[58]

Key Message 3

Climate and National Security

Climate change, variability, and extreme events, in conjunction with other factors, can exacerbate conflict, which has implications for U.S. national security. Climate impacts already affect U.S. military infrastructure, and the U.S. military is incorporating climate risks in its planning.

Climate change and extremes increase risks to national security through direct impacts on U.S. military infrastructure and by affecting factors, including food and water availability, that can exacerbate conflict outside U.S. borders.[59,60] Droughts, floods, storm surges, wildfires, and other extreme events stress nations and people through loss of life, displacement of populations, and impacts on livelihoods.[61,62] Increases in the frequency and severity of such events, as well as other aspects of climate change, may require a larger military mission focus on climate-sensitive areas such as coasts, drought-prone areas, and the Arctic.[60]

Climate change is already affecting U.S. Department of Defense (DoD) assets by, among other impacts, damaging roads, runways, and waterfront infrastructure.[63] DoD is working to both fully understand these threats and incorporate projected climate changes into long-term planning to reduce risks and minimize impacts. There are many examples of DoD's planning and action for risks to its assets from climate change. DoD has performed a comprehensive scenario-driven examination of climate risks from sea level rise to all of its coastal military sites,[64] including atolls in the Pacific Ocean.[65] In the Arctic, the U.S. Coast Guard and Navy are pursuing strategies to respond to the changing geopolitical significance resulting from the projected absence of summer sea ice in the next few decades (Ch. 2: Climate, KM 7).[66,67,68,69]

The risks climate change may hold for national security more broadly are connected to the relationships between climate-related stresses on societies and conflict. Direct linkages between climate-related stress and conflict are unclear,[70] but climate variability has been shown to affect conflict through intermediate processes, including resource competition, commodity price shocks, and food insecurity.[71,72] The potential for conflict increases where there is a history of civil violence, conflict elsewhere in the region, low GDP or economic growth, economic shocks, weak governance, and lack of access to basic needs.[61] For example, droughts around the world in 2010 contributed to a doubling of global wheat prices in 2011 and a tripling of bread prices in Egypt.[73] This and other factors, including national trade policy and poverty, contributed to the civil unrest that ultimately resulted in the 2011 Egyptian revolution.[73] While the 2010 droughts were not the sole cause of the revolution, they contributed to destabilization of an already unstable region. Likewise, drought in Somalia has forced herders to sell livestock they could not provide for, reducing their incomes and leading some to join armed groups.[74] Water scarcity and climate-related variations in water availability can increase tensions and conflict between countries.[75] In these and other instances, conflict was related to stress from climate-related events, but non-climatic factors also had an important role.[76,77,78,79,80,81,82,83] However, in some cases, water scarcity and variability can result in cooperation rather than conflict.[61,84]

Human migration is another potential national security issue. Extreme weather events can in some cases result in population displacement. For example, in 1999 the United States granted Temporary Protected Status to 57,000 Honduran and 2,550 Nicaraguan nationals in response to Hurricane Mitch.[85] In 2013, more than 4 million people were internally displaced by Typhoon Haiyan in the Philippines,[86] and the United States committed 13,400 military personnel to the relief effort (Figure 16.3).[87] Six months after Typhoon Haiyan, more than 200,000 people remained without adequate shelter.[88] While neither Hurricane Mitch nor Typhoon Haiyan was solely attributable to climate change,[89] tropical cyclones are projected to increase in intensity, which would increase the risk of forced migration.[2,49] Slower changes, including sea level rise and reduced agricultural productivity related to changes in temperature and precipitation patterns, could also affect migration patterns.[61] However, whether migration in response to climate change will generally cause or exacerbate violent conflict is still uncertain (Ch. 27: Hawai'i & Pacific Islands, KM 6).[90,91]

U.S. Military Relief Efforts in Response to Typhoon Haiyan

Figure 16.3: The U.S. military conducted humanitarian and disaster relief efforts in the aftermath of Typhoon Haiyan in the Philippines in 2013. (upper left) An officer aboard an MH-60R Seahawk helicopter prepares to drop off humanitarian supplies. (upper right) A sailor assists a Philippine nurse in treating a patient’s head wound at the Immaculate Conception School refugee camp. (lower left) Residents displaced by the storm fill the cargo hold of a C-17 Globemaster aircraft. (lower right) Sailors aboard the aircraft carrier USS *George Washington* move a pallet of drinking water across the flight deck. Photo credit: U.S. Department of Defense.

Key Message 4

Transboundary Resources

Shared resources along U.S. land and maritime borders provide direct benefits to Americans and are vulnerable to impacts from a changing climate, variability, and extremes. Multinational frameworks that manage shared resources are increasingly incorporating climate risk in their transboundary decision-making processes.

The shared borders of the United States are extensive. Land borders with Canada (13 states) and Mexico (4 states) include shared rivers and lakes. Maritime borders are shared with 21 countries by Hawai‘i and other island areas, including the U.S. Caribbean, the U.S.-Affiliated Pacific Islands, and the Arctic region.[92,93]

Climate variability and change, as well as related extreme events across shared U.S. borders, can have direct and indirect impacts on those living in the United States. For example, increased temperatures coupled with decreased precipitation in northern Mexico can lead to an increase in the intensity of dust storms and wildfires, which can cross the border into the United States.[94,95,96,97,98,99] Similarly, transport of smoke from wildfires across the Canadian borders can lead to air quality and health concerns in the United States (Figure 16.4) (see also Ch. 24: Northwest, Box 24.7). Movement of fish species is affected by changes in water temperature (Ch. 9: Oceans, KM 2; Ch. 20: U.S. Caribbean, KM 2) as illustrated by the migration of Pacific hake, an economically important fish species that migrated northward from the United States to Canadian waters due to warmer ocean temperatures during the 2015 El Niño.[100] Additionally, climate impacts are likely to exacerbate cross-border issues related to water, wildlife, trade, transportation, health (Box 16.1) (see also Ch. 14: Human Health), infrastructure, energy, natural resources (such as biodiversity and forests), food security, human migration, and cultural resources. Shared water resources such as rivers and lakes are particularly sensitive to changes in precipitation (Figure 16.4). In the U.S.–Mexico drylands region, large areas are projected to become drier (Ch. 23: S. Great Plains),[101,102] which is expected to present increasing demands for water resources on top of existing stresses associated with population growth.[103,104] Along the U.S.–Canada border, changing weather patterns along the Columbia River, which originates in Canada, affect the amount of water available for irrigation, drinking water supplies, and hydroelectric power generation.[105]

Transboundary Climate-Related Impacts

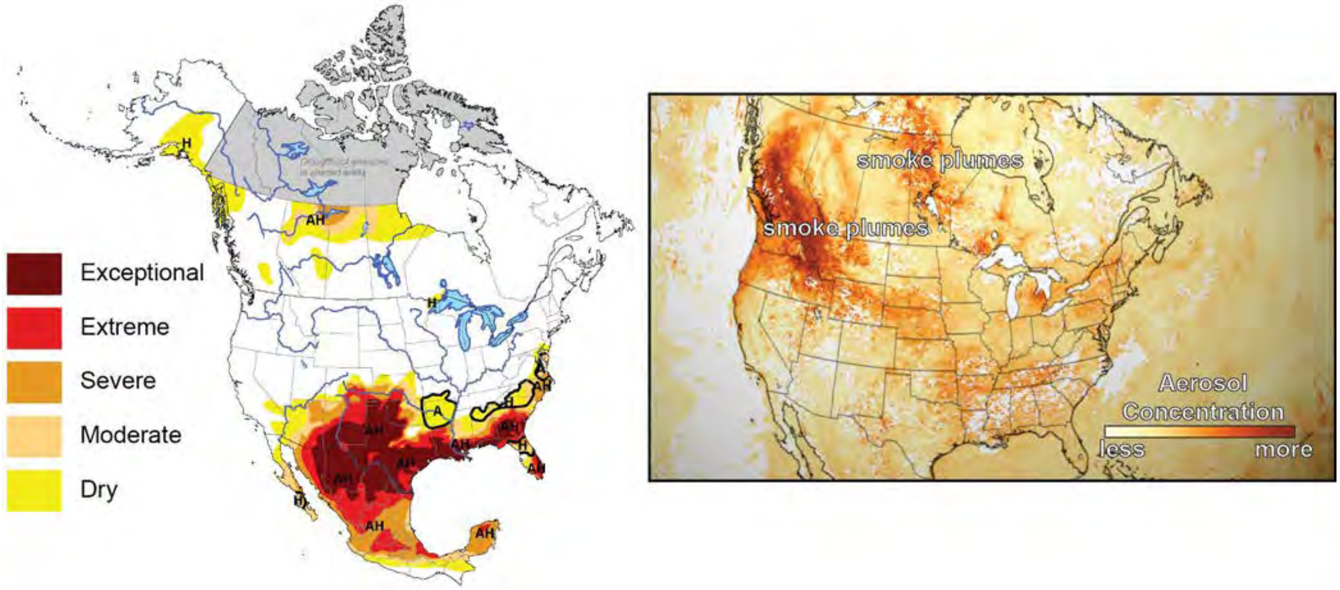


Figure 16.4: Shown here are examples of climate-related impacts spanning U.S. national borders. (left) The North American Drought Monitor map for June 2011 shows drought conditions along the US–Mexico border. Darker colors indicate greater intensity of drought (the letters A and H indicate agricultural and hydrological drought, respectively). (right) Smoke from Canadian wildfires in 2017 was detected by satellite sensors built to detect aerosols in the atmosphere. The darker orange areas indicate higher concentrations of smoke and hazy conditions moving south from British Columbia to the United States. Sources: (left) adapted from NOAA 2018,[114] (right) adapted from NOAA 2018.[115]

Box 16.1: Implications of Global Health Risks for the United States

Climate effects outside the United States can impact human health within the Nation as well as U.S. interests abroad, such as deployed military personnel.[116,117] For example, the past two decades have seen the introduction or reintroduction into the United States of several vector-borne diseases, including West Nile virus, dengue, chikungunya, and, most recently, Zika (Ch. 14: Human Health, Box 14.2).[118,119,120] While climate is only one factor influencing the spread of these diseases, warmer conditions and precipitation changes projected to occur outside and inside the United States could influence disease transmission across and within U.S. borders as well as habitat suitability for disease-carrying insects and pests.[121,122,123] Warmer temperatures provide the opportunity for mosquitoes and other disease-carrying pests to increase their geographic range. These changes, in combination with international travel patterns, could facilitate establishment of these diseases, especially in South Florida, the Texas-Mexico border area, and the U.S. Caribbean Territories.[124,125]

The management process of shared water resources is increasingly incorporating climate information into the decision-making process. Several agreements between countries have recently been restructured to consider changing weather patterns and related management challenges to include climate risk and adaptive management into their near- and long-term strategies. Along the Mexican border, the International Boundary and Water Commission, which implements water treaties between the United States and Mexico, is exploring an array of adaptive water management strategies (Ch. 25: Southwest, Box 25.1)[106] and utilizes an adaptive approach that can help with managing climate-related impacts on Colorado River water.[107] An example of this adaptive management approach is the design of flexible surface water and groundwater storage facilities, coupled with governance mechanisms that continuously account for changing climate conditions and water demand.

The International Joint Commission is also using adaptive management to address climate risks to U.S.–Canadian waters.[108] At the subnational level, the U.S.–Canada Great Lakes Water Quality Agreement incorporated a new annex in 2012 to identify, quantify, understand, and predict the impacts of climate change on Great Lakes water quality,[109] which has helped foster the binational development of new climate products for the Great Lakes (Ch. 21: Midwest, KM 3). Researchers are incorporating climate information into computer models of streamflow and reservoirs along the U.S.–Canada border to help decision-makers understand the long-term potential impacts to flood risk management, hydropower generation, and water availability in the Columbia River Basin.[110] This work is led by U.S. and Canadian agencies in partnerships with academic institutions and regional entities and can be utilized to inform management over long periods of time. These examples of including climate risk into the management of shared river and lake resources can be a model for improving resilience of other shared resources, such as fisheries.

In addition to government-to-government management of transboundary resources, public–private partnerships are increasingly helping to manage climate risks associated with these resources. For example, numerous efforts exist of transboundary collaboration in the Rio Grande–Rio Bravo Basin (Ch. 23: S. Great Plains, Case Study "Rio Grande Valley and Transboundary Issues"), including a bilateral public–private partnership that has implemented collaborative science, restoration, and monitoring actions to restore the river, with climate adaptation as one of the objectives. The partnership consists of businesses, nongovernmental conservation organizations, federal and state agencies, academic institutions, private foundations, and the public from both Mexico and the United States.[104,111,112,113] The U.S. Caribbean (Ch. 20: U.S. Caribbean, KM 6) and Hawai'i and the Pacific Islands (Ch. 27: Hawai'i & Pacific Islands) are actively engaged with international partners to build adaptive capacity and reduce risks associated with climate change uncertainty at the regional level. Such international engagement may be more in demand in the future to address increasing vulnerabilities of transboundary resources.

Box 16.2: Benefits of International Scientific Cooperation on Climate Research

Cooperation with international science efforts significantly enhances understanding of the impacts of climate variability and climate change here in the United States. As described in the Executive Summary of the recently published *Climate Science Special Report: Fourth National Climate Assessment, Volume I*, changes in the Earth's atmosphere, oceans, land surface, and ice sheets can have major effects on U.S. climate and interests.[3] For example, projected sea level changes in the United States are driven in part by changes that occur outside of our borders in ice sheets, glaciers, and water temperatures.[64,126,127] While localized phenomena, such as coastal subsidence (sinking of land) and regional variance in sea levels, contribute to global sea level rise, understanding the contribution of global-scale changes is critical. Rainfall and temperature patterns in parts of the United States are affected by the El Niño–Southern Oscillation (ENSO), a climatic phenomenon that occurs in the tropical Pacific Ocean. Understanding such global-scale phenomena exceeds the capabilities of any one country alone.[3,128] Furthermore, international collaboration can enhance institutional adaptive capacity as noted in the U.S. Caribbean chapter (Ch. 20) of this report. Through the Global Change Research Act of 1990, Congress recognizes and mandates the importance of U.S. engagement and leadership in international scientific research.[129] Cooperation with other international and national scientific organizations enables the United States to better observe, understand, assess, and manage the impacts of climate processes on U.S. interests within and outside of national borders. Examples of benefits to the United States of international scientific cooperation include

- *access to observations, data, and knowledge* that can shed light on how distant processes affect U.S. climate;[130,131,132]
- *opportunities to leverage funding and equipment* in the development and maintenance of climate observing systems, spreading the cost among countries that participate, including the United States;[133,134,135,136]
- *knowledge of climate impacts in regions and sectors of interest to the United States*, which can be used to inform decisions about humanitarian and development assistance, national security, and transboundary resource management;[51,137]
- *the ability to shape the priorities of an increasingly global and interdisciplinary research community*, which can help focus attention and resources on issues relevant to the United States through participation in joint research efforts[138,139] and assessments;[140,141,142] and
- *mechanisms to share technical expertise and experiences with other countries, regions, and communities with respect to climate services, adaptation, resilience building, and sustainable development* in order to apply lessons learned in other regions to U.S. risk management challenges.[143,144,145,146]

Box 16.3: How Well Are Climate Risks to U.S. International Interests Understood and Addressed?

There is high confidence that climate change, variability, and extreme events can result in profound consequences for U.S. international interests relating to economy and trade (Key Message 1), development and humanitarian assistance (Key Message 2), national security (Key Message 3), and managing shared resources across our borders (Key Message 4). Projections of climate change indicate that these impacts will continue throughout the century and will likely accelerate in the future.[3]

Despite this level of confidence, the mechanisms by which climate impacts beyond American borders can affect U.S. interests are not uniformly well understood. Some of this uncertainty arises because these impacts are part of complex systems, and understanding how climate change, variability, and extremes affect such systems can be challenging (Ch. 17: Complex Systems). For example, as noted in Key Message 3, the connections between climate and national security are complex because national security can be affected through intermediate processes such as resource competition. Such processes are challenging to model and forecast because they can be affected by such difficult-to-predict factors as policy decisions, human behavior, and climate surprises.[147]

In addition, the literature on climate impacts on U.S. international interests is at an early stage of development. For example, while there is a relatively well-developed literature on the potential global economic impacts of climate change (e.g., IPCC 2014, Mani et al. 2018[1,148]), there is a much more limited literature on the implications of such impacts for U.S. businesses, their supply lines, economics, and trade (see Key Message 1). Research on the potential consequences of international climate change on U.S. economics and trade, coupled with analyses of the impacts of climate change within U.S. borders, could provide key insights to better understand impacts and inform actions that promote the well-being of the U.S. economy.

Efforts are underway to adapt to climate change, variability, and extreme events in all four of the Key Message topics addressed in this chapter. However, our understanding about the effectiveness of these particular adaptations and their potential to offset adverse impacts (or take advantage of positive impacts) is quite limited (Ch. 28: Adaptation, Figure 28.1). One explanation is that many of these international-related adaptations have not been in place long (such as the incorporation of climate change projections into transboundary water management efforts; Key Message 4), and there have been relatively few attempts to assess and evaluate their effectiveness. In addition, multiple stakeholders (such as other development organizations, host country governments, nongovernmental organizations, and the private sector) and other factors (such as condition of infrastructure, governance) may have a role in adaptation beyond our borders, thus making it challenging to assess the efficacy of international adaptation actions. Nonetheless, it appears to be highly unlikely that the measures implemented so far will fully avoid or offset the adverse impacts of climate change, variability, and extremes on U.S. international interests.

Acknowledgments

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Opening Image Credit

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Traceable Accounts

Process Description

The Fourth National Climate Assessment (NCA4) is the first U.S. National Climate Assessment (NCA) to include a chapter that addresses the impacts of climate change beyond the borders of the United States. This chapter was included in NCA4 in response to comments received during public review of the Third National Climate Assessment (NCA3) that proposed that future NCAs include an analysis of international impacts of climate change as they relate to U.S. interests.

This chapter focuses on the implications of international impacts of climate change on U.S. interests. It does not address or summarize all international impacts of climate change; that very broad topic is covered by Working Group II of the Intergovernmental Panel on Climate Change (IPCC; e.g., IPCC 2014[1]). The U.S. government supports and participates in the IPCC process. The more focused topic of how U.S. interests can be affected by climate impacts outside of the United States is not specifically addressed by the IPCC.

The topics in the chapter—economics and trade, international development and humanitarian assistance, national security, and transboundary resources—were selected because they illustrate ways in which U.S. interests can be affected by international climate impacts. These topics cut across the world, so the chapter does not focus on impacts in specific regions.

The transboundary section was added to address climate-related impacts across U.S. borders. While the regional chapters address local and regional transboundary impacts, they do not address impacts that exist in multiple regions or agreements between the United States and its neighbors that create mechanisms for addressing such impacts.

The science section is part of the chapter because of the importance of international scientific cooperation to our understanding of climate science. That topic is not treated as a separate section because it is not a risk-based issue and therefore not an appropriate candidate to have as a Key Message.

The U.S. Global Change Research Program (USGCRP) put out a call for authors for the International chapter both inside and outside the Federal Government. The USGCRP asked for nominations of and by individuals with experience and knowledge on international climate change impacts and implications for the United States as well as experience in assessments such as the NCA.

All of the authors selected for the chapter have extensive experience in international climate change, and several had been authors on past NCAs. Section lead assignments were made based on the expertise of the individuals and, for those authors who are current federal employees, based on the expertise of the agencies. The author team of ten individuals is evenly divided between federal and non-federal personnel.

The coordinating lead author (CLA) and USGCRP organized two public outreach meetings. The first meeting was held at the Wilson Center in Washington, DC, on September 15, 2016, as part of the U.S. Agency for International Development's (USAID) Adaptation Community Meetings and solicited input on the outline of the chapter and asked for volunteers to become chapter authors or otherwise contribute to the chapter. A public review meeting regarding the International chapter was held on April 6, 2017, at Chemonics in Washington, DC, also as part of USAID's Adaptation Community Meetings series. The USGCRP and chapter authors shared information about the progress to date of the International chapter and sought input from stakeholders to help inform further development of the chapter, as well as to raise general awareness of the process and timeline for NCA4.

The chapter was revised in response to comments from the public and from the National Academy of Sciences. The comments were reviewed and discussed by the entire author team and the review editor, Dr. Diana Liverman of the University of Arizona. Individual authors drafted responses to comments on their sections, while the CLA and the chapter lead (CL) drafted responses to comments that pertained to the entire chapter. All comments were reviewed by the CLA and CL. The review editor reviewed responses to comments and revisions to the chapter to ensure that all comments had been considered by the authors.

Key Message 1

Economics and Trade

> The impacts of climate change, variability, and extreme events outside the United States are affecting and are virtually certain to increasingly affect U.S. trade and economy, including import and export prices and businesses with overseas operations and supply chains (*very likely*, *medium confidence*).

Description of evidence base

Major U.S. firms are concerned about potential climate change impacts to their business (e.g., Peace et al. 2013, Peace and Maher 2015[10,11] and illustrative examples of SEC filings describing climate risks to U.S. companies operating abroad[6,7,8,9]). Examples include the 2011 food price spike[20,21] and the 2011 Bangkok flooding; corresponding prolonged and cascading impacts to transportation and supply chains are documented in the citations related to those issues.[23,24,25] Future changes in precipitation, temperature, and sea level (among other factors) are very likely, as described in USGCRP,[3] and are very likely to exacerbate impacts on the U.S. economy and trade, relative to past impacts.

Major uncertainties

The literature base on the impacts of climate change outside U.S. borders to the U.S. economy and trade is significantly smaller than that on climate change impacts within U.S. borders. In particular, few studies have attempted to quantify the magnitude of the past impacts of climate variability and change that occur outside the United States on U.S. economics and trade. Since there is limited literature, it is unclear how climate-driven regional shifts in economic activity will affect U.S. economics and trade. Nonetheless, the general nature of the main types of impacts described in this section are relatively well known.

Description of confidence and likelihood

The portion of the main message pertaining to the future is *very likely* due to the likelihood of future climate change[3] and persistence of the sensitivity of the U.S. economy and its trade to climate conditions. There is *medium confidence* that climate change and extremes outside the

United States are impacting and will increasingly impact our trade and economy because there is insufficient empirical analysis on the causal relationships between past international climate variations outside the United States and U.S. economics and trade to provide higher confidence at this time. No attempt was made in this chapter to define the net impact of international climate change on the U.S. economy and trade; such a statement would have had very low confidence due to the current paucity of quantitative analyses.

Key Message 2

International Development and Humanitarian Assistance

The impacts of climate change, variability, and extreme events can slow or reverse social and economic progress in developing countries, thus undermining international aid and investments made by the United States and increasing the need for humanitarian assistance and disaster relief (*likely*, *high confidence*). The United States provides technical and financial support to help developing countries better anticipate and address the impacts of climate change, variability, and extreme events.

Description of evidence base

The link between climate variability, natural disasters, and socioeconomic development is fairly well established (e.g., UNISDR 2015, Hallegatte et al. 2017[149,150]), though some uncertainties about this relationship remain.[151] Humanitarian disasters driven by climate impacts have led to specific changes in U.S. development assistance. For instance, the Famine Early Warning Systems Network (FEWS NET) was created after the droughts that contributed to mass starvation in Ethiopia in the mid-1980s. More recent crises in the Horn of Africa prompted major investments in resilience at the USAID.[152]

The relationship between climate change and socioeconomic development has been assessed extensively by the Intergovernmental Panel on Climate Change through its assessment reports (e.g., IPCC 2014[1]). There is some research on the economic costs and benefits from climate change (e.g., Nordhaus 1994, Stern et al. 2006, Estrada et al. 2017, Tol 2018[153,154,155,156]). However, it can be difficult to separate climate impacts on a sector from the role of other impacts, such as weak governance (Ch. 17: Complex Systems).

The United States has long invested in socioeconomic development in poorer countries with the intention of reducing poverty and encouraging stability. Additionally, stable and prosperous countries make for potential trading partners and a reduced risk of conflict. These ideas are presented in numerous U.S. development, diplomacy, and security strategies (e.g., U.S. Department of State and USAID 2018, 2015[40,41]). There is ample evidence that the United States has invested in measures to reduce climate risks and build resilience in developing countries (e.g., USAID 2016[157]). However, this chapter does not assess the efficacy of these efforts.

Major uncertainties

Climate change adaptation is an emerging field, and most adaptation work is being carried out by governments, local communities, and development practitioners through support from development agencies and multilateral institutions. Evaluations of the effectiveness of adaptation interventions are generally conducted at the project level for its funder, and results may not be publicized. Some research is emerging on the economic benefits of adaptation interventions (e.g., Hallegatte et al. 2016, Chambwera et al. 2014[158,159]). Over time, it is likely that more activities will be implemented, more evaluations will be conducted, and the evidence base will grow.

Description of confidence and likelihood

There is *high confidence* in the Key Message. There is ample evidence that the impacts of climate variability and change negatively affect the economies and societies of developing countries and set back development efforts. There is also evidence of these impacts leading to additional U.S. interventions, whether through humanitarian or other means, in some places.

Key Message 3

Climate and National Security

> Climate change, variability, and extreme events, in conjunction with other factors, can exacerbate conflict, which has implications for U.S. national security (*medium confidence*). Climate impacts already affect U.S. military infrastructure, and the U.S. military is incorporating climate risks in its planning (*high confidence*).

Description of evidence base

Based on an assessment of a wide range of scientific literature on climate and security, multiple national security reports have framed climate change as a stressor on national security.[59,60,62,160,161,162,163] A large body of research has examined how stress due to adverse climatic conditions may affect human and national security in relation to conflict. While a few studies clearly link climatic stress to insecurity conflict,[164,165] more often studies do not find a measurable direct response.[70,77,82,166,167,168,169,170] Instead, the relationship between climate and conflict is often framed as climate stress affecting conflict through intermediate processes, including commodity price shocks and food and water security, which are themselves documented stressors on conflict.[61,71,72] Many studies focus on Africa, but evidence exists throughout the world.[76,77,78,80,81,82,83] Additional complexity arises from evidence of a range of societal responses to resource scarcity such as that brought on by climate change and natural variability.[61]

The U.S. military is observing climate change impacts to its infrastructure and is taking a scenario-driven, risk-based approach to address resultant challenges. Exceedance probability plots of the type used to support engineering siting and design analysis were used but modified to include responses to time-specific tidal phases and historical trends to create an estimate of the "present day" exceedance probability. The hindcast projections kept pace with an Intermediate-Low sea level rise scenario of approximately 5 mm/year (about 0.2 inches/year).[171] The focus for Department of Defense (DoD) infrastructure management, however, is the resultant increased trend for exceedances that would challenge infrastructure functional integrity (such as negative impacts to critical roadways and airfields).[171] In an effort to understand risks to the integrity of coastal facilities more broadly, the DoD uses a scenario-driven risk management approach to support decision-making regarding its coastal installations and facilities. The scenario approaches provide a framework for the inherent uncertainties of future events while providing decision support. Scenarios are not simply predictions about the future but rather plausible futures bounded by observations and the constraints of physics. Using scenarios, decision-makers can then examine risks through the lens of event impacts, costs of additional analysis, and the results of inaction. In this way, inaction is recognized as an important decision in its own right.[64]

Major uncertainties

The impact and risk of conflict related to climate change is difficult to separate from other drivers of environmental vulnerability, including economic activity, education, health, and food security.[61,70] There is currently a lack of robust theories that fully explain causality and associations between climate change and conflict.

Datasets on climate change, conflict, and security are often limited in length and pose statistical difficulties.[70] However, recent advances in statistical analysis have begun to allow the quantification of indirect effects of multiple variables connecting climatic pressures and violence.[172] These results are preliminary, mostly due to a lack of necessary data and the difficulty of quantifying relevant social variables, such as identity politics or grievances. There is a widespread pattern of examining instances of conflict for drivers, precluding the possibility of finding that climate-related stressors did not result in conflict. There is a need to analyze situations where no conflict occurred despite existing climate risks. Intercomparison of quantitative studies of the link between conflict and adverse climate conditions is complicated because the wide range of climatic and social indicators differ in spatial and temporal coverage, often due to a lack of data availability. Prehistoric and premodern evidence of the impact of climate change on conflict is not necessarily relevant to modern societies,[167] and some of the climate shifts currently being faced are unprecedented over centuries to millennia.[170] Therefore, the possible existence of a relationship is better understood than its particulars and is best expressed in the formulation that climate extremes and change *can* exacerbate conflict.

The ongoing Syrian conflict is often framed in terms of climate change. However, it is not possible to draw conclusions on the role of climate in the outcome of an ongoing conflict. Moreover, the role of climate variability (such as drought), the contribution of climate change to such variability, and the contribution of climate variability to the subsequent conflict is a matter of active debate in the assessed literature.[173,174,175,176]

The documented impacts of climate on national security largely occur through processes associated with natural climate variability, such as drought, El Niño, and tropical storms. While observed and projected increases in extreme weather and climate events have been attributed to climate change, uncertainty remains.[48,177,178,179]

Similarly, additional studies are underway to determine the potential impacts of climate change on DoD resources and mission capabilities. Many of these efforts seek to assess the vulnerability of infrastructure to climate change across a wide variety of ecosystems.[180,181,182]

Description of confidence and likelihood

There is consensus on framing climate as a stressor on other factors contributing to national security. Given the knowledge of factors that increase the risk of civil wars, and evidence that some of these factors are sensitive to climate change, the IPCC found justifiable concern that "climate change or changes in climate variability [could] increase the risk of armed conflict in certain circumstances."[61] However, the literature examining specific causality does not result in a high confidence conclusion to link climate and conflict, which is reflected in the Key Message *medium confidence* assignment. Multiple schools of thought exist on the mechanisms and degree of linkages, and models are incomplete. Data are improving and evidence continues to emerge, but the inconsistent evidence limits our ability to assign a probability to this Key Message.

Nonetheless, with regard to climate impacts on physical infrastructure, the DoD observes changes in the infrastructure at its installations that are consistent with climate change. In keeping with sound stewardship and prudence, it uses scenario-driven approaches to identify areas of risk while continuing to research and provide resilient responses to the observed changes.

Key Message 4

Transboundary Resources

Shared resources along U.S. land and maritime borders provide direct benefits to Americans and are vulnerable to impacts from a changing climate, variability, and extremes (*very likely*, *high confidence*). Multinational frameworks that manage shared resources are increasingly incorporating climate risk in their transboundary decision-making processes.

Description of evidence base

In the U.S.–Mexico drylands region, large areas are projected to become drier,[102] which will present increasing demands for water resources on top of existing stresses related to population growth.[103,104] There is *high confidence* that resources critical to livelihoods at borders between the United States and neighboring nations are becoming increasingly vulnerable to impacts of climate change and that the multinational frameworks that manage these resources are increasingly incorporating research-based understanding of the climate risks that these resources face. The literature supporting the Key Message is substantial, increasing in quantity and robustness.[96,97,98,99,100,105] The current impacts are well documented, and the projections of future impacts are aligned with the robust projections of future climate variability.[94,95] The literature also provides examples of bilateral agreements and management frameworks in place to manage these resources. Examples of the impacts include the migration northward into Canadian waters of Pacific hake, a migratory species sensitive to water temperature, during periods of warmer water temperature.[100] One example of a bilateral management framework is the inclusion in 2012 of a climate change impacts annex to the U.S.–Canada Great Lakes Water Quality Agreement to identify, quantify, understand, and predict climate change impacts on the water quality of the Great Lakes.[109]

Major uncertainties

Impacts on shared resources along U.S. international borders are already being experienced. Uncertainties about the impacts are aligned with the uncertainties associated with projections of future climate variability. As elaborated upon in multiple regional chapters of this report (Ch. 18: Northeast; Ch. 20: U.S. Caribbean; Ch. 21: Midwest; Ch. 24: Northwest; Ch. 25: Southwest; Ch. 26: Alaska; Ch. 27: Hawai'i & Pacific Islands), weather patterns in these border regions are projected to continue to change with varying degrees of likelihood and confidence.

Description of confidence and likelihood

There is *high confidence* in the main message. There is sufficient empirical analysis on the relationships between past climate variations along U.S. international borders. The statement about the likelihood that impacts on shared resources will affect the bilateral frameworks established to manage these resources is based on expert understanding of the integration of climate risk into existing and future frameworks.

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Impacts, Risks, and Adaptation in the United States: Fourth National Climate Assessment, Volume II

17

Sector Interactions, Multiple Stressors, and Complex Systems

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17 Sector Interactions, Multiple Stressors, and Complex Systems

Landslide blocking a road in California

Key Message 1

Interactions Among Sectors

The sectors and systems exposed to climate (for example, energy, water, and agriculture) interact with and depend on one another and other systems less directly exposed to climate (such as the financial sector). In addition, these interacting systems are not only exposed to climate-related stressors such as floods, droughts, and heat waves, they are also subject to a range of non-climate factors, from population movements to economic fluctuations to urban expansion. These interactions can lead to complex behaviors and outcomes that are difficult to predict. It is not possible to fully understand the implications of climate change on the United States without considering the interactions among sectors and their consequences.

Key Message 2

Multisector Risk Assessment

Climate change risk assessment benefits from a multisector perspective, encompassing interactions among sectors and both climate and non-climate stressors. Because such interactions and their consequences can be challenging to identify in advance, effectively assessing multisector risks requires tools and approaches that integrate diverse evidence and that consider a wide range of possible outcomes.

Key Message 3

Management of Interacting Systems

The joint management of interacting systems can enhance the resilience of communities, industries, and ecosystems to climate-related stressors. For example, during drought events, river operations can be managed to balance water demand for drinking water, navigation, and electricity production. Such integrated approaches can help avoid missed opportunities or unanticipated tradeoffs associated with the implementation of management responses to climate-related stressors.

Key Message 4

Advancing Knowledge

Predicting the responses of complex, interdependent systems will depend on developing meaningful models of multiple, diverse systems, including human systems, and methods for characterizing uncertainty.

Executive Summary

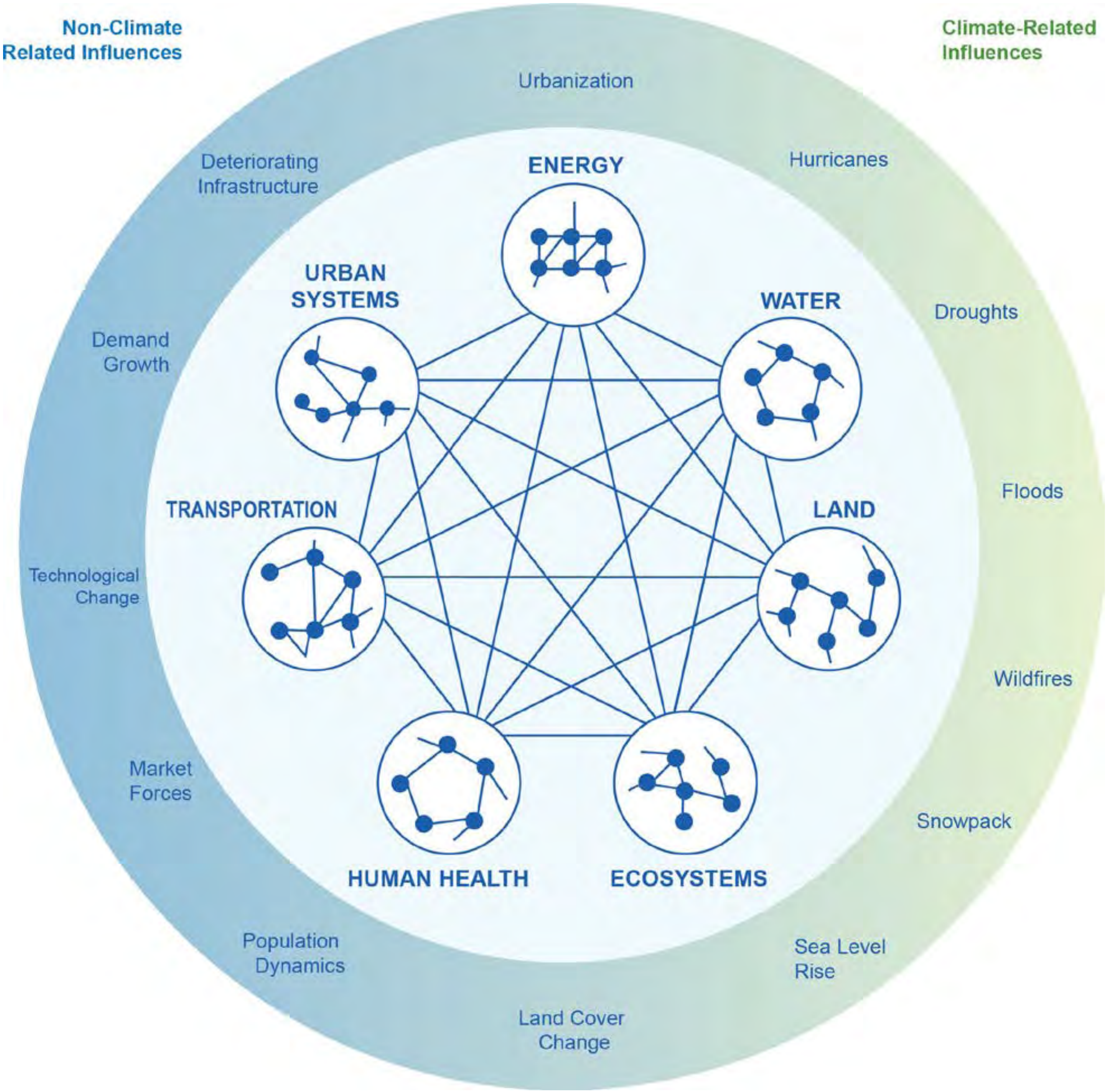
The world we live in is a web of natural, built, and social systems—from global and regional climate; to the electric grid; to water management systems such as dams, rivers, and canals; to managed and unmanaged forests; and to financial and economic systems. Climate affects many of these systems individually, but they also affect one another, and often in ways that are hard to predict. In addition, while climate-related risks such as heat waves, floods, and droughts have an important influence on these interconnected systems, these systems are also subject to a range of other factors, such as population growth, economic forces, technological change, and deteriorating infrastructure.

A key factor in assessing risk in this context is that it is hard to quantify and predict all the ways in which climate-related stressors might lead to severe or widespread consequences for natural, built, and social systems. A multisector perspective can help identify such critical risks ahead of time, but uncertainties will always remain regarding exactly how consequences will materialize in the future. Therefore, effectively assessing multisector risks requires different tools and approaches than would be applied to understand a single sector by itself.

In interacting systems, management responses within one system influence how other systems respond. Failure to anticipate interdependencies can lead to missed opportunities for managing the risks of climate change; it can also lead to management responses that increase risks to other parts of the system. Despite the challenge of managing system interactions, there are opportunities to learn from experience to guide future risk management decisions.

There is a large gap in the multisector and multiscale tools and frameworks that are available to describe how different human systems interact with one another and with the earth system, and how those interactions affect the total system response to the many stressors they are subject to, including climate-related stressors. Characterizing the nature of such interactions and building the capacity to model them are important research challenges.

Complex Sectoral Interactions



Sectors are interacting and interdependent through physical, social, institutional, environmental, and economic linkages. These sectors and the interactions among them are affected by a range of climate-related and non-climate influences. *From Figure 17.1 (Sources: Pacific Northwest National Laboratory, Arizona State University, and Cornell University).*

Introduction

The world we live in is a web of natural, built, and social systems—from global and regional climate; to the electric grid; to water management systems such as dams, rivers, and canals; to managed and unmanaged forests; and to financial and economic systems. Climate affects many of these systems individually, but they also affect one another, and often in ways that are hard to predict. In addition, while climate-related risks such as heat waves, floods, and droughts have an important influence on these interdependent systems, these systems are also subject to a range of other factors, such as population growth, economic forces, technological change, and deteriorating infrastructure (Figure 17.1).

Complex Sectoral Interactions

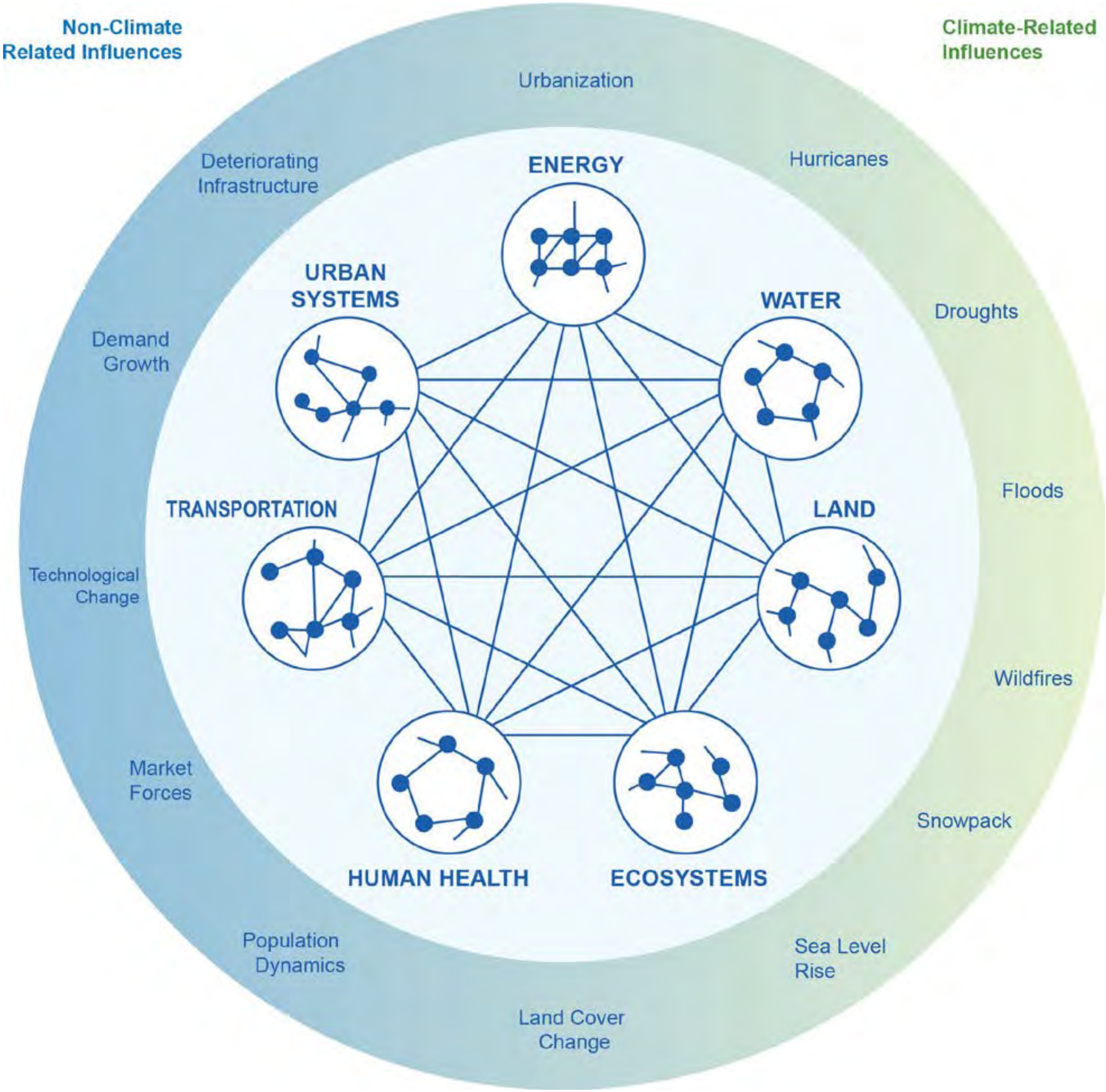


Figure 17.1: Sectors are interacting and interdependent through physical, social, institutional, environmental, and economic linkages. These sectors and the interactions among them are affected by a range of climate-related and non-climate influences. Sources: Pacific Northwest National Laboratory, Arizona State University, and Cornell University.

Assessing the risks associated with climate change requires us to acknowledge that understanding the risks to individual sectors is important but may not always be sufficient to characterize the risks to interdependent systems. Improved understanding of the complex dynamics that arise from interactions among systems is therefore essential to understand risk and manage our response to a changing climate. Characterizing the nature of such interactions and building the capacity to model them are important research challenges.

Regional and Sectoral Summary

Examples of interactions among sectors and systems can be found across the regions in this assessment. The cascading failures resulting from hurricanes are considerations across several coastal regions, including the Southern Great Plains (for example, Hurricane Harvey in 2017; see Box 17.1), the Southeast (for example, Hurricane Irma in 2017), and the Caribbean (for example, Hurricane Maria in 2017). Energy, water, and land systems subject to both climate-related stressors (such as droughts and heat waves) and nonclimate influences (such as changes to population, urbanization, and economic development) are important considerations in the Southwest, the Southern Great Plains (for example, the 2012–2015 drought in Texas), and the Northwest (for example, the snow drought in Oregon in 2015). The feedbacks between forest fires and water quality and availability have created challenges in regions including the Southeast (for example, the Appalachian region in 2016) and the Southwest (for example, the Sierra Nevada range over the last five years). Changes in arctic permafrost have caused significant erosion, leading to new risks in transportation and human health in Alaska. The natural gas and other energy industries rely on the effective management of not only railroads and transportation networks but also the diminishing water supply in the Northern Great Plains region. A need for cross-sector planning for climate change impacts in the Great Lakes region has led to new adaptation networks in the Midwest. In Hawai‘i, increasing ocean temperatures and ocean acidification threaten coral reefs and marine biodiversity, with attendant economic impacts to tourism, fishery yields, and populations who depend on these for their livelihoods. Increasingly frequent and intense storms, heavy precipitation events, warmer water temperatures, and a rise in sea level in the Chesapeake Bay in the Northeast are projected to impact local populations, who depend on productive fisheries and ecosystems for their livelihoods, resources, and culture.

Box 17.1: Hurricane Harvey: Cascading Failures and Lessons from Emerging Management Approaches

Hurricane Harvey, which struck Houston, Texas, in August 2017 (Figure 17.2), provides a clear example of how impacts from extreme weather events can cascade through tightly connected natural, built, and social systems exposed to severe climate-related stressors (see Key Message 1) (see also Ch. 23: S. Great Plains, Box 23.1 for more information on Hurricane Harvey). Harvey knocked out power to 300,000 customers in Texas,[1] with cascading effects on critical infrastructure facilities such as hospitals, water and wastewater treatment plants, and refineries. Eleven percent of U.S. refining capacity and a quarter of oil production from the U.S. Gulf of Mexico were shut down. Actual and anticipated gasoline shortages caused price spikes regionally and nationally.[2]

In addition to causing direct death and injury, the storm affected public health by disrupting supporting systems. In addition, floodwaters carried toxins and pathogens. Flooding inundated a total of 43 EPA Superfund toxic sites (damaging the protective cap at one site and leading to a short-term release of dioxins), and flooded wastewater treatment plants spilled untreated sewage.[3] Although most hospitals were able to remain open

Box 17.1: Hurricane Harvey: Cascading Failures and Lessons from Emerging Management Approaches, *continued*

(sometimes on backup power), their ability to serve their patients was strained. Widespread power outages forced evacuations that exceeded the emergency shelter capacity, and otherwise healthy people who had no access to shelters or needed power for medical devices turned to hospitals. Roadways clogged with debris, and floodwater hampered the ability to get supplies and evacuate vulnerable patients. Disrupted communications networks interfered with hospitals' ability to coordinate with each other and emergency services.[4]

These interconnected infrastructure systems operate within the context of non-climate influences, including social institutions and policy environments (see Key Message 3) (see also Ch. 11: Urban, Key Message 3). For example, in the area affected by Hurricane Harvey, regional land management practices over the last several decades have reduced the area covered by wetlands, forests, and prairies, which historically absorbed storm water runoff.[5] These natural environments have been increasingly replaced with impermeable surfaces, decreasing Houston's resilience to flooding.[5]

Hurricanes have struck densely populated, interconnected U.S. urban systems several times, including Hurricane Katrina in New Orleans in 2005 and Superstorm Sandy in New York City in 2012. While each city and storm is unique, planners and decision-makers can learn from past events and outstanding examples of resilience. During Harvey, the Texas Medical Center in Houston, the world's largest medical center, remained fully functional despite disruptions to transportation, water, and electricity, in large part due to lessons learned and resilience investments made following the devastation of Tropical Storm Allison in 2001 and Hurricane Ike in 2008.[6] In the aftermath of Superstorm Sandy, the mayor of New York City explicitly brought climate-related risks into response planning and called for a more holistic risk management strategy (see Key Message 3), initiated through the Special Initiative for Rebuilding and Resiliency and the Climate Change Adaptation Task Force.[7] This task force brought together stakeholders from major infrastructure and health sectors such as water, transportation, energy, and communications to recognize and address interdependencies.

Figure 17.2: Hurricane Harvey led to widespread flooding and knocked out power to 300,000 customers in Texas in 2017, with cascading effects on critical infrastructure facilities such as hospitals, water and wastewater treatment plants, and refineries. The photo shows Port Arthur, Texas, on August 31, 2017—six days after Hurricane Harvey made landfall along the Gulf Coast. Photo credit: Staff Sgt. Daniel J. Martinez, U.S. Air National Guard.

Key Message 1

Interactions Among Sectors

The sectors and systems exposed to climate (for example, energy, water, and agriculture) interact with and depend on one another and other systems less directly exposed to climate (such as the financial sector). In addition, these interacting systems are not only exposed to climate-related stressors such as floods, droughts, and heat waves, they are also subject to a range of non-climate factors, from population movements to economic fluctuations to urban expansion. These interactions can lead to complex behaviors and outcomes that are difficult to predict. It is not possible to fully understand the implications of climate change on the United States without considering the interactions among sectors and their consequences.

The sectors and systems subject to climate-related risks do not exist in isolation; they interact with one another and with other sectors and systems. For example, agricultural systems require water for irrigation, which is supplied from lakes, rivers, dams, and reservoirs. Forest management influences the runoff that makes its way into these water systems. Electricity systems use water for hydroelectric power as well as for cooling thermoelectric power plants. Many urban transportation systems rely on electricity to power subways and buses. Meanwhile, medical services, and public health more broadly, are enabled by transportation, water, electricity, and communications (Ch. 11: Urban, KM 3). To most effectively assess the risks associated with climate-related stressors such as floods, droughts, or heat waves, the interactions among these systems must be considered in addition to the effects of these stressors on individual systems.[8]

In addition, climate-related stressors are not the only influences to which natural, built, and social systems are exposed. For example, population movements and demographic changes, economic growth, and changes in industrial activity can all influence systems exposed to climate-related stressors as well as systems that interact with them (see, for example, Box 17.3). Such factors can have powerful impacts on these systems or alter their vulnerability to climate-related stressors. For example, rapid population growth in the coastal United States over the past half-century has significantly increased society's exposure to extreme weather events like hurricanes.[9] These demographic trends may have a greater impact on future hurricane damages than sea level rise or changes in storm intensity.[10]

A long history of research on complex systems (e.g., Simon 2000[11]), spanning disciplines from meteorology[12] to ecology[13] to paleontology[14] to computer science, [15] has shown that systems that depend on one another are subject to new and often complex behaviors that do not emerge when these systems are considered in isolation. These behaviors, in turn, raise the prospect of unanticipated, and potentially catastrophic, risks.[16] For example, failures can cascade from one system to another; that is, failures in one system can lead to increased risks or failures in other systems. Such cascades have been observed with Hurricane Harvey (see Box 17.1), the Northeast blackout (see Box 17.5),[17] and erosion and permafrost thaw in Alaska (Ch. 26: Alaska, KM 3), where failures in physical infrastructure systems had downstream consequences for human health and safety. Tightly connected supply chains can quickly transmit impacts from events such as floods, droughts, heat waves, and tropical cyclones in one region or part of the world to systems in another (see Ch. 16: International, KM 1). For example, the spike in food prices in 2010–2011 was driven in part by drought-related declines in production of basic grains in Australia and Eastern Europe, which provided a short-term income increase to U.S. farmers of those commodities (see Ch. 16: International, KM 1).[18]

Similarly, changes in one part of a system may alter the thresholds and tipping points in other parts of the system (see Kopp et al. 2017[19]). For example, the overuse and depletion of groundwater removes a backstop in times of drought (see Box 17.3). Forest wildfires can affect water and air quality and render soil impermeable, altering both health and flood risks (see Box 17.4). Interactions among systems can also buffer systems from shocks and introduce a measure of system stability or recovery potential that might not have otherwise existed (see Box 17.5). For example, social networks, which are increasingly reflected in social media enabled by communications infrastructure, can have an important influence on the resilience of communities to natural hazards. Compound events, such as simultaneous temperature extremes and drought, can produce greater economic costs than events considered separately.[19] The complexity of the interactions that exist among these various systems limits the ability to predict the consequences of climate-related stressors with confidence. This poses important challenges for risk assessment as well as the management of those risks.

Box 17.2: Uncovering System Complexities: Wolves and the Yellowstone Ecosystem

A lone gray wolf in Yellowstone National Park. © Michelle Callahan/Flickr (CC BY 2.0).

One challenge in understanding interconnected systems is that interactions are often not revealed until some stress or intervention occurs (see Key Message 1). In addition, societal values and actions can play an important role in such systems. A non-climate example illustrates this challenge very clearly—the consequences of the 1995 reintroduction of wolves into the Yellowstone National Park ecosystem.[20] Concurrent with the eradication of wolves in the early 20th century, streamside willow populations declined as elk herds grew and browsed them more heavily. Willows along the small stream network were reduced to short stature or eliminated entirely. Beavers abandoned streams that lacked willows needed for food and dam construction. In spite of the controversy over wolf reintroductions because of predation on livestock, the National Park Service reintroduced wolves in 1995-1996.[21] Since wolves have been reintroduced, there have been some effects on willow stands, but these appear to largely be due to reductions in overall elk number, rather than strictly to behavioral responses to the presence of the wolves.[22] But in areas where beavers were also lost, the overall system has not returned to its state before the eradication of wolves. The changes due to the loss of beavers have apparently reduced the capacity of the system to return to its original state, even when the wolves returned.[23,24] This example illustrates the unpredictable nature of complex, interconnected systems and how they may react to multiple stressors and interventions driven by societal decisions. It also illustrates that there is no guarantee that such systems, once perturbed, will return to their original state when management actions are taken.[25] Because climate change is a stress that is outside the recent experience of species in many ecosystems, it, too, may uncover complexities due to ecosystem-level interactions that might not be immediately apparent.

Box 17.3: Energy, Water, and Land Linkages

Climate-related stressors such as extreme temperatures, large precipitation events, floods, and droughts highlight the interactions among energy, water, and land systems. These climate-related stressors also interact with non-climate influences such as population, markets, technology, and infrastructure to affect energy, water, and land systems individually as well as the dynamics between these sectors. Understanding how risks evolve under a changing climate, and classifying which risks are the most consequential, poses a significant challenge but is critically important to develop response strategies that enhance resilience across systems. Risks to energy, water, and land systems must be considered in the context of both climate-related and non-climate-related influences as well as the broader social and institutional context (Figure 17.3). As risks evolve, the vulnerabilities and exposure rates for energy, water, and land systems also evolve (see Key Message 1).[26]

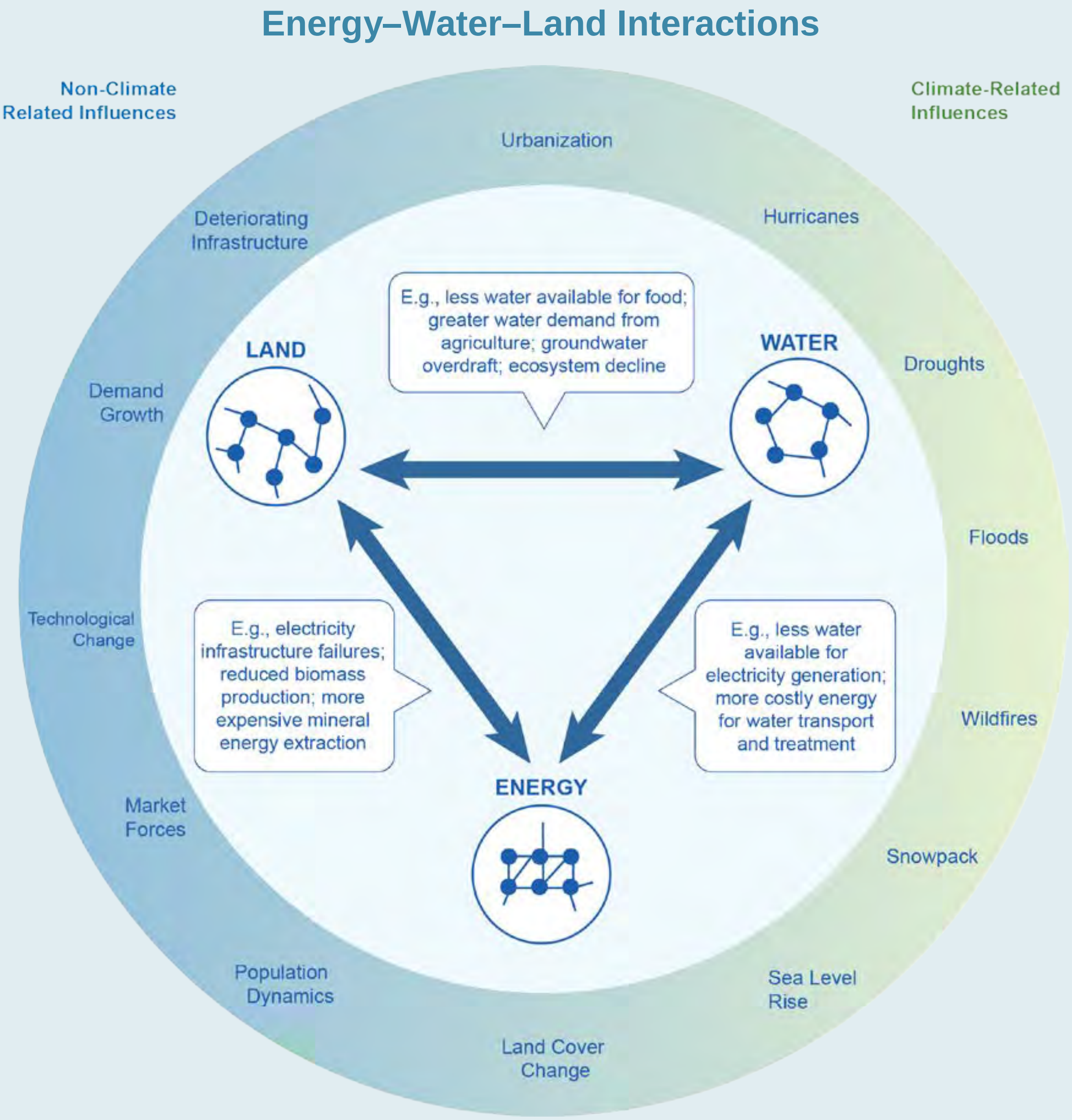


Figure 17.3: Energy, water, and land systems are interconnected and impacted by both climate-related and non-climate stressors. These influences affect these systems individually as well as the dynamics among these sectors. A multisector perspective is necessary to understand risks and develop response strategies that enhance resilience across multiple systems. Sources: Pacific Northwest National Laboratory, Arizona State University, and Cornell University.

Box 17.3: Energy, Water, and Land Linkages, *continued*

The interactions between climate, energy, water, and land in California present a compelling example that illustrates the need to understand complex systems to develop response strategies. Hydropower generation supplies an average of 15% of the state's total electricity consumption,[27] while at the same time the state's thermoelectric power plants rely on water for cooling. Meanwhile, the State Water Project is California's largest single electricity consumer, demanding an average of 2%-3% of total generation for pumping and conveyance.[28] This emphasizes the importance of water for energy and of energy for water.[29] The state's agricultural sector demands approximately 40% of average available freshwater[30] and uses substantial amounts of summer seasonal peak load electricity to pump groundwater, particularly during droughts. Along with uncertainty about future drought and precipitation extremes,[19,31,32] California faces an increasing population, deteriorating infrastructure, and potential energy and water resource limits for an agricultural sector that is evolving to depend on declining groundwater aquifers (Ch. 25: Southwest, KM 1).

The complexity of interconnected energy, water, and land systems highlights the potential impacts of societal choices and the need for institutional integration to explicitly account for sectoral interdependencies and multiple stressors (see Key Message 3).[33,34] Choices in any one sector to confront the many climate-related stressors facing that sector (such as floods, droughts, deteriorating infrastructure, land surface subsidence [sinking], landslides, and wildfires) have the potential to yield cascading cost, reliability, and resilience impacts across the full, connected system (see Key Message 3).[35,36,37,38,39] Taking California's recent droughts as an example, when surface water supplies were strongly curtailed from 2002 to 2016, the result was increased well pumping to meet agricultural demands, which led to a loss of approximately 5.0 cubic miles (20.7 km^3) of groundwater)[40]—or about the size of Lake Powell. Increasing well depths and lost hydropower production influence farmers' decisions about both capital investments in pumping wells and transitions to higher-profit tree and vine crops that cannot be fallowed.[27] Using groundwater as a key economic backstop for agriculture during droughts raises significant concerns about the reversibility of aquifer depletions, the weakening of levees, and accelerating rates of land surface subsidence,[35,39,41,42,43] all of which may alter the future resilience of California's energy, water, and land systems to climate extremes (Ch. 25: Southwest, KM 1).

Key Message 2

Multisector Risk Assessment

Climate change risk assessment benefits from a multisector perspective, encompassing interactions among sectors and both climate and non-climate stressors. Because such interactions and their consequences can be challenging to identify in advance, effectively assessing multisector risks requires tools and approaches that integrate diverse evidence and that consider a wide range of possible outcomes.

The number and complexity of possible interactions among systems affected by climate expand the scope of climate change risk assessment. Recent assessments have acknowledged the importance of this expanded perspective. For example, Chapter 10 of the Third National Climate Assessment (NCA3) [44] highlighted interactions among energy, water, and land systems that people and economies depend on. Other recent climate change impact assessments (e.g., Oppenheimer et al. 2014, Houser et al. 2015, Rosenzweig et al. 2017[45,46,47]) have highlighted risks emerging from interactions among different sectors, geographic regions, and stressors.

A key factor in assessing risk in this context is that it is hard to quantify all the ways in which climate-related stressors might lead to severe or widespread consequences for natural, built, and social systems. A multisector perspective can help identify critical risks ahead of time, but uncertainties will always remain regarding exactly how consequences will materialize in the future. In some cases, interactions are well known. For example, yearly fluctuations in river flows affect hydropower generation, in turn shaping energy costs and profits and reliance on other energy sources (see Box 17.3). Yet even in these cases, it is often difficult to quantify all relevant processes and interactions. Sometimes, interactions are only obvious in retrospect, such as those associated with many past hurricanes (see Box 17.1) or the Northeast blackout (see Box 17.5), with impacts cascading through different parts of the built environment and affecting human health, well-being, and livelihoods. In still other cases, all the relevant interactions are simply not fully understood, for example in the context of the linkages between wildfires, pine bark beetles, and forest management (see Box 17.4).

Therefore, effectively assessing multisector risks requires different tools and approaches than would be applied to understand a single sector by itself. For example, as land management, infrastructure, and climate all change through time, statistical analysis of extreme weather events based on the past becomes less accurate in predicting future outcomes (Ch. 28: Adaptation, KM 2).[48] Approaches can be applied to integrate diverse evidence, combining quantitative and qualitative results and drawing from the natural and social sciences and other forms of analysis.[49,50,51] As one example, models and numerical estimates can be complemented by methods quantifying expert judgment in order to consider uncertainties not well represented by the models. For instance, models and expert judgment have been used together to inform understanding of future sea level rise.[52] Scenarios can also be used to explore preparedness across possible futures, including extreme outcomes that have been rare in historical experience but may be particularly consequential in the future.[50,53,54,55] Such scenarios in assessment can inform understanding of different decisions and choices for managing climate risks, responding to uncertainties about the future by starting with goals and priorities people have.

Box 17.4: Wildfires, Pine Bark Beetles, and Forest Management

Multiple stressors (see Key Message 1) act on U.S. forest ecosystems, impacting wildfire frequency and intensity in complex ways (see Key Message 2) (see also Ch. 6: Forests, KM 1). In the western United States, particularly in Colorado and California, wildfires have become more frequent and larger in area (see Ch. 6: Forests, Figure 6.4; see also Ch. 24: Northwest, KM 1 for an additional example), and this trend is expected to continue as the climate warms (see Ch. 25: Southwest, KM 2).[56] Drought, preceded by warm, wet seasons, can increase fuel flammability and availability. In addition to these climate-related stresses, choices about land use and land-cover change, increased pest populations, human migration, and earth system processes all impact forest ecosystems.[56,57] The interaction of these stressors can alter the vulnerability of these systems, both exacerbating and diminishing the likelihood and impact of wildfire. For example, as humans have moved and expanded the wildland-urban interface, increased fire suppression practices have led to changes in vegetation structure.[58] Without natural fires, vegetation has become denser, resulting in significantly larger and more damaging wildfires.[56] Meanwhile, the interaction of pests with wildfire includes feedback that is oftentimes nonlinear. Warmer winters have allowed pests such as the bark beetle to reach higher elevations and cause significant tree mortality.[59] Insect-killed trees influence fuels and fire behavior, while in some cases wildfire can mitigate the risk of

Box 17.4: Wildfires, Pine Bark Beetles, and Forest Management, *continued*

bark beetle.[58] The impacts of beetle-killed trees on fire likelihood vary over time, with an initial high probability of crown fires followed by the possibility of surface fires.[60]

Wildfires have significant health and economic impacts. Fine particles and ozone precursors released during fires can lead to increased cardiovascular and respiratory damage (Ch. 13: Air Quality, KM 2).[61] Increased wildfires are projected to increase costs associated with health effects, loss of homes and other property, wildfire response, and fuel management.[62] However, risk analysis and planning around wildfire entail the challenge of accounting for all of the stressors acting on the system. Meanwhile, the stressors interact with one another and vary across temporal and sectoral scales (see Key Messages 2 and 4). Efforts are being made to improve prospective vulnerability assessments.[57] The majority of research focuses only on first-order direct fire impacts and fails to recognize indirect and cascading consequences, such as erosion and the health impacts of smoke.[63] To conduct prospective analyses, most modeling efforts include climate and land-use and land-cover change as primary drivers but have a difficult time predicting human-induced stressors such as migration and settlement.[57]

Wildfire at the Wildland–Urban Interface

Figure 17.4: Wildfires pose significant health and economic impacts through interfaces between wildlands and human settlements. Shown here is a wildfire in the Whiskeytown National Recreation Area in California in August 2004. Photo credit: Carol Jandrall, National Park Service.

Key Message 3

Management of Interacting Systems

The joint management of interacting systems can enhance the resilience of communities, industries, and ecosystems to climate-related stressors. For example, during drought events, river operations can be managed to balance water demand for drinking water, navigation, and electricity production. Such integrated approaches can help avoid missed opportunities or unanticipated tradeoffs associated with the implementation of management responses to climate-related stressors.

In interacting systems, management responses within one system influence how other systems respond. Within water basins, for example, upstream management decisions can constrain downstream water-dependent management decisions that affect agriculture, transportation, domestic and commercial use, and environmental protection. Failure to anticipate such interdependencies can lead to missed opportunities for managing the risks of climate change; they can also lead to management responses that increase risks to other parts of the system. For example, the use of groundwater in California as an agricultural backstop in the recent drought may alter California's resilience to future droughts (see Box 17.3).

In practice, managers of agricultural, natural resource, or infrastructure systems do manage at least some degree of system interdependencies. For example, electrical utilities account for the management of water resources to provide power plant cooling capacity, manage fuel supply chains through transportation networks,[64] and manage demand from customers. This requires utilities to acquire appropriate operational permits, licenses, and contracts relevant to other systems and to incorporate the characteristics of those systems in strategic planning and risk management. At the same time, water utilities are users of electricity, particularly those that rely on desalination, which is very energy intensive. Hence, efforts to enhance the resilience of water supply systems to drought can have important consequences for the energy sector and electricity costs.[65] Such indirect risks can be challenging to manage, particularly when system managers have no operational control or jurisdiction over the interacting system. When drought reduced barge traffic on the Mississippi in 2013, farmers had limited options other than seeking more expensive transportation options or incurring delays in getting their products to market.[66,67] More holistic management approaches therefore hold the potential for anticipating these risks and developing effective strategies and practices for risk reduction.

Despite the challenge of managing system interactions, there are opportunities to learn from experience to guide future risk management decisions (Ch. 28: Adaptation, KM 3). The financial sector has invested significantly in understanding and managing systemic risks—including those associated with climate change and climate policy.[68] Mechanisms include risk assessment, financial disclosures, contingency planning, and the development of regulations and industry standards that recognize system interdependencies. Another example is that of the Department of Defense (DoD), which integrates consideration for the implications of climate change and variability for food, water, energy, human migration, supply chains, conflict, and disasters into decision-making and operations around the world.[69] In so doing, the DoD focuses on enhancing preparedness, building partnerships with other public and private organizations, and including climate change in existing planning processes.[69,70]

These strategies are relevant to any organization attempting to enhance its resilience to climate change.

A multisector perspective recognizes that systems have multiple points of vulnerability, that risk can propagate between systems, and that anticipating threats and disruptions requires situational awareness within and between systems.[71,72] Translating the growing awareness of such complexities into the design of policies and practices that effectively address climate change risks, however, requires rethinking how systems are managed in order to identify opportunities for risk reduction or greater efficiency. For example, risk can be reduced by building excess capacity, flexibility, and redundancy into systems.[73] Reserve margins for electricity grids, multi-objective reservoir management, grain storage, multimodal transportation networks, and redundant communications are all mechanisms that provide flexibility for coping with a broad range of risks. Resilience can also be enhanced by planning for system recovery in the event of diverse types of disruptions. For example, restoring power in the wake of a natural disaster is critical for restoring other services such as transportation, water, health, and communications (see Box 17.5). Nevertheless, the costs of designing, constructing, operating, and monitoring resilient, interacting systems that are robust to multiple sources of stress can be significant. Hence, consideration of the costs and benefits of resilience over the entire life cycle of the system may be necessary to make the business case.

Box 17.5: Cascading Failures: Electricity, Public Health, and the 2003 Northeast Blackout

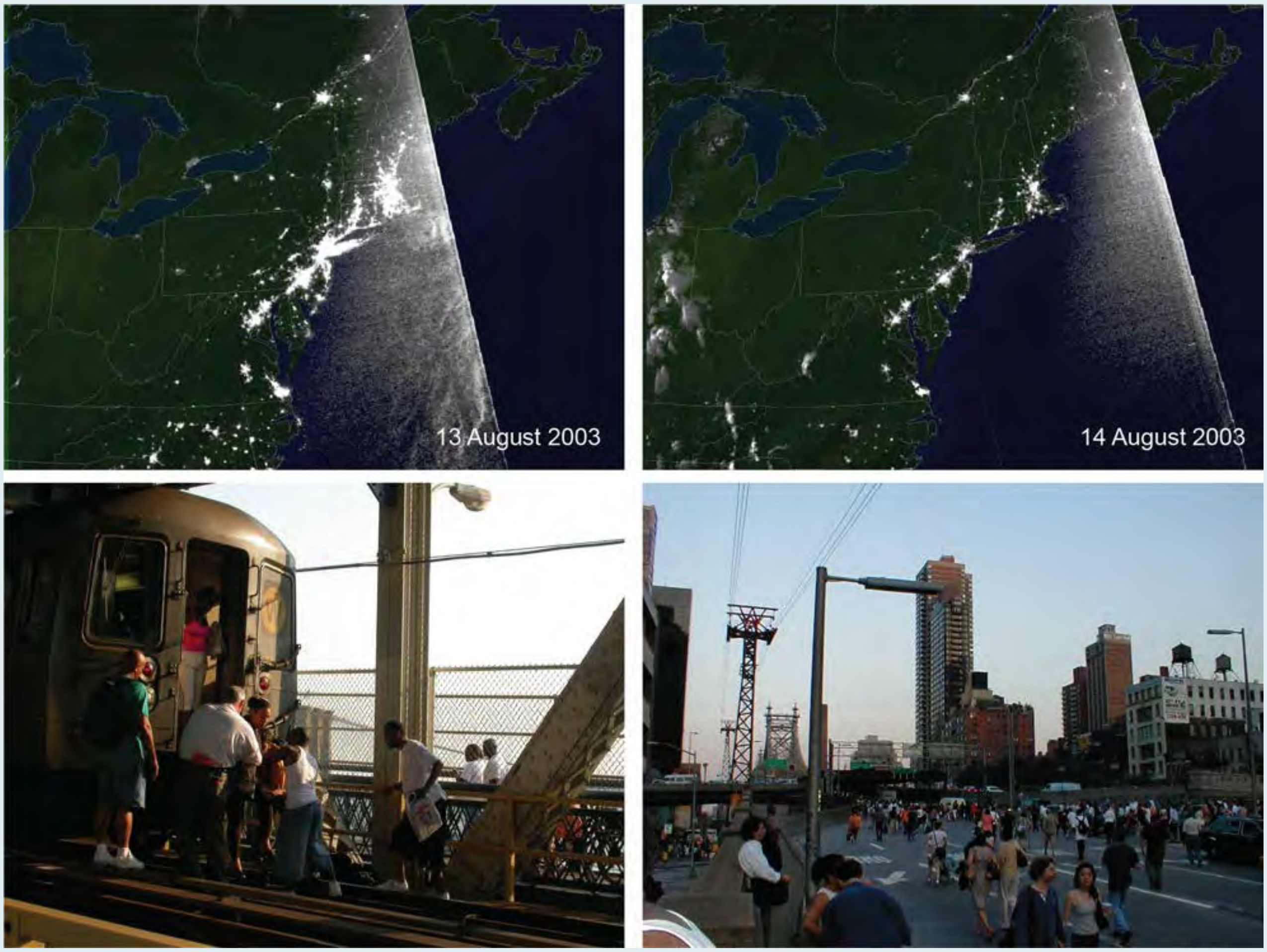
The interactions among severe weather, electric power infrastructure, and public health demonstrate how impacts can cascade within and across sectors (see Key Message 1) and how risk management depends on understanding these interactions (see Key Message 3). The 2016 Climate and Health Assessment identified the impacts of climate-related extreme events on critical infrastructure as a major threat to public health, but it also emphasized the influence of non-climatic factors such as inequalities in income and education as well as individual behavioral choices on health outcomes (Ch. 14: Human Health, KM 1).[67]

More frequent and severe heat waves in many parts of the United States would increase stresses on electric power, increasing the risk of cascading failures within the electric power network that could propagate into other sectors (Ch. 4: Energy, KM 1).[74] Hot weather increases demand for electricity, mostly for residential air conditioning, while reducing transmission efficiency and pushing power infrastructure closer to its operating tolerances (Ch. 4: Energy, KM 1).[75] The Northeast blackout in August 2003, which affected the Northeast and the Canadian province of Ontario, is a familiar example of a cascading network failure that has been well documented (Figure 17.5) (see also Ch. 11: Urban, KM 3). In 2003, a single electrical line warmed on a hot day and sagged into vegetation, tripping out of service. Redirected power overloaded other lines, causing them to trip as well. The disruption cascaded through the network until at the peak of the outage it affected an estimated 50 million people in the Northeast and Canada's Ontario province.[76] Depending on the location, the outage lasted several hours to up to two days, resulting in economic losses of $4-$10 billion due to disruption of businesses and industries.[76]

In the decade following the blackout, despite improvements in reliability and vegetation control standards, weather-related outages actually increased, accounting for 80% of major outages reported; about 20% of weather-related outages cause cascading failures.[77] In addition, today's grid is increasingly large, complex, and heavily loaded, which some researchers suggest increases the potential for blackouts.[78,79] Conversely, others suggest that tighter integration with communications and information technology (IT) infrastructure will improve resilience.[80]

Box 17.5: Cascading Failures: Electricity, Public Health, and the 2003 Northeast Blackout, *continued*

Given the challenges facing today's grid, lessons from the 2003 blackout can still help the public health sector plan for and manage complex consequences of disruptions to interacting infrastructures.[81] Power outages compromise other critical infrastructures, including telecommunications, IT infrastructure, transportation systems, and water and wastewater treatment. In 2003, these disruptions had a broad range of implications for public health, including reduced access to medical equipment and pharmacies, isolation in multistory buildings, slow emergency response times, hospital closures, and temporary loss of disease surveillance systems.[82,83] These impacts translated into health consequences; one study estimated that the event caused 90 excess deaths during August.[83] Maintaining a resilient healthcare infrastructure system therefore depends on being able to successfully adapt, respond, and recover when supporting infrastructure systems are disrupted (see Key Message 3).[84] This reflects the importance of emergency response and disaster risk reduction planning at the community level as well as consideration of the health implications of urban design and infrastructure planning.[67]



Northeast Blackout

Figure 17.5: During the August 2003 blackout, an estimated 50 million people in Canada and the northeastern United States lost power, with cascading impacts on public health and critical infrastructure. These images show (clockwise from upper left): nighttime satellite imagery of the area before the outage; the same view during the blackout; people walking on the Manhattan Bridge; and passengers being evacuated from a subway train on the Manhattan Bridge during the outage. Image credits: (top) NOAA; (bottom left) Jack Szwergold (CC BY-NC 2.0); (bottom right) Eric Skiff (CC BY-SA 2.0).

Key Message 4

Advancing Knowledge

Predicting the responses ofcomplex, interdependent systems will depend on developing meaningful models of multiple, diverse systems, including human systems, and methods for characterizing uncertainty.

Although it is clear that climate-related and non-climate stressors impact multiple natural, built, and social systems simultaneously, thereby altering societal risks, the tools available for predicting these dynamics lag those that predict the dynamics of individual systems. There are many existing modeling efforts that explore complex natural systems, including climate models and numerical weather forecasting models. Although these models are applied to scenarios driven by social and policy decisions, the models themselves rarely incorporate the feedback relationships to social systems and policy contexts.[85,86,87,88] Engineering and resource management models that explicitly incorporate societal economic decisions and represent built systems at a very high resolution have not traditionally been linked to climate projections. Some integrated human–earth system models are explicitly designed to identify system linkages but frequently lack key features or sufficient resolution of the inherent dynamics of the natural environment.[89,90] These and other intersectoral models are also used to create scenarios of how combined natural–human systems might evolve (for example, the Shared Socioeconomic Pathways [SSPs]) (see Scenario Products section of App. 3).[53] Such scenarios can be useful for exploring the range of possible outcomes of larger trends, but the results should not be considered predictive. There is a large gap, therefore, in the multisector and multiscale tools and frameworks that are available to describe how different human systems interact with one another and with the earth system and how those interactions affect the total system response to the many stressors they are subject to, including climate-related stressors.[91] However, increasing recognition of this gap has given rise to a number of innovative research projects that seek to directly link climate scenarios or earth system models to high-resolution models of built infrastructure and human systems (e.g., Allen et al. 2016; Voisin et al. 2016; Ke et al. 2016; Zhou et al. 2017, 2018; Tidwell et al. 2016[92,93,94,95,96,97]).

The responses of interacting systems to both climate-related and non-climate stressors exhibit deep uncertainty, especially when interactions with societal decisions are included. Deep uncertainty arises when there is a lack of clarity about the appropriate models to apply, the relative probability of various scenarios, and the desirability of alternative outcomes.[98] Risk management decisions must therefore be made in the face of these uncertainties (see Key Message 2). An important research challenge is therefore advancing scientific methods and tools that can be applied in climate research, risk assessment, and risk management for complex, interdependent systems under deep uncertainty.[99]

Acknowledgments

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Opening Image Credit

Landslide in California: © gece33/E+/Getty Images.

Traceable Accounts

Process Description

The scope of this chapter was developed to fill a gap in previous National Climate Assessments (NCAs), notably the risks that emerge from interactions among sectors. Previous NCAs have touched on this subject, for example the energy, water, and land use chapter in the Third National Climate Assessment (NCA3). However, these assessments never included a chapter specifically focused on a general treatment of this topic. Emerging scientific research is highlighting the links between sectors and the potential complexity and implications of these interactions, from complex system dynamics such as cascading failures to management approaches and approaches to risk. These concepts were then incorporated into a detailed terms of reference for the chapter, outlining the scope and the general content to be included in the document.

The author team for this chapter was constructed to bring together the necessary diverse experience, expertise, and perspectives. Our authors brought expertise and experience in multiscale, multisector research and modeling, with a focus in specific sectors or sectoral combinations including critical infrastructure, energy–water–land interactions, and ecosystems. The authors also had expertise in complex systems science and previous experience in assessment processes.

The chapter was developed through technical discussions, a literature review, and expert deliberation by chapter authors through email and phone discussions. The team evaluated the state of the science on the analysis of sectoral interdependencies, compounding stressors, and complex system science. Case studies were drawn from a range of sources intended to represent the key themes in the chapter.

Key Message 1

Interactions Among Sectors

The sectors and systems exposed to climate (for example, energy, water, and agriculture) interact with and depend on one another and other systems less directly exposed to climate (such as the financial sector). In addition, these interacting systems are not only exposed to climate-related stressors such as floods, droughts, and heat waves, they are also subject to a range of non-climate factors, from population movements to economic fluctuations to urban expansion. These interactions can lead to complex behaviors and outcomes that are difficult to predict. It is not possible to fully understand the implications of climate change on the United States without considering the interactions among sectors and their consequences. (*High Confidence*)

Description of evidence base

A suite of examples across this assessment and within this chapter demonstrate the interactions between systems and the potentially important implications of these linkages. Examples in this chapter include Hurricane Harvey; the 2003 Northeast blackout; energy–water–land systems in California and throughout the nation; forest systems facing influences from wildfires, drought, and pine bark beetles; and the implications of the reintroduction of wolves in Yellowstone. Each of these examples is supported by its own evidence base; the linkages between systems and the importance of non-climate influences is self-evident from these examples. Beyond these examples, a small set of recent literature has begun to explore ways to more systematically quantify the implications of including sectoral interdependencies in climate risk assessment (e.g., Harrison et al. 2016[8]).

In addition to literature specific to risk assessment in the context of climate change, there is a long history of research on complex systems[11] that raises the potential for a range of dynamics that might emerge from sectoral interdependencies and compounding stressors. This includes research spanning disciplines from meteorology[12] to ecology[13] to paleontology[14] to computer science.[15] This literature supports the conclusion that more complex dynamics may occur when multiple systems interact with one another.

Major uncertainties

The interactions between sectors and systems relevant to climate risk assessment are self-evident, and there are clear examples of unanticipated dynamics emerging from these interactions in the past. Yet our understanding is limited regarding the precise nature of complex system behavior in the context of climate risk assessment and its ultimate influence on the outcomes of such assessments. As noted in Key Message 4, the available tools and frameworks are simply not sufficient at this point to identify key risks emerging from intersectoral interdependencies and compounding stressors.

Description of confidence and likelihood

We have *high confidence* in this message, because there is high agreement and extensive evidence that a range of critical intersectoral interdependencies and compounding stressors are present and relevant to climate risk assessment. At the same time, the precise impact of these on system dynamics is not well understood.

Key Message 2

Multisector Risk Assessment

Climate change risk assessment benefits from a multisector perspective, encompassing interactions among sectors and both climate and non-climate stressors. Because such interactions and their consequences can be challenging to identify in advance, effectively assessing multisector risks requires tools and approaches that integrate diverse evidence and that consider a wide range of possible outcomes. *(High Confidence)*

Description of evidence base

Recent climate change assessments (e.g., Oppenheimer et al. 2014, Houser et al. 2015[45,46]) emphasize that a multisector perspective expands the scope of relevant risks and uncertainties associated with climate change impacts. Assessing these risks requires attention to multiple interacting sectors, geographic regions, and stressors, such as 1) interactions in the management of water, land, and energy (see Box 17.3), or 2) spatial compounding of impacts if, for example, multiple infrastructure systems fail within a city (see Box 17.1). Risk assessment also requires attention to indirect and long-distance climate change impacts, for instance resulting from human migration or conflict.[45,100] Analyses of historical events (see Box 17.5), evaluations of statistical risk (e.g., Carleton and Hsiang 2016[101]), and process-based modeling projections are some of the methods demonstrating these complex interactions across sectors, scales, and stressors.

Different tools and approaches are required to assess multisector risks. Approaches can be applied to integrate diverse evidence, combining quantitative and qualitative results and drawing from the natural and social sciences and other forms of analysis.[47,49,51] For instance, models and expert judgment have been used together to inform our understanding of future sea level rise,[52] and scenarios can also be used to explore preparedness across possible futures.[53,54,55]

Major uncertainties

For interdependent systems affected by multiple stressors, the number and complexity of possible interactions are greater, presenting deeper uncertainties. It is often difficult or impossible to represent all relevant processes and interactions in analyses of risks, especially quantitatively. For example, quantitative projections can evaluate probabilities of well-understood sectoral interactions but will be limited by processes or parameters that are poorly known or unknowable. This is why the integration of diverse evidence and attention to deeper uncertainties are important in multisector risk assessment.

Description of confidence and likelihood

We have *high confidence* in this Key Message because there is high agreement that a multisector perspective alters risk assessment, as is reflected in recent climate change assessments. However, the evidence basis for multisector evaluations is emerging.

Key Message 3

Management of Interacting Systems

The joint management of interacting systems can enhance the resilience of communities, industries, and ecosystems to climate-related stressors. For example, during drought events, river operations can be managed to balance water demand for drinking water, navigation, and electricity production. Such integrated approaches can help avoid missed opportunities or unanticipated tradeoffs associated with the implementation of management responses to climate-related stressors. *(High Confidence)*

Description of evidence base

Recent literature has documented that the management of interacting infrastructure systems is a key factor influencing their resilience to climate and other stressors. A range of studies have argued that the complexity of institutional arrangements in mature, democratic economies like the United States poses challenges to the pursuit of climate adaptation objectives and sustainability more broadly.[72,102,103,104,105] The complexity associated with interacting systems of systems poses significant challenges to integrated management.[105] The allocation of authority and responsibility for system management across multiple levels of government as well as between public and private sectors often contributes to decision-making by one actor being enabled or constrained by other actors.[72,103]

The interdependencies among systems reflect the potential value in the development of more integrated management strategies.[72] This concept of integrated management is reflected in existing literatures, particularly those associated with integrated water resources management [106,107,108,109] and integrated infrastructure planning.[110,111,112] Such studies often address integration within sectors or systems, with less consideration for integration between or among systems. This has the potential to lead to missed opportunities for improving management practice.[72] However, assessments of energy,[113] urban infrastructure,[75] and coupled energy–water–land[114] systems conducted as part of NCA3[44] identified a range of interdependencies across multiple sectors (see Dawson 2015[115]).

A range of strategies have been proposed for enhancing the capacity to manage system interdependencies and climate change risk. Significant effort has been invested in understanding and modeling system dynamics to enhance capabilities for risk and vulnerability assessment. These efforts have largely focused on physical infrastructure systems, infrastructure networks, and the potential for cascading failures.[116,117,118,119] Such capabilities help to identify what can be monitored in complex systems to enhance situational awareness, anticipate disruptions, and increase resilience.[71,120,121]

There is ample evidence of comanagement of interdependent systems, often as a function of resource assurance and/or contingency planning. For example, the use of water for electricity generation (hydropower or cooling in thermal generation) involves regulatory constraints around water use as well as operational decision-making regarding water management.[72,114,122,123,124,125] These interactions have been a major focus of studies addressing the climate–water–energy nexus. Meanwhile, emergency managers as well as agricultural, commercial, and industrial supply chains often develop contingency plans in the event of disruptions of transportation, telecommunica- tions, water, and/or electricity.[81,126,127,128,129]

A key element of such planning is to build redundancy and flexibility into system operations.[73] Evidence suggests that adding flexibility or robustness to systems or transforming systems such that they interact or behave in fundamentally different ways can increase construction, maintenance, or procurement costs.[82,130,131] However, a number of studies exploring the valuation of resilience actions and investments have concluded that the benefits of resilience interventions can be significantly greater than the costs, provided the long-term mitigating effects of the intervention are factored in.[132,133,134]

Given the complexity of governance systems, the responsibility for the design and implementation of such strategies for integrated management rests on a broad range of actors. Over the latter part of the 20th century, the privatization of infrastructure, including energy, telecommunications, and water, transferred infrastructure management, responsibility, and risk to the private sector.[135] Nevertheless, local, state, and federal governments continue to have critical roles in regulation, risk assessment, and research and development. In addition, many institutions, organizations, and individuals either have infrastructure dependencies or influence the dynamics, operations, investment, and performance of infrastructure.[136] The increasing interconnectedness of both infrastructure and the people who use and manage that infrastructure is leading to both new challenges and opportunities for comanaging these systems, particularly in urban areas.[137,138,139]

A growing literature is identifying opportunities to enhance consideration of human health and other benefits in the design of urban landscapes and infrastructure.[67,140,141,142,143]

Major uncertainties

The dominant uncertainties associated with the management of climate risks and system interdependencies include understanding indirect effects and feedbacks between systems, particularly with respect to predicting system responses. Technological change could have significant implications for the resilience, interconnectedness, and responses of systems to climate-related stressors and other disturbances. Such change could increase the complexity of integrated management with implications that could be positive or negative with respect to vulnerability. In addition, the future evolution of governance and regulatory dimensions of infrastructures systems, as well as consumer choices and behavior, are associated with irreducible uncertainty, largely because they involve choices yet to be made.

Description of confidence and likelihood

There is high agreement and extensive evidence that institutional arrangements and governance are critical to the management of systems and their interdependencies. This finding is reflected in scientific assessments, modeling studies, and observations of system responses and performance, as well as in theories emerging from complex systems science. Furthermore, a history of management practice associated with water, energy, transportation, telecommunications, food, and health systems that spans decades to centuries provides evidence for the importance of system interdependencies. Thus, there is *high confidence* in this message.

Key Message 4

Advancing Knowledge

> Predicting the responses of complex, interdependent systems will depend on developing meaningful models of multiple, diverse systems, including human systems, and methods for characterizing uncertainty. *(High Confidence)*

Description of evidence base

This Key Message is based on an understanding of a range of analyses and modeling tools described throughout the chapter.

Major uncertainties

Because the Key Message is the authors' assessment of the overall state of development of research tools and models, and the subsequent importance of developing research tools, the concept of major uncertainties is not entirely appropriate. This is a matter of the authors' judgment, not calculation or assessment of underlying probabilities.

Description of confidence and likelihood

See above. No likelihood statement is appropriate, and the *high confidence* is based on the authors' assessment of the underlying literature and development of methods and modeling tools.

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18 Northeast

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18 Northeast

Bartram Bridge in Pennsylvania

Key Message 1

Changing Seasons Affect Rural Ecosystems, Environments, and Economies

The seasonality of the Northeast is central to the region's sense of place and is an important driver of rural economies. Less distinct seasons with milder winter and earlier spring conditions are already altering ecosystems and environments in ways that adversely impact tourism, farming, and forestry. The region's rural industries and livelihoods are at risk from further changes to forests, wildlife, snowpack, and streamflow.

Key Message 2

Changing Coastal and Ocean Habitats, Ecosystems Services, and Livelihoods

The Northeast's coast and ocean support commerce, tourism, and recreation that are important to the region's economy and way of life. Warmer ocean temperatures, sea level rise, and ocean acidification threaten these services. The adaptive capacity of marine ecosystems and coastal communities will influence ecological and socioeconomic outcomes as climate risks increase.

Key Message 3

Maintaining Urban Areas and Communities and Their Interconnectedness

The Northeast's urban centers and their interconnections are regional and national hubs for cultural and economic activity. Major negative impacts on critical infrastructure, urban economies, and nationally significant historic sites are already occurring and will become more common with a changing climate.

Key Message 4

Threats to Human Health

Changing climate threatens the health and well-being of people in the Northeast through more extreme weather, warmer temperatures, degradation of air and water quality, and sea level rise. These environmental changes are expected to lead to health-related impacts and costs, including additional deaths, emergency room visits and hospitalizations, and a lower quality of life. Health impacts are expected to vary by location, age, current health, and other characteristics of individuals and communities.

Key Message 5

Adaptation to Climate Change Is Underway

Communities in the Northeast are proactively planning and implementing actions to reduce risks posed by climate change. Using decision support tools to develop and apply adaptation strategies informs both the value of adopting solutions and the remaining challenges. Experience since the last assessment provides a foundation to advance future adaptation efforts.

Executive Summary

The distinct seasonality of the Northeast's climate supports a diverse natural landscape adapted to the extremes of cold, snowy winters and warm to hot, humid summers. This natural landscape provides the economic and cultural foundation for many rural communities, which are largely supported by a diverse range of agricultural, tourism, and natural resource-dependent industries (see Ch. 10: Ag & Rural, Key Message 4).[1] The recent dominant trend in precipitation throughout the Northeast has been towards increases in rainfall intensity,[2] with increases in intensity exceeding those in other regions of the contiguous United States. Further increases in rainfall intensity are expected,[3] with increases in total precipitation expected during the winter and spring but with little change in the summer.[4] Monthly precipitation in the Northeast is projected to be about 1 inch greater for December through April by end of century (2070–2100) under the higher scenario (RCP8.5).[4]

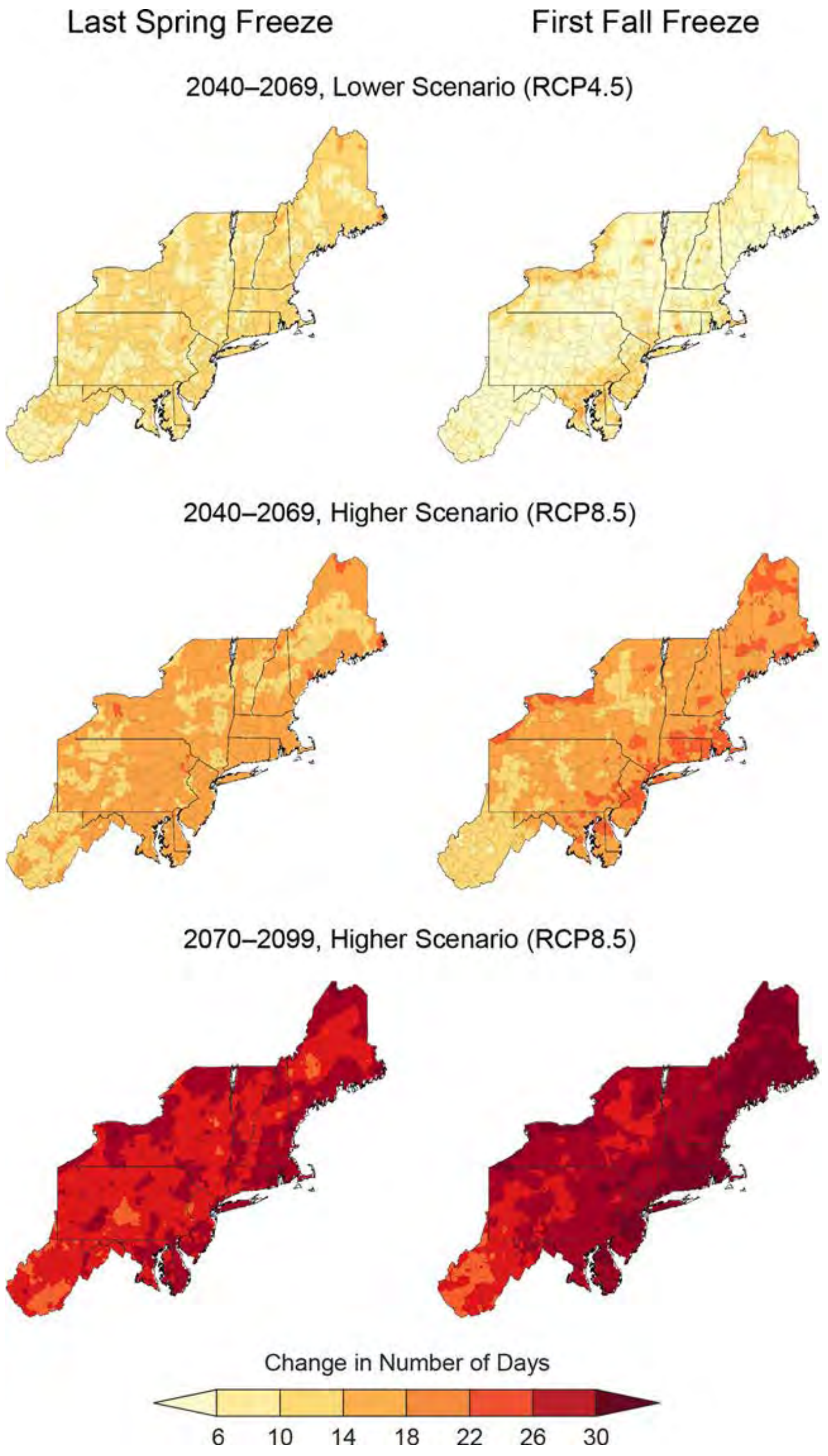
Ocean and coastal ecosystems are being affected by large changes in a variety of climate-related environmental conditions. These ecosystems support fishing and aquaculture,[5] tourism and recreation, and coastal communities.[6] Observed and projected increases in temperature, acidification, storm frequency and intensity, and sea levels are of particular concern for coastal and ocean ecosystems, as well as local communities and their interconnected social and economic systems. Increasing temperatures and changing seasonality on the Northeast Continental Shelf have affected marine organisms and the ecosystem in various ways. The warming trend experienced in the Northeast Continental Shelf has been associated with many fish and invertebrate species moving northward and to greater depths.[7,8,9,10,11] Because of the diversity of the Northeast's coastal landscape, the impacts from storms and sea level rise will vary at different locations along the coast.[12,13]

Northeastern cities, with their abundance of concrete and asphalt and relative lack of vegetation, tend to have higher temperatures than surrounding regions due to the urban heat island effect. During extreme heat events, nighttime temperatures in the region's big cities are generally several degrees higher than surrounding regions, leading to higher risk of heat-related death. Urban areas are at risk for large numbers of evacuated and displaced populations and damaged infrastructure due to both extreme precipitation events and recurrent flooding, potentially requiring significant emergency response efforts and consideration of a long-term commitment to rebuilding and adaptation, and/or support for relocation where needed. Much of the infrastructure in the Northeast, including drainage and sewer systems, flood and storm protection assets, transportation systems, and power supply, is nearing the end of its planned life expectancy. Climate-related disruptions will only exacerbate existing issues with aging infrastructure. Sea level rise has amplified storm impacts in the Northeast (Key Message 2), contributing to higher surges that extend farther inland, as demonstrated in New York City in the aftermath of Superstorm Sandy in 2012.[14,15,16] Service and resource supply infrastructure in the Northeast is at increasing risk of disruption, resulting in lower quality of life, economic declines, and increased social inequality.[17] Loss of public services affects the capacity of communities to function as administrative and economic centers and triggers disruptions of interconnected supply chains (Ch. 16: International, Key Message 1).

Increases in annual average temperatures across the Northeast range from less than 1°F (0.6°C) in West Virginia to about 3°F (1.7°C) or more in New England since 1901.[18,19] Although the relative risk of death on very hot days is lower today than it was a few decades ago, heat-related illness and death remain significant public health problems in the Northeast.[20,21,22,23] For example, a study in New York City estimated that in 2013 there were 133 excess deaths due to extreme heat.[24] These projected increases in temperature are expected to lead to substantially more premature deaths, hospital admissions, and emergency department visits across the Northeast.[23,25,26,27,28,29] For example, in the Northeast we can expect approximately 650 additional premature deaths per year from extreme heat by the year 2050 under either a lower (RCP4.5) or higher (RCP8.5) scenario and from 960 (under RCP4.5) to 2,300 (under RCP8.5) more premature deaths per year by 2090.[29]

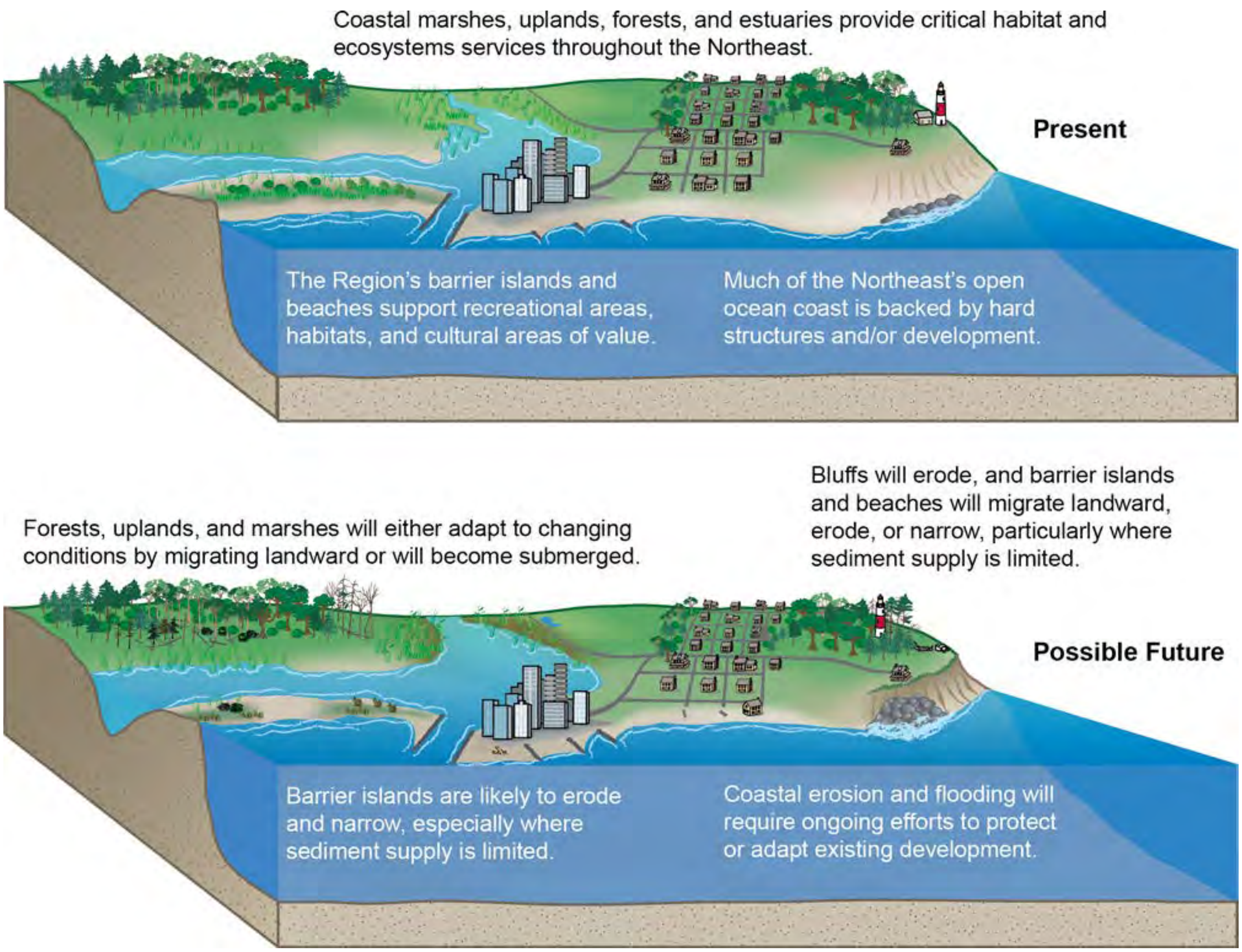
Communities, towns, cities, counties, states, and tribes across the Northeast are engaged in efforts to build resilience to environmental challenges and adapt to a changing climate. Developing and implementing climate adaptation strategies in daily practice often occur in collaboration with state and federal agencies (e.g., New Jersey Climate Adaptation Alliance 2017, New York Climate Clearinghouse 2017, Rhode Island STORMTOOLS 2017, EPA 2017, CDC 2015[30,31,32,33,34]). Advances in rural towns, cities, and suburban areas include low-cost adjustments of existing building codes and standards. In coastal areas, partnerships among local communities and federal and state agencies leverage federal adaptation tools and decision support frameworks (for example, NOAA's Digital Coast, USGS's Coastal Change Hazards Portal, and New Jersey's Getting to Resilience). Increasingly, cities and towns across the Northeast are developing or implementing plans for adaptation and resilience in the face of changing climate (e.g., EPA 2017[33]). The approaches are designed to maintain and enhance the everyday lives of residents and promote economic development. In some cities, adaptation planning has been used to respond to present and future challenges in the built environment. Regional efforts have recommended changes in design standards when building, replacing, or retrofitting infrastructure to account for a changing climate.

Lengthening of the Freeze-Free Period



These maps show projected shifts in the date of the last spring freeze (left column) and the date of the first fall freeze (right column) for the middle of the century (as compared to 1979–2008) under the lower scenario (RCP4.5; top row) and the higher scenario (RCP8.5; middle row). The bottom row shows the shift in these dates for the end of the century under the higher scenario. By the middle of the century, the freeze-free period across much of the Northeast is expected to lengthen by as much as two weeks under the lower scenario and by two to three weeks under the higher scenario. By the end of the century, the freeze-free period is expected to increase by at least three weeks over most of the region. *From Figure 18.3 (Source: adapted from Wolfe et al. 2018*[35]*).*

Coastal Impacts of Climate Change



Coastal marshes, uplands, forests, and estuaries provide critical habitat and ecosystems services throughout the Northeast.

The Region's barrier islands and beaches support recreational areas, habitats, and cultural areas of value.

Much of the Northeast's open ocean coast is backed by hard structures and/or development.

Forests, uplands, and marshes will either adapt to changing conditions by migrating landward or will become submerged.

Bluffs will erode, and barrier islands and beaches will migrate landward, erode, or narrow, particularly where sediment supply is limited.

Barrier islands are likely to erode and narrow, especially where sediment supply is limited.

Coastal erosion and flooding will require ongoing efforts to protect or adapt existing development.

(top) The northeastern coastal landscape is composed of uplands and forested areas, wetlands and estuarine systems, mainland and barrier beaches, bluffs, headlands, and rocky shores, as well as developed areas, all of which provide a variety of important services to people and species. (bottom) Future impacts from intense storm activity and sea level rise will vary across the landscape, requiring a variety of adaptation strategies if people, habitats, traditions, and livelihoods are to be protected. *From Figure 18.7 (Source: U.S. Geological Survey)*.

Background

The Northeast region is characterized by four distinct seasons and a diverse landscape that is central to the region's cultural identity, quality of life, and economic success. It is both the most heavily forested and most densely populated region in the country. Residents have ready access to beaches, forests, and other natural areas and use them heavily for recreation. Colorful autumn foliage, winter recreation, and summer vacations in the mountains or at the beach are all important parts of the Northeast's cultural identity, and this tourism contributes billions of dollars to the regional economy. The seasonal climate, natural systems, and accessibility of certain types of recreation are threatened by declining snow and ice, rising sea levels, and rising temperatures. By 2035, and under both lower and higher scenarios (RCP4.5 and RCP8.5), the Northeast is projected to be more than 3.6°F (2°C) warmer on average than during the preindustrial era. This would be the largest increase in the contiguous United States and would occur as much as two decades before global average temperatures reach a similar milestone.[36]

The region's oceans and coasts support a rich maritime heritage and provide an iconic landscape, as well as economic and ecological services. Highly productive marshes,[37,38] fisheries,[39,40] ecosystems,[41,42] and coastal infrastructure[43,44] are sensitive to changing environmental conditions, including shifts in temperature, ocean acidification, sea level, storm surge, flooding, and erosion. Many of these changes are already affecting coastal and marine ecosystems, posing increasing risks to people, traditions, infrastructure, and economies (e.g., Colburn et al. 2016[45]). These risks are exacerbated by increasing demands on these ecosystems to support human use and development. The Northeast has experienced some of the highest rates of sea level rise[46] and ocean warming[39] in the United States, and these exceptional increases relative to other regions are projected to continue through the end of the century.[47,48,49,50]

The Northeast is quite varied geographically, with a wide spectrum of communities including densely populated cities and metropolitan regions and relatively remote hamlets and villages (Figure 18.1). Rural and urban areas have distinct vulnerabilities, impacts, and adaptation responses to climate change.[51,52] The urbanized parts of the Northeast are dependent on the neighboring rural areas' natural and recreational services, while the rural communities are dependent on the economic vitality and wealth-generating capacity of the region's major cities. Rural and urban communities together are under increasing threat of climate change and the resulting impacts, and adaptation strategies reveal their interdependence and opportunities for successful climate resilience.[51] Rural–urban linkages[53,54,55] in the region could also be altered by climate change impacts.

In rural areas, community identity is often built around the prominence of small, multigenerational, owner-operated businesses and the natural resources of the local area. Climate variability can affect human migration patterns[56] and may change flows into or out of the Northeast as well as between rural and urban locations. Published research in this area, however, is limited. The Northeast has long been losing residents to other regions of the country.[57] Droughts and flooding can adversely affect ecosystem function, farm economic viability, and land use. Although future projections of major floods remain ambiguous, more intense precipitation events (Ch. 2: Climate, KM 6)[58] have increased the risk of some types of inland floods, particularly in valleys, where people, infrastructure, and agriculture tend to be concentrated. With little redundancy in their infrastructure and, therefore, limited economic resilience, many rural communities have limited ability to cope with climate-related changes.

Population Density

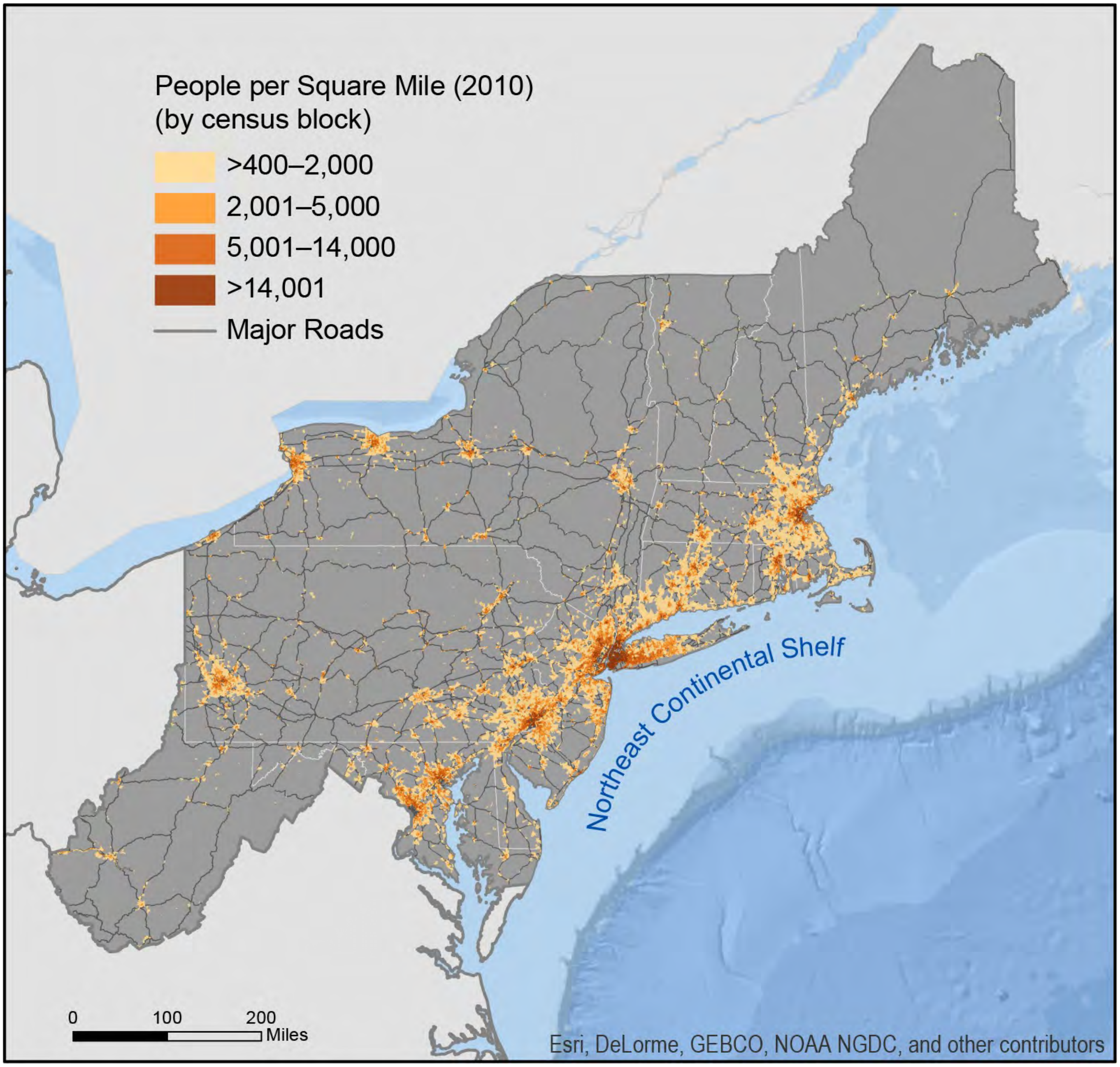


Figure 18.1: A satellite mosaic overlaid with primary roads and population density highlights the diverse characteristics of the region in terms of settlement patterns, interconnections among population centers of varying sizes, and variability in relief across the ocean shelf. Sources: U.S. Department of Transportation, U.S. Geological Survey, and ERT, Inc.

Residents in urban areas face multiple climate hazards, including temperature extremes, episodes of poor air quality, recurrent waterfront and coastal flooding, and intense precipitation events that can lead to increased flooding on urban streams. These physical changes may lead to large numbers of evacuated and displaced populations and damaged infrastructure; sustaining communities may require significant investment and planning to provide emergency response efforts, a long-term commitment to rebuilding and adaptation, and support for relocation. Underrepresented communities, such as the poor, elderly, language-isolated, and recent immigrants, are more vulnerable due to their limited ability to prepare for and cope with extreme weather and climate events.[59] Service infrastructure in the Northeast is at increasing risk of disruption, resulting in lower quality of life, economic declines, and enhanced social inequality.[17] Interdependencies across critical infrastructure sectors such as water, energy, transportation, and telecommunication (and related climate security issues) can lead to cascading failures during extreme weather and climate-related disruptions (Ch. 17: Complex Systems).[17,59,60] The region's high density of built environment sites and facilities, large number of historic structures, and older housing and infrastructure compared to other regions suggest that urban centers in the Northeast are particularly vulnerable to climate shifts and extreme weather events. For example, because much of the historical development of industry and commerce in New England occurred along rivers, canals, coasts, and other bodies of water, these areas often have a higher density of contaminated sites, waste management facilities, and petroleum storage facilities that are potentially vulnerable to flooding. As a result, increases in flood frequency or severity could increase the spread of contaminants into soils and waterways, resulting in increased risks to the health of nearby ecosystems, animals, and people—a set of phenomena well documented following Superstorm Sandy.[61,62,63]

The changing climate of the Northeast threatens the health and well-being of residents through environmental changes that lead to health-related impacts and costs, including additional deaths, emergency room visits and hospitalizations, higher risk of infectious diseases, lower quality of life, and increased costs associated with healthcare utilization. Health impacts of climate change vary across people and communities of the Northeast and depend on social, socioeconomic, demographic, and societal factors; community adaptation efforts; and underlying individual vulnerability (see Key Message 5) (see also Ch. 28: Adaptation).

Maintaining functioning, sustainable communities in the face of climate change requires effective adaptation strategies that anticipate and buffer impacts, while also enabling communities to capitalize upon new opportunities. Many northeastern cities already have or are rapidly developing short-term and long-term plans to mitigate climate effects and to plan for efficient investments in sustainable development and long-term adaptation strategies. Although timely adaptation to climate-related impacts would help reduce threats to people's health, safety, economic well-being, and ways of life, changes to those societal elements will not be avoided completely.

Key Message 1

Changing Seasons Affect Rural Ecosystems, Environments, and Economies

The seasonality of the Northeast is central to the region's sense of place and is an important driver of rural economies. Less distinct seasons with milder winter and earlier spring conditions are already altering ecosystems and environments in ways that adversely impact tourism, farming, and forestry. The region's rural industries and livelihoods are at risk from further changes to forests, wildlife, snowpack, and streamflow.

The distinct seasonality of the Northeast's climate supports a diverse natural landscape adapted to the extremes of cold, snowy winters and warm to hot, humid summers. This natural landscape provides the economic and cultural foundation for many rural communities, which are largely supported by a diverse range of agricultural, tourism, and natural resource-dependent industries (Ch. 10: Ag & Rural, KM 4).[1] The outdoor recreation industry contributes nearly $150 billion in consumer spending to the Northeast economy and supports more than one million jobs across the region.[64] Additionally, agriculture, fishing, forestry, and related industries together generate over $100 billion in economic activity annually, supporting more than half a million jobs in production and processing region-wide.[65] Projected changes in the Northeast's seasons will continue to affect terrestrial and aquatic ecosystems, forest productivity, agricultural land use, and other resource-based industries.[1] Alpine, freshwater aquatic, and certain forest habitats are most at risk.[66] Without efforts to mitigate climate change, warming winters and earlier spring conditions under a higher scenario (RCP8.5) will affect native ecosystems and the very character of the rural Northeast.[67]

Seasonal differences in Northeast temperature have decreased in recent years as winters have warmed three times faster than summers.[3] By the middle of this century, winters are projected to be milder still, with fewer cold extremes, particularly across inland and northern portions of the Northeast.[3] This will likely result in a shorter and less pronounced cold season with fewer frost days and a longer transition out of winter into the growing season.[68] Under the higher scenario (RCP8.5), the trend of decreasing seasonality continues for the northern half of the region through the end of the century, but by then summer temperatures across the Mid-Atlantic are projected to rise faster than those in winter.[4]

A Changing Winter–Spring Transition

Forests are already responding to the ongoing shift to a warmer climate, and changes in the timing of leaf-out affect plant productivity, plant–animal interactions, and other essential ecosystem processes.[69,70] Warmer late-winter and early-spring temperatures in the Northeast have resulted in trends towards earlier leaf-out and blooming, including changes of 1.6 and 1.2 days per decade, respectively, for lilac and honeysuckle (Ch. 7: Ecosystems, Figure 7.3).[71] The increase in growing season length is partially responsible for observed increases in forest growth and carbon sequestration.[72]

While unusual winter or early-spring warmth has caused plants to start growing and emerge from winter dormancy earlier in the spring, the increased vulnerability of species to subsequent cold spells is yet unknown. Early emergence from winter dormancy causes plants to lose their tolerance to cold temperatures and risk damage by temperatures they would otherwise tolerate. Early budbreak followed by hard freezes has led to widespread loss of fruit crops and reduced seasonal growth of native tree species in the Northeast.[35,73]

Shifting seasonality can also negatively affect the health of forests (Ch. 6: Forests, KM 1) and wildlife, thereby impacting the rural industries dependent upon them. Warmer winters will likely contribute to earlier insect emergence[74] and expansion in the geographic range and population size of important tree pests such as the hemlock woolly adelgid, emerald ash borer, and southern pine beetle.[75,76,77] Increases in less desired herbivore populations are also likely, with white-tailed deer and nutria (exotic South American rodents) already being a major concern in different parts of the region.[78] According to State Farm Insurance,[79] motorists in West Virginia and Pennsylvania are already the first and third group of claimants most likely to file an insurance claim that is deer-related. Erosion from nutria feeding in lower Eastern Shore watersheds of Maryland has resulted in widespread conversion of marsh to shallow open water, changing important ecosystems that can buffer against the adverse impacts from climate change.[80] Species such as moose, which drive a multimillion-dollar tourism industry, are already experiencing increased parasite infections and deaths from ticks.[81,82,83] Warmer spring temperatures are associated with earlier arrivals of migratory songbirds,[84] while birds dependent upon spruce–fir forests in the northern and mountainous parts of the region are already declining and especially vulnerable to future change.[85] Northern and high-elevation tree species such as spruce and fir are among the most vulnerable to climate change in the Northeast.[70,86,87]

A nutria shows off its signature orange teeth. These large South American rodents are already a major concern in parts of the Northeast. Photo credit: ©Jason Erickson/iStock/Getty Images Plus.

Challenges for Natural Resource-Based Industries

Shorter, more moderate winters will present new challenges for rural industries. Poor surface and road conditions or washout have the potential to limit future logging operations, which need frozen or snow-covered soils to meet environmental requirements for winter operations.[70,88] Maple syrup production is linked to climate through potential shifts in sugar maple habitat,[89] tapping season timing and duration,[90,91] and the quality of both the trees and sap.[92,93] Climate change is making sugar maple tapping more challenging by increasing variability within and between seasons. Research into how the industry can adapt to these changes is ongoing.[89,94,95] With changes in weather and ecology come shifts in the cultural relationships to seasons as they have historically existed. Indigenous women from across these northeastern forests have come together to protect and sustain cultural traditions of the land they call Maple Nation. These climate impacts not only threaten the maple tree itself but also the seeds, soil, water, plants, and cultural lifeways that Indigenous peoples and tribal nations in the region associate with them.[96,97]

On the other hand, the impacts of warming on forests and ecosystems during the summer and autumn are less well understood.[98] In the summer, flowering in many agricultural crops and tree fruits is regulated in part by nighttime temperature, and growers risk lower yields as these temperatures rise.[35] Warmer autumn temperatures[98] influence processes such as leaf senescence (the change in leaf color as photosynthesis ceases), fruit ripening, insect phenology,[35] and the start of bird migration and animal hibernation.[99] October temperatures are the best predictor of leaf senescence in the northern hemisphere,[100] but other climatic factors can also shift the timing of autumn processes. Agricultural drought can advance leaf coloring and leaf drop, while abundant soil moisture can delay senescence.[101,102] Early frost events or strong winds can also result in sudden leaf senescence and loss.[98] Many deciduous trees are projected to experience an overall increase in their amount of autumn foliage color.[103]

As Northeast winters warm, scenarios project a combination of less early winter snowfall and earlier snowmelt, leading to a shorter snow season.[104,105] The proportion of winter precipitation falling as rain has already increased and will likely continue to do so in response to a northward shift in the snow–rain transition zone projected under both lower and higher scenarios (RCP4.5 and RCP8.5).[106,107,108] The shift in precipitation type and fewer days below freezing[3,4,35] are expected to result in fewer days with snow on the ground; decreased snow depth, water equivalent, and extent; an earlier snowmelt;[105,109,110] and less lake ice.[111] Warming during the winter–spring transition has already led to earlier snowmelt-related runoff in areas of the Northeast with substantial snowpack (Figure 18.2).[112] Earlier snowmelt-related runoff and lower spring peak streamflows in these areas are expected in the 2041–2095 period compared with the 1951–2005 period.[105]

Historical Changes in the Timing of Snowmelt-Related Streamflow

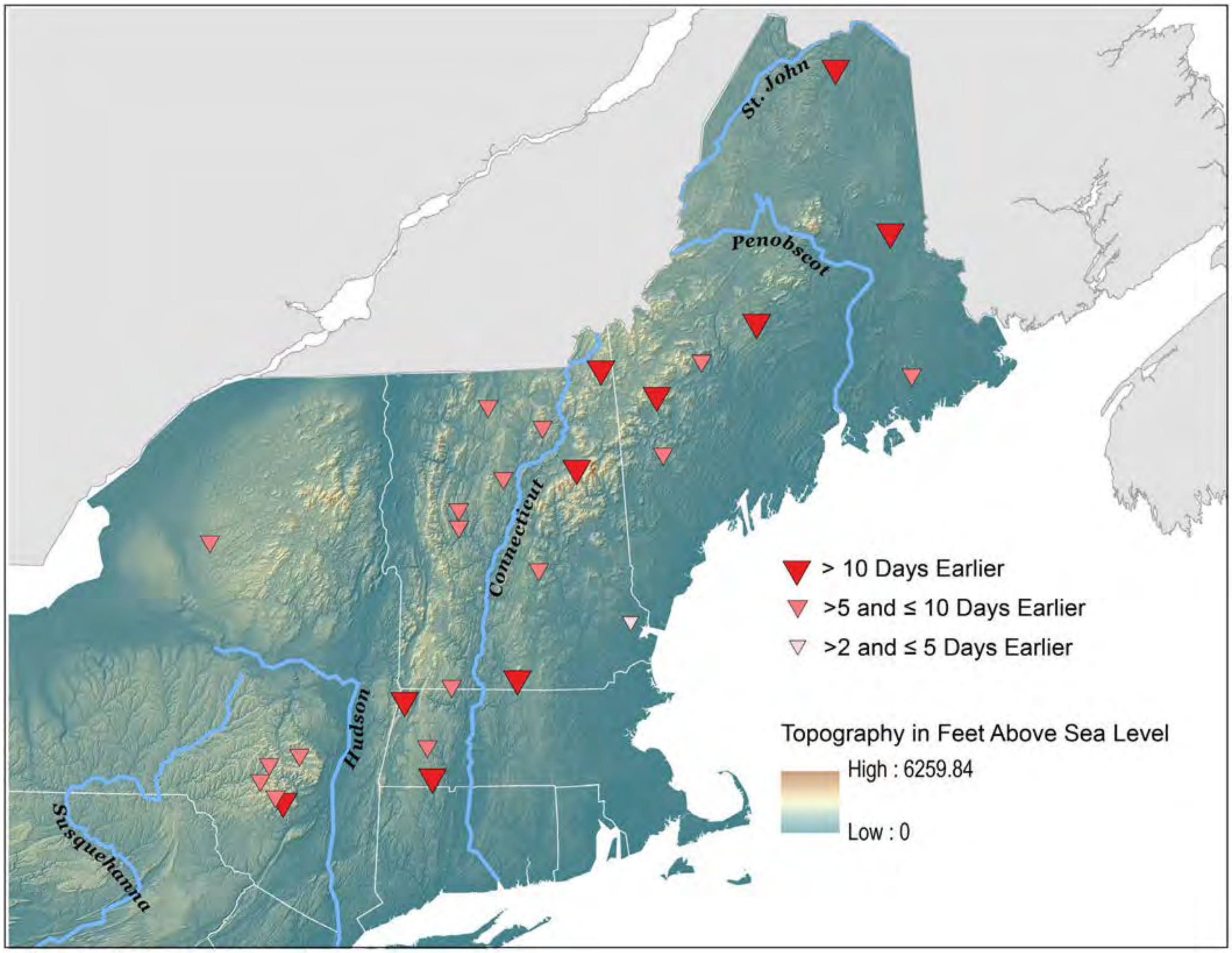


Figure 18.2: This map of part of the Northeast region shows consistently earlier snowmelt-related streamflow timing for rivers from 1960 to 2014. Each symbol represents the change for an individual river over the entire period. Changes in the timing of snowmelt potentially interfere with the reproduction of many aquatic species[113] and impact water-supply reservoir management because of higher winter flows and lower spring flows.[114] The timing of snowmelt-related streamflow in the Northeast is sensitive to small changes in air temperature. The average winter–spring air temperature increase of 1.67°F in the Northeast from 1940 to 2014 is thought to be the cause of average earlier streamflow timing of 7.7 days.[112] The timing of snowmelt-related streamflow is a valuable long-term indicator of winter–spring changes in the Northeast. Source: adapted from Dudley et al. 2017;[112] Digital Elevation Model CGIAR–CSI (CGIAR Consortium for Spatial Information). Reprinted with permission from Elsevier.

The Northeast winter recreation industry is an important economic resource for rural areas, supporting approximately 44,500 jobs and generating between $2.6–$2.7 billion in revenue annually.[115,116] Like other outdoor tourism industries, it is strongly influenced by weather and climate, making it particularly vulnerable to climate change.[116,117,118] Even under the lower scenario (RCP4.5), the average length of the winter recreation season and the number of recreational visits are projected to decrease by mid-century.[118] Under the same scenario, lost time for snowmaking is expected to delay the start of the ski season across southern areas, potentially impacting revenues during the winter holiday season. Activities that rely on natural snow and ice cover are projected to remain economically viable in only far northern parts of the region by end of century under the higher scenario (RCP8.5).[117,118]

Sensitivity to projected changes in winter climate varies geographically, and venues are adapting by investing in artificial snowmaking, opening higher-elevation trails, and offering a greater range of activities and services.[115,117] As the margin for an economically viable winter recreation season (a season with more than 100 days for skiing; more than 50 for snowmobiling) shifts northward and toward higher elevations, some affected areas will be able to extend their seasons with artificial snowmaking. However, the capacity of some vulnerable southern and low-elevation locations to adapt in the long term is expected to be limited by warming nighttime temperatures.[115,116,119] Markets farther north may benefit from a greater share of regional participation depending on recreationist preferences like travel time[118,120] and perceived snow cover conditions informed by local weather, referred to as the backyard effect.[121]

Intense Precipitation

The recent dominant trend in precipitation throughout the Northeast has been towards increases in rainfall intensity,[2,58] with recent increases in intensity exceeding those in other regions in the contiguous United States. Further increases in rainfall intensity are expected,[3] with increases in precipitation expected during the winter and spring with little change in the summer.[4] Monthly precipitation in the Northeast is projected to be about 1 inch greater for December through April by end of century (2070–2100) under the higher scenario (RCP8.5).[4]

Studies suggest that Northeast agriculture, with nearly $21 billion in annual commodity sales,[122] will benefit from the changing climate over the next half-century[35,123] due to greater productivity over a longer growing season (Figure 18.3) (see also Ch. 10: Ag & Rural). However, excess moisture is already a leading cause of crop loss in the Northeast.[35] Recent and projected increases in precipitation amount, intensity, and persistence[124,125] indicate increasing impacts on agricultural operations. Increased precipitation can result in soil compaction,[126] delays in planting, and reductions in the number of days when fields are workable.[127] If the trend in the frequency of heavy rainfall prior to the last frost continues, overly wet fields could potentially prevent Northeast farmers from taking full advantage of an earlier spring.[35] Increased soil erosion and agricultural runoff—including manure, fertilizer, and pesticides[128,129]—are linked to excess nutrient loading of water bodies as well as possible food safety or public health issues from food and waterborne infections.[130] Warmer winters are likely to increase livestock productivity in the Northeast[129] but are expected to also increase pressure from weeds and pests,[35] demand for pesticides,[128] and the risk of human health effects from increased chemical exposures.[130]

The projected changes in precipitation intensity and temperature seasonality would also affect streams and the biological communities that live in them. Freshwater aquatic ecosystems are vulnerable to changes in streamflow, higher temperatures, and reduced water quality.[131] Such ecosystems are especially vulnerable to increases in high flows, decreases in low flows, and the timing of snowmelt.[113,132,133] The impact of heavy precipitation on streamflows partly depends upon watershed conditions such as prior soil moisture and snowpack conditions, which vary throughout the year.[134,135,136,137] Although the annual minimum streamflows have increased during the last century,[138,139,140] late-summer warming[4,141] could lead to decreases in the minimum streamflows in the late summer and early fall by mid-century.[142]

Species that are particularly vulnerable to temperature and flow changes include stream invertebrates, freshwater mussels, amphibians, and coldwater fish.[66,131,143] For example, a recent study of the habitat suitable for dragonflies and damselflies (species that are a good indicator of ecosystem health along rivers) in the Northeast projected, under both the lower and higher scenarios (RCP4.5 and RCP8.5), habitat declines of 45%–99% by 2080, depending on the species.[144] Other particularly vulnerable groups include species with water-dependent habitats, such as salamanders and coldwater fish.[66,145] Increasing temperatures within freshwater streams threaten coldwater fisheries across northern New England and south through the Appalachian Mountains. A decrease in recreational fishing revenue is expected by end of this century under a higher scenario (RCP8.5) with the loss of coldwater habitat.[29,131,146]

Lengthening of the Freeze-Free Period

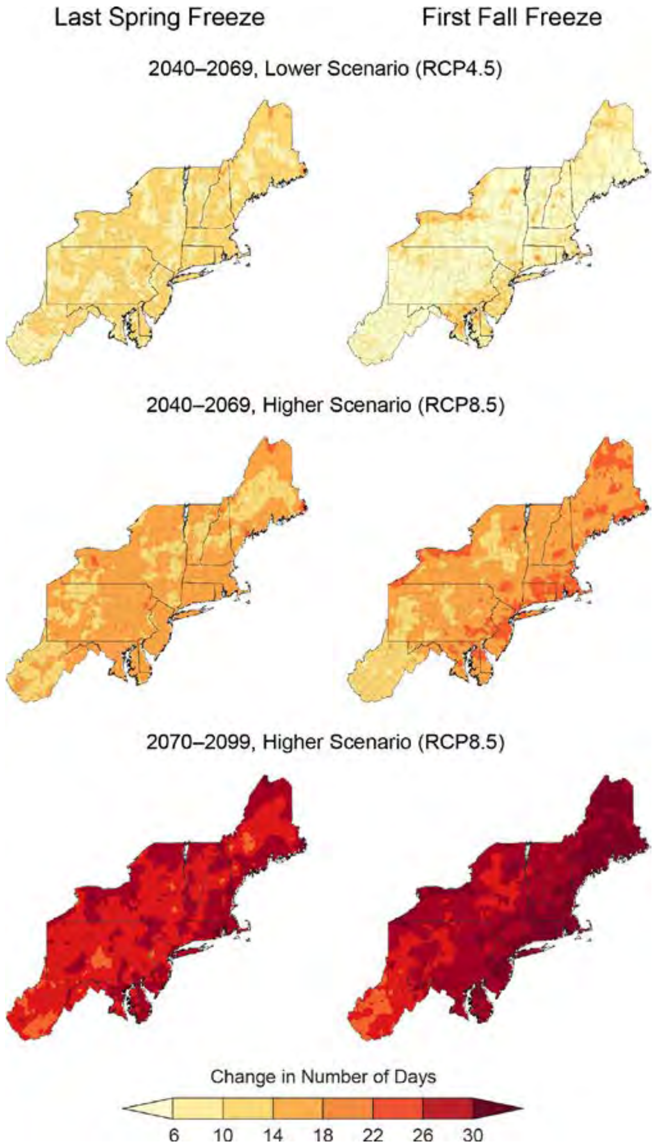


Figure 18.3: These maps show projected shifts in the date of the last spring freeze (left column) and the date of the first fall freeze (right column) for the middle of the century (as compared to 1979–2008) under the lower scenario (RCP4.5; top row) and the higher scenario (RCP8.5; middle row). The bottom row shows the shift in these dates for the end of the century under the higher scenario. By the middle of the century, the freeze-free period across much of the Northeast is expected to lengthen by as much as two weeks under the lower scenario and by two to three weeks under the higher scenario. By the end of the century, the freeze-free period is expected to increase by at least three weeks over most of the region. Source: adapted from Wolfe et al. 2018.[35]

Key Message 2

Changing Coastal and Ocean Habitats, Ecosystem Services, and Livelihoods

The Northeast's coast and ocean support commerce, tourism, and recreation that are important to the region's economy and way of life. Warmer ocean temperatures, sea level rise, and ocean acidification threaten these services. The adaptive capacity of marine ecosystems and coastal communities will influence ecological and socioeconomic outcomes as climate risks increase.

Ocean and coastal ecosystems are being affected by large changes in a variety of climate-related environmental conditions. These ecosystems support fishing and aquaculture,[5] tourism and recreation, and coastal communities.[6] They also provide important ecosystem services (benefits to people provided by the functions of various ecosystems), including carbon sequestration,[147] wave attenuation,[148,149] and fish[150] and shorebird[151] habitats. Observed and projected increases in temperature, acidification, storm frequency and intensity, and sea levels are of particular concern for coastal and ocean ecosystems, as well as local communities and their interconnected social and economic systems (Box 18.1).

Change in Sea Surface Temperature on the Northeast Continental Shelf

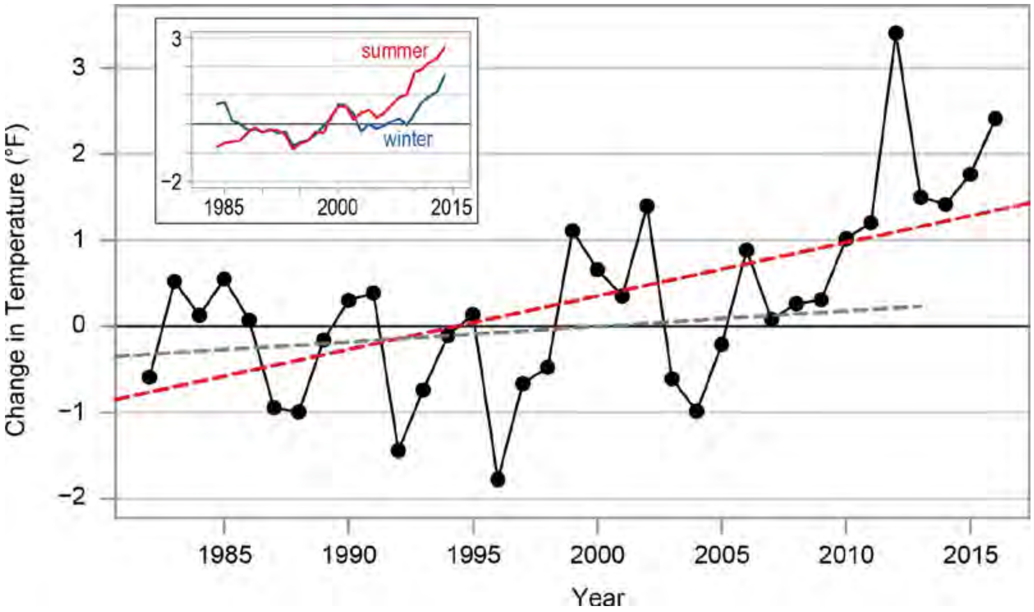


Figure 18.4: The figure shows annual average sea surface temperature (SST) differences from the 1982–2011 average (black dots and line). Over the period 1982–2016, sea surface temperature on the Northeast Continental Shelf has warmed at a rate of 0.06°F (0.033°C) per year (red dashed line). This rate is three times faster than the 1982–2013 global SST warming rate of 0.018°F (0.01°C) per year (gray dotted line).[39] The inset shows Northeast Continental Shelf seasonal SST differences from the 1982–2011 average as five-year rolling means for summer (July, August, September; red line) and winter (January, February, March; blue line). These seasons are centered on the warmest (summer) and coolest (winter) months for Northeast Shelf SSTs. Both seasons have warmed over the time period, but the summer warming rate has been stronger. Source: Gulf of Maine Research Institute.

Ocean Warming

Ocean and coastal temperatures along the Northeast Continental Shelf have warmed by 0.06°F (0.033°C) per year over the period 1982–2016 (Figure 18.4), which is three times faster than the 1982–2013 global average rate of 0.018°F (0.01°C) per year.[39] Over the last decade (2007–2016), the regional warming rate has been four times faster than the long-term trend, with temperatures rising 0.25°F (0.14°C) per year (Figure 18.4). Variability in ocean temperatures over the Northeast Continental Shelf (see Figure 18.1 for the location) has been related to the northern position of the Gulf Stream, the volume of water entering from the Labrador Current, and large-scale background warming of the oceans.[39,48,152,153] In addition to this warming trend, seasonality is also changing. Warming has been strongest during the summer months, and the duration of summer-like sea surface temperatures has expanded.[154] In parts of the Gulf of Maine, the summer-like season lengthened by two days per year since 1982, largely due to later fall cooling; the summer-like period expanded less rapidly (about 1 day per year) in the Mid-Atlantic, primarily due to earlier spring warming.[154]

Increasing temperatures and changing seasonality on the Northeast Continental Shelf have affected marine organisms and the ecosystem in various ways (Ch. 7: Ecosystems, KM 1; Ch. 9: Oceans). Seasonal ocean temperature changes have shifted characteristics of the spring phytoplankton blooms[158] and the timing of fish and invertebrate reproduction,[163,164] migration of marine fish that return to freshwater to spawn,[165,166] and marine fisheries.[155] As the timing of ecosystem conditions and biological events shifts, interactions between species and human activities such as fishing or whale watching will likely be affected.[42,155,163,166,167,168] These changes have the potential to affect economic activity and social features of fishing communities, working waterfronts, travel and tourism, and other natural resource-dependent local economies.

The warming trend experienced in the Northeast Continental Shelf has been associated with many fish and invertebrate species moving northward and to greater depths (Ch. 1: Overview, Figure 1.2h).[7,8,9,10,11] As these shifts have occurred, communities of animals present in a given area have changed substantially.[169] Species interactions can be affected if species do not shift at the same rate; generally, species groups appear to be moving together,[10] but overlap between pairs of specific species has changed.[42]

Rising ocean temperatures have also affected the productivity of marine populations. Species at the southern extent of their range, such as northern shrimp, surf clams, and Atlantic cod, are declining as waters warm,[39,170,171] while other species, such as black sea bass, are experiencing increased productivity.[11] Some species, such as American lobster and surf clam, have declined in southern regions where temperatures have exceeded their biological tolerances but have increased in northern areas as warming waters have enhanced their productivity.[40,171,172,173] The productivity of some harvested and cultured species may also be indirectly influenced by changing levels of marine pathogens and diseases. For example, increasing prevalence of shell disease in lobsters and several pathogens in oysters have been associated with rising water temperatures;[174,175] other pathogens that infect shellfish pose risks to human health (see Key Message 4).

Temperature-related changes in the distribution and productivity of species are affecting fisheries. Some fishermen now travel farther to catch certain species[176] or target new species that are becoming more prevalent as waters warm.[155] However, these types of responses do not always keep pace with ecosystem change due to constraints associated with markets, shoreside infrastructure, and regulatory limits such as access to quota licenses or permits.[177,178,179] In addition, stock assessment and fishery management processes do not explicitly account for temperature influences on the managed species. In the case of Gulf of Maine cod, rising temperatures have been associated with changes in recruitment, growth, and mortality; failure to account for declining productivity as a result of warming led to catch advice that allowed for overfishing on the stock.[39,180] Proactive conservation and management measures can support climate resilience of fished species. For example, long-standing industry and management measures to protect female and large lobsters have supported the growth of the Gulf of Maine–Georges Bank stock

Box 18.1: Ocean Heat Wave Provides Glimpse of Climate Future

In 2012, sea surface temperatures on the Northeast Continental Shelf rose approximately 3.6°F (2°C) above the 1982–2011 average. This departure from normal was similar in magnitude to the changes projected for the end of the century under the higher scenario (RCP8.5) and represented the largest, most intense warm water event ever observed in the Northwest Atlantic Ocean (Ch. 9: Oceans).[155,156,157] This heat wave altered seasonal cycles of phytoplankton and zooplankton,[158,159] brought Mid-Atlantic fish species into the Gulf of Maine,[155] and altered the occurrence of North Atlantic right whales in the Gulf of Maine.[160] Commercial fisheries were also affected. A fishery for squid developed quickly along the coast of Maine, but the New England lobster fishery was negatively affected. Specifically, early spring warming triggered an early start of the fishing season, creating a glut of lobster in the supply chain and leading to a severe price collapse.[155] During 2012, the dockside price for lobster hit its lowest level in the past decade and dropped from an average per-pound value of $3.62 for June and July 2000–2011 to just $2.37 in those months in 2012. The experience during the 2012 ocean heat wave revealed vulnerabilities in the lobster industry and prompted a variety of adaptive responses, such as expanding processing capacity and further developing domestic and international markets[161] in an attempt to buffer against similar industry impacts in the future. Although an outlier when compared with our current climate, the ocean temperatures in 2012 were well within the range projected for the region by the end of the century under the higher scenario (RCP8.5).[162] The 2012 ocean heat wave provided a glimpse of impacts affecting ecological and social systems, and experiences during this event can serve as a stress test to guide adaptation planning in years to come (akin to 2015 in the Northwest) (see Ch. 24: Northwest, Box 24.7).

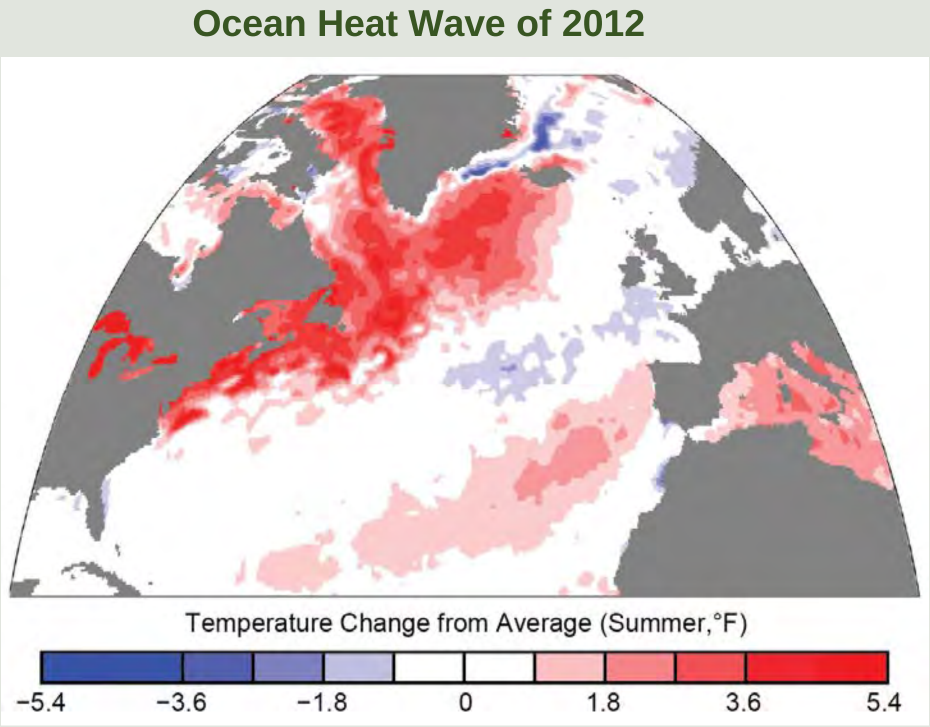


Figure 18.5: The map shows the difference between sea surface temperatures (SST) for June–August 2012 in the Northwest Atlantic and the average values for those months in 1982–2011.[155] While ocean temperatures during 2012 were exceptionally high compared to the current climate, they were within the range of end-of-century temperatures projected for the region under the higher scenario (RCP8.5). This heat wave affected the Northeast Continental Shelf ecosystem and fisheries, and similar extreme events are expected to become more common in the future (Ch. 9: Oceans). Source: adapted from Mills et al. 2013.[155] Reprinted with permission from Elsevier.

as waters warmed, but the lack of these measures in southern New England exacerbated declines in that stock as temperatures increased.[40]

Ocean Acidification

In addition to warming, coastal waters in the Northeast, particularly in the Gulf of Maine, are sensitive to the effects of ocean acidification because they have a low capacity for maintaining stable pH levels.[181,182] These waters are particularly vulnerable to acidification due to hypoxia (low-oxygen conditions)[183] and freshwater inputs, which are expected to increase as climate change progresses.[142,181,184] At the coastal margins, acidification is exacerbated by nutrient loading from land-based runoff and atmospheric deposition during heavy rainfall events. When added to the system, these nutrients promote the growth of algae that release carbon dioxide, which contributes to acidification, as they decay.[185]

Fisheries and aquaculture rely on shell-forming organisms that can suffer in more acidic conditions (Ch. 9: Oceans).[181,182,186] Some of the most valuable wild- and culture-based fisheries in the region harvest shelled organisms—including lobsters, scallops, blue crabs, oysters, surf clams, and mussels.[5] To date, there have been few studies of how local populations and different life stages will be affected by ocean acidification,[182] but actions taken by industry to counter the potential negative impacts are emerging. For example, when an oyster hatchery in Maine experienced low survival rates of larval oysters following exposure to low pH water during large runoff events, it collaborated with scientists to develop systems to monitor and control carbonate conditions in the facility (Ch. 9: Oceans).[187]

Future Projections of Ocean Warming and Acidification

Climate projections indicate that in the future, the ocean over the Northeast Continental Shelf will experience more warming than most other marine ecosystems around the world.[48,49] Continued warming and acidification are expected to further affect species and fisheries in the region. Future projections indicate that declines in the density of a zooplankton species, *Calanus finmarchicus*—an important food source for many fish and whales in the Northeast Shelf region—will occur as waters continue to warm through the end of the century.[188] Northward species distribution trends are projected to continue as ocean waters warm further.[189] A species vulnerability assessment indicated that approximately 50% of the commercial, forage, and protected fish and invertebrate species on the Northeast Continental Shelf will be highly or very highly vulnerable to climate change through 2050 under the higher scenario (RCP8.5).[143] In general, species in the southern portion of the region are expected to remain stable through mid-century, but many species in the northern portion are expected to be negatively affected by warming and acidification over that timeframe.[143,186] Species population models projected forward under future ocean conditions also indicate declines of species that support some of the most valuable and iconic fisheries in the Northeast, including Atlantic cod,[39,190] Atlantic sea scallops,[191] and American lobster.[40] In addition, species that are already endangered and federally protected in the Northeast—such as Atlantic sturgeon, Atlantic salmon, and right whales—are expected to be further threatened by climate change.[192,193,194,195]

Changes in Distribution and Abundance of Marine Species

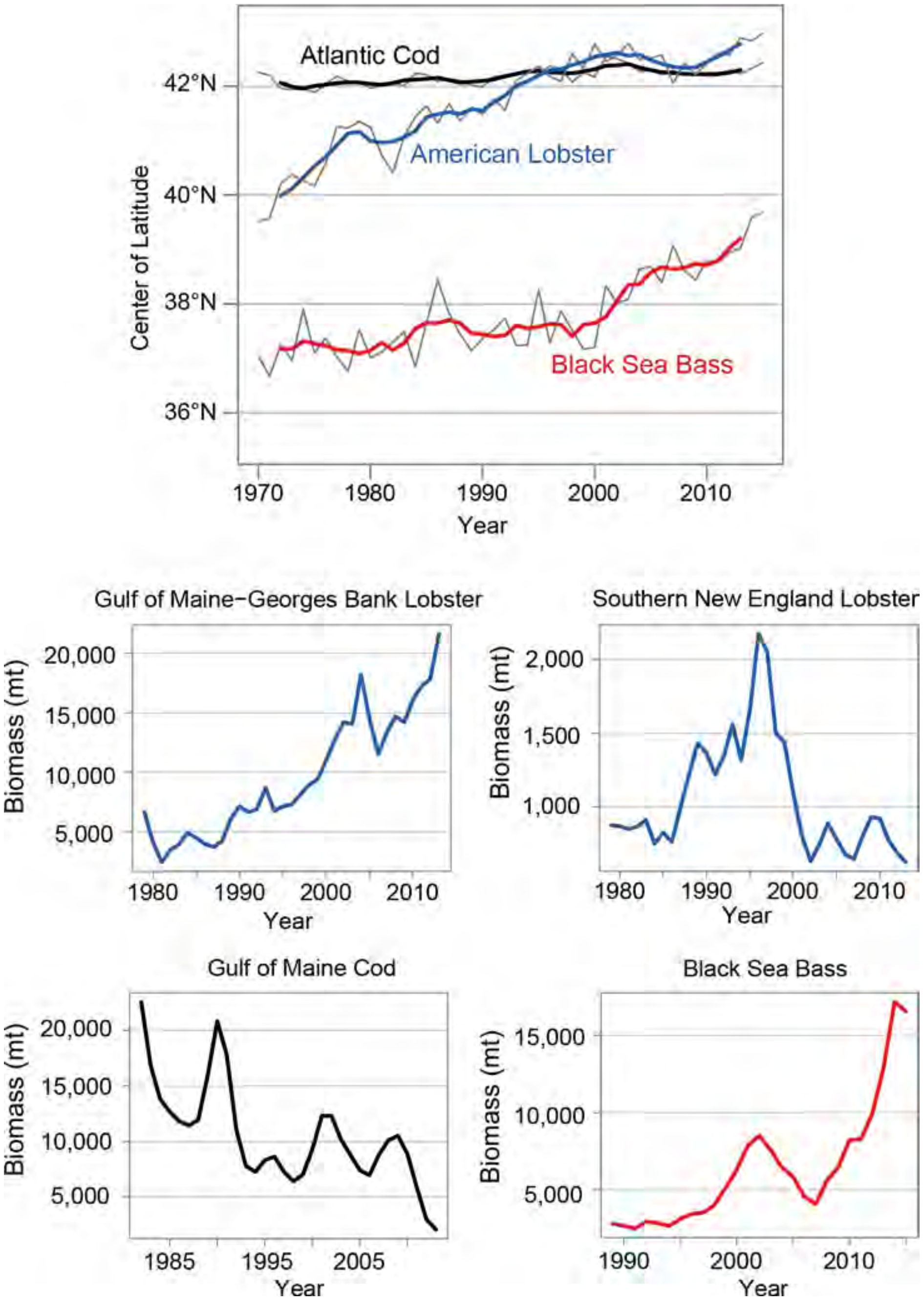


Figure 18.6: The figure shows changes over time in geographic distribution (top panel) and biomass (four bottom panels) for various marine species along the Northeast Shelf. As waters in the region have warmed, the spatial distributions of many fish species have been shifting northward, while population trends of several marine species show more variability over time. The top panel shows shifts in spatial distribution over time for select fish species, based on their latitudinal centers of biomass. The four panels on the bottom show biomass estimates for the same marine resource stocks. Gulf of Maine cod, a coldwater species, has not shifted in location but has declined in biomass, while black sea bass (a warmwater species) has moved northward and increased in biomass as waters have warmed. The lobster distribution shift reflects declines in productivity of the southern stock and increasing biomass of the northern stock. Sources: (black sea bass) adapted from Northeast Fisheries Science Center 2017;[204] (all others) Gulf of Maine Research Institute.

A number of coastal communities in the Northeast region have strong social and cultural ties to marine fisheries, and in some communities, fisheries represent an important economic activity as well.[196,197] Future ocean warming and acidification, which are expected under all scenarios considered, would affect fish stocks and fishing opportunities available to coastal communities. Fisheries targeting species at the southern extent of their range have already experienced substantial declines in landings with rising ocean temperatures,[170,173,198,199,200] and this pattern is projected to continue in the future (e.g., Cooley et al. 2015, Pershing et al. 2015, Le Bris et al. 2018[39,40,191]). Fishers may need to travel farther to fishing locations for species they currently catch,[189] increasing fuel and crew costs. Distribution shifts (Figure 18.6) can also create opportunities to target new species moving into an area.[155] The impacts and opportunities associated with these changes will not be evenly shared within or among fisheries, fleets, or communities; as such, adaptation may alter social dynamics, cultural ties, and economic benefits.[201,202,203]

Sea Level Rise, Storms, and Flooding

Along the Mid-Atlantic coast (from Cape Hatteras, North Carolina, to Cape Cod, Massachusetts), several decades of tide gauge data through 2009 have shown that sea level rise rates were three to four times higher than the global average rate.[46,205,206] The region's sea level rise rates are increased by land subsidence (sinking)—largely due to vertical land movement related to the melting of glaciers from the last ice age—which leaves much of the land in this region sinking with respect to current sea level.[47,207,208,209] Additionally, shorter-term fluctuations in the variability of ocean dynamics,[210,211] atmospheric shifts,[212,213] and ice mass loss from Greenland and Antarctica[214] have been connected to these recent accelerations in the sea level rise rate in the region. For example, a slowdown of the Gulf Stream during a shorter period of extreme sea level rise observed over 2009–2010 has been linked to a weakening of the Atlantic meridional overturning circulation—the northward flow of upper-level warm, salty waters in the Atlantic (including the Gulf Stream current) and the southward flow of colder, deeper waters.[215] These higher-than-average rates of sea level rise measured in the Northeast have also led to a 100%–200% increase in high tide flooding in some places, causing more persistent and frequent (so-called nuisance flooding) impacts over the last few decades.[44,47,216,217]

Coastal flood risks from storm-driven precipitation and surges are major drivers of coastal change[218,219] and are also amplified by sea level increases.[217,220,221] Storms have unique climatological features in the Northeast—Nor'easters (named for the low-pressure systems typically impacting New England and the Mid-Atlantic with strong northeasterly winds blowing from the ocean over coastal areas) typically occur between September and April, and when coupled with the Atlantic hurricane season between June and September, the region is susceptible to major storms nearly year-round. Storm flood heights driven by hurricanes in New York City increased by more than 3.9 feet (1.2 m) over the last thousand years.[14] When coupled with storm surges, sea level rise can pose severe risks of flooding, with consequent physical and mental health impacts on coastal populations (see Key Messages 4 and 5).

Coastal Impacts of Climate Change

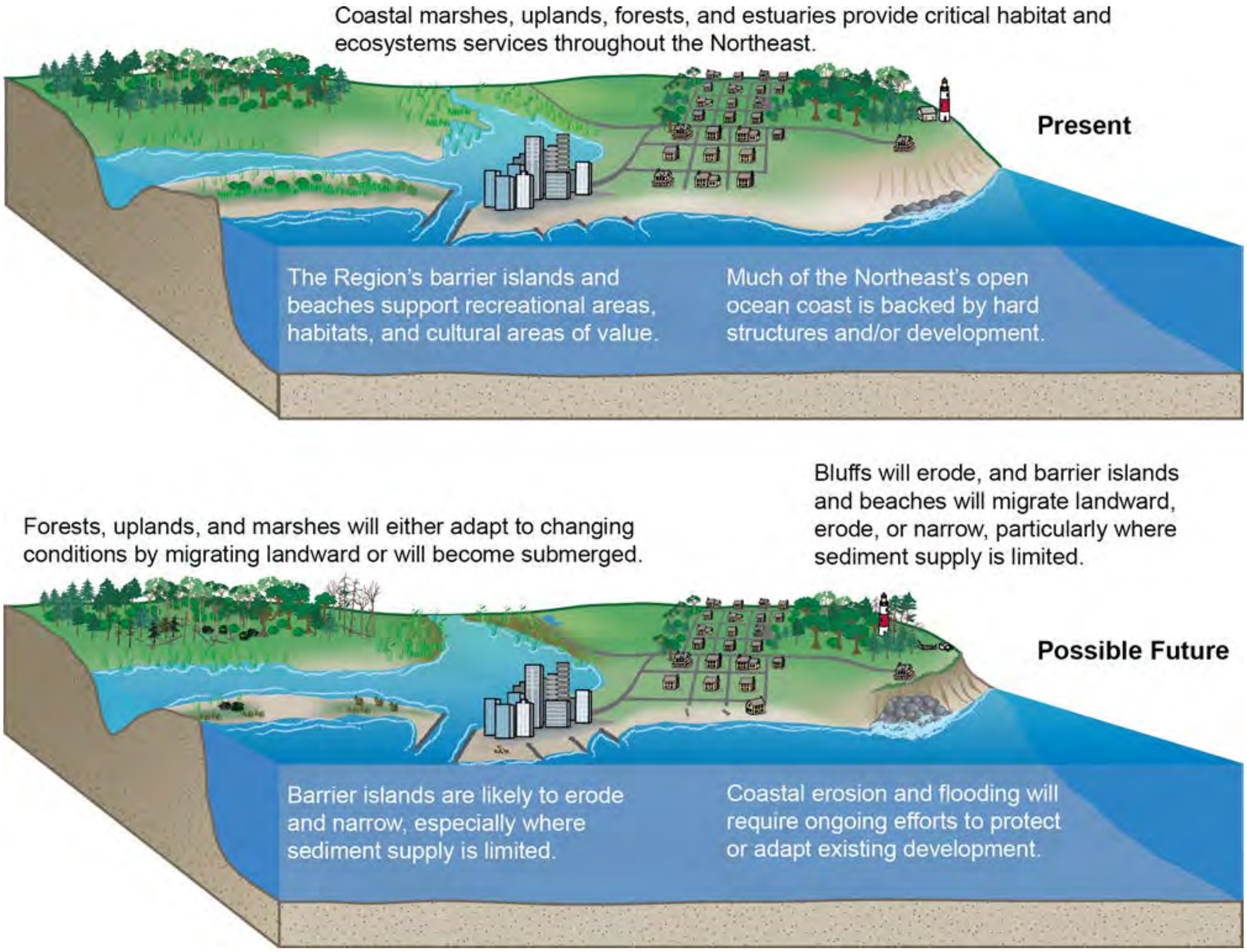


Figure 18.7: (top) The northeastern coastal landscape is composed of uplands and forested areas, wetlands and estuarine systems, mainland and barrier beaches, bluffs, headlands, and rocky shores, as well as developed areas, all of which provide a variety of important services to people and species. (bottom) Future impacts from intense storm activity and sea level rise will vary across the landscape, requiring a variety of adaptation strategies if people, habitats, traditions, and livelihoods are to be protected. Source: U.S. Geological Survey.

Landscape Change and Impacts on Ecosystems Services

Because of the diversity of the Northeast's coastal landscape, the impacts from storms and sea level rise will vary at different locations along the coast (Figure 18.7).[12,13] Rocky and heavily developed coasts have limited infiltration capacity to absorb these impacts, and thus, these low-elevation areas will become gradually inundated.[222,223] However, more dynamic environments, such as mainland and barrier beaches, bluffs, and coastal wetlands, have evolved over thousands of years in response to physical drivers. Such responses include erosion, overwashing, vertical accretion (increasing elevation due to sediment movement), flooding in response to storm events,[218,224,225] and landward migration over the longer term as sea level has risen.[226] Uplands, forests, and agricultural lands can provide transitional areas for these more dynamic settings, wherein the land gradually converts to a tidal marsh.

Varied ecosystem services and natural features have long attracted and sustained people along the coast of the Northeast region. Ecosystem services—including the provisioning of groundwater resources, the filtering of non-point source pollution, sequestering carbon, mitigating storm impacts and erosion, and sustaining working waterfronts and cultural features such as iconic regional landscapes, recreation, and traditions—are facing multiple climate threats. Marshes and beaches serve as the first line of defense for coastal property and infrastructure in the face of storms.[227] They also provide critical habitat for a variety of migratory shorebirds and, when combined with nearshore seagrass and estuaries, serve as nurseries for many commercial marine species.[37,38,150,151,228,229] Regional marshes trap and store carbon[147,230,231,232] and help to capture non-point source pollution before it enters seawater.[233,234,235] Regional beaches are important tourist and recreational attractions, and many coastal national parks and national historic sites throughout the region help preserve cultural heritage and iconic coastal landscapes.[236,237] The Northeast coast is also home to many Indigenous peoples whose traditions and ways of life are deeply tied to land and water (Box 18.2). Coastal tribes often have limited resources, infrastructure, and land ownership, and these limitations can worsen the impacts of climate change and prohibit relocation (Ch. 15: Tribes, KM 1 and 3).

Box 18.2: Indigenous Peoples and Tribal Nations

Indigenous peoples and tribal nations of the Northeast region have millennia-long relationships with the diverse landscapes and climate zones found throughout the region.[238,239,240] Currently, for the 18 federally recognized, numerous state-recognized, and federally unrecognized tribal nations of the Northeast,[241,242] the challenges of adapting to a changing climate add additional uncertainty to existing efforts for reclamation of land and sovereignty and the revitalization of languages and cultures (Ch. 15: Tribes, KM 1 and 3).[97,243] However, in response to a regional shift in the seasons, there has been an increase in climate adaptation work by tribes over the last decade (Ch.15: Tribes, Figure 15.1). These projects have been framed by Indigenous knowledges to address impacts to culturally and economically important resources and species, such as brown ash, sweetgrass, forests, and sugar maple, as well inland and ocean fisheries.[238,244,245,246] These projects provide important results for the tribal nations themselves but could also provide examples of adaptation and survival for other tribal nations and non-tribal communities to consider as they work towards a deeper and more complex engagement to address future landscapes.[97,240] Although not all tribally led climate research and projects across regions have been reported or published, there are even fewer publicly available examples in the Northeast region, and especially for state-recognized and unrecognized tribes. This seems to present itself as a potential future research opportunity for tribal engagement and collaborations in the Northeast (Ch. 15: Tribes).[97]

Projections of Future Sea Level Rise and Coastal Flooding

Projections for the region suggest that sea level rise in the Northeast will be greater than the global average of approximately 0.12 inches (3 mm) per year.[247,248] According to Sweet et al. (2017),[47] the more probable sea level rise scenarios—the Intermediate-Low and Intermediate scenarios from a recent federal interagency sea level rise report (App. 3: Data & Scenarios)—project sea level rise of 2 feet and 4.5 feet (0.6 m and 1.4 m) on average in the region by 2100, respectively.[47] The worst-case and lowest-probability scenarios, however, project that sea levels in the region would rise upwards of 11 feet (3 m) on average by the end of the century.[47] The higher projections for the region as compared with most others in the United States are due to continued changes in oceanic and atmospheric dynamics, thermal expansion, ice melt contributions from Greenland and Antarctica, and ongoing subsidence in the region due to tectonics and non-tectonic effects such as groundwater withdrawal.[47,50,249,250,251,252] Furthermore, the strongest hurricanes are anticipated to become both more frequent and more intense in the future, with greater amounts of precipitation (Ch. 2: Climate, Box 2.5).[50,253,254,255] Thirty-two percent of open-coast north and Mid-Atlantic beaches are predicted to overwash during an intense future nor'easter type storm,[256] a number that increases to more than 80% during a Category 4 hurricane.[257,258]

Future Adaptability of the Coastal Landscape

The dynamic ability of coastal ecosystems to adapt to climate-driven changes depends heavily upon sufficient sediment supply, elevation and slope, barriers to migration,[225] tidal restrictions, wave climatology,[219,259] and the rates of sea level rise. Although nearly 70% of the Northeast coast has some physical ability to dynamically change,[13] an estimated 88% of the Northeast population lives on developed coastal landforms that have limited ability to naturally adapt to sea level rise.[260] Built infrastructure along the coast, such as seawalls, bulkheads, and revetments, as well as natural barriers, such as coastal bluffs, limits landward erosion; jetties and groins interrupt alongshore sediment supply; and culverts and dams create tidal restrictions that can limit habitat suitability for fish communities (see Figure 18.7).[261] An estimated 26% of open ocean coast from Maine to Virginia contains engineering structures.[262] While these structures can help mitigate hazards to people and property, they also reduce the land area for ecosystem migration, as well as the adaptive capacity of natural coastal environments.[43,227,263,264] The ability of marshes in the region to respond to sea level-induced change varies by location, with some areas increasing in elevation, experiencing vegetation shifts, and/or expanding in extent while others are not.[265,266,267,268,269,270,271] Forest diebacks, or "ghost forests," due to wetland encroachment[70,272] are being observed in southern New Jersey and Maryland (Figure 18.8), although one study found that southern New England forests are not showing similar signs of dieback.[273]

Forest Dieback Due to Sea Level Rise

Figure 18.8: Atlantic white cedars dying near the banks of the Bass River in New Jersey show wetland encroachment on forested areas. Photo credit: Ted Blanco/Climate Central.

Projected changes in climate will threaten the integrity of coastal landforms and ecosystems that provide services people and animals rely on and that act as important natural buffers to hazards. Under more extreme scenarios (such as the higher scenario, RCP8.5), marshes are unlikely to survive and, thus, would convert to open water.[224,274,275] At lower rates of sea level rise, marsh health will depend heavily upon site-specific hydrologic, physical, and sediment supply conditions.[259,275,276,277,278] Long-term coastal erosion, as driven by sea level rise and storms, is projected to continue, with one study finding the shoreline likely to erode inland at rates of at least 3.3 feet (1 m) per year among 30% of sandy beaches along the U.S. Atlantic coast.[279] Continued increases in the rate of sea level rise—on the order of 0.08 inches (2 mm) per year above the 20th-century rate—could cause much of the open ocean coasts in the Mid-Atlantic to transition to a state wherein coastal barrier systems migrate landward more rapidly, experience reductions in width or height, and overwash and breach more frequently.[280] Such an increase is projected to occur this century under the Intermediate-Low scenario, which suggests that global sea levels will rise approximately 0.24 inches (6 mm) per year.[47]

An ongoing challenge, now and in the future, is to adequately account for and determine the monetary value of the ecosystem services provided by marine and coastal environments[6,41,281] and to adaptively manage the ecosystems to achieve targets that are responsive to both development and conservation.[282]

These changes to the coastal landscape would threaten the sustainability of communities and their livelihoods. Historical settlement patterns and ongoing development combine to increase the regional vulnerability of coastal communities to sea level rise, coastal storms, and increased inundation during high tides and minor storms. For example, estimates of coastal property losses and protective investments through 2100 due to sea level rise and storm surge vary from less than $15 billion for southeastern Massachusetts to in excess of $30 billion for coastal New Jersey and Delaware under either the lower (RCP4.5) or higher (RCP8.5) scenarios (discounted at 3%).[29] Saltwater intrusion can also impact drinking water supplies, including the alteration of groundwater systems.[283,284] A growing area of research explores potential migration patterns in response to climate-related coastal impacts, where coastal states such as Massachusetts, New Jersey, and New York are anticipated to see large outflows of migrants, a pattern that would stress regional locations further inland.[285] In addition to property and infrastructure impacts (Key Message 3), the facilities and cultural resources that support coastal tourism and recreation (such as parking lots, pavilions, and boardwalks), as well as cultural landscapes and historic structures,[236,237] will be at increased risk from high tide flooding, storm surge, and long-term inundation. In some locations, these culturally and socially important structures also support economic activity; for example, many fishing communities rely on small docks and other shoreside infrastructure for their fishing operations, increasing the risk of substantial disruption if they are lost to sea level rise and increasing storm frequency.[45,286]

Key Message 3

Maintaining Urban Areas and Communities and Their Interconnectedness

The Northeast's urban centers and their interconnections are regional and national hubs for cultural and economic activity. Major negative impacts on critical infrastructure, urban economies, and nationally significant historic sites are already occurring and will become more common with a changing climate.

Climate–Infrastructure Interaction and Heightened Risks

Northeastern cities, with their abundance of concrete and asphalt and relative lack of vegetation, tend to have higher temperatures than surrounding regions due to the urban heat island effect (increased temperatures, typically measured during overnight periods, in highly urbanized areas in comparison to outlying suburban, exurban, and rural locations). During extreme heat events, nighttime temperatures in the region's big cities are generally several degrees higher than surrounding regions, leading to higher risk of heat-related death. In urban areas, the hottest days in the Northeast are also often associated with high concentrations of urban air pollutants including ground-level ozone (Ch. 13: Air Quality, KM 1). This combination of heat stress and poor urban air quality can pose a major health risk to vulnerable groups: young children, elderly, socially or linguistically isolated, economically disadvantaged, and those with preexisting health conditions, including asthma. Vulnerability is further heightened as key infrastructure, including electricity for air conditioning, is more likely to fail precisely when it is most needed—when demand exceeds available supply—with the potential for substantial negative health consequences.[287]

Finally, vulnerability to heat waves is not evenly distributed throughout the region. Rather, outdoor versus indoor air temperatures, baseline health, occupation, and access to air conditioning are important determinants of vulnerability (see Key Message 4).

Urban areas are at risk for large numbers of evacuated and displaced populations and damaged infrastructure due to both extreme precipitation events and recurrent flooding, potentially requiring significant emergency response efforts and consideration of long-term commitment to rebuilding and adaptation, and/or support for relocation where needed. Poor, elderly, historically marginalized, recent immigrants, and linguistically or socially isolated individuals as well as those populations with existing health disparities are more vulnerable to precipitation events and flooding due to a limited ability to prepare for and cope with such events.[59]

Critical Infrastructure Service Disruption

Much of the infrastructure in the Northeast, including drainage and sewer systems, flood and storm protection assets, transportation systems, and power supply, is nearing the end of its planned life expectancy. Current water-related infrastructure in the United States is not designed for the projected wider variability of future climate conditions compared to those recorded in the last century (Ch. 3: Water, KM 2). In order to make Northeast systems resilient to the kind of extreme climate-related disruptions the region has experienced recently—and the sort of disruptions projected for the future—would require significant new investments in infrastructure. For example, in Pennsylvania, bridges are expected to be more prone to damage during extreme weather events, because the state leads the country in the highest percentage of structurally deficient bridges.[288] Pennsylvania's water treatment and wastewater systems are also notably aging, requiring an estimated $28 billion in new investment over the next 20 years for repairs and to meet increasing demands.[288]

Climate-related disruptions will only exacerbate existing issues with aging infrastructure. Sea level rise has amplified storm impacts in the Northeast region (Key Message 2), contributing to higher surges that extend further inland, as demonstrated in New York City.[14,15,16] Sea level rise is leading to an increase in the frequency of coastal flooding, a trend that is projected to grow for cities such as Baltimore and Washington, DC.[289] High tide flooding has increased by a factor of 10 or more over the last 50 years for many cities in the Northeast region and will become increasingly synonymous with regular inundation, exceeding 30 days per year for an estimated 20 cities by 2050 even under a very low scenario (RCP2.6).[216] More frequent high tide flooding (also referred to as nuisance, or sunny day, flooding) will be experienced at low-elevation cities and towns in the region (Figure 18.9). Sea level rise (see Key Message 2) under higher scenarios will likely increase property losses from hurricanes and other coastal storms for the region by \$6–\$9 billion per year by 2100, while changes in hurricane activity could raise these estimates to \$11–\$17 billion per year.[260] In other words, projected future costs are estimated to continue along a steep upward trend relative to what is being experienced today. However, there is limited published research that quantifies the costs associated with increased damage across an entire system in response to amplified storm events. Actions to replace and/or significantly modify the Northeast's aging infrastructure provide opportunities to incorporate climate change adaptation and resilience into standard capital upgrades, reducing these future costs.

King Tide Flooding in Northeast

Figure 18.9: The photo shows king tide flooding on Dock Street in Annapolis, Maryland, on December 21, 2012. Photo credit: Amy McGovern (CC BY 2.0).

Mitigation in the Northeast

The Northeast region has traditionally been a leader in greenhouse gas mitigation action, serving as a potential model for other states. The Regional Greenhouse Gas Initiative is the first mandatory market-based program in the United States to cap and reduce CO_2 emissions from the power sector through a cooperative effort among Connecticut, Delaware, Maine, Maryland, Massachusetts, New Hampshire, New York, Rhode Island, and Vermont.

Impacts on Urban Economies

Service and resource supply infrastructure in the Northeast region is at increasing risk of disruption, resulting in lower quality of life, economic declines, and increased social inequality.[17] Loss of public services affects the capacity of communities to function as administrative and economic centers and triggers disruptions of interconnected supply chains (Ch. 16: International, KM 1). Interdependencies across critical infrastructure sectors such as water, energy, transportation, and telecommunication can lead to cascading failures during extreme weather and climate-related disruptions,[17,59] as occurred during the 2003 blackout in New York City (Ch. 17: Complex Systems, Box 17.5; Ch. 11: Urban). For example, the Northeast is projected to experience a significant increase in summer heat and the number and/or duration of heat waves that will further stress summertime energy peak load demands from higher air conditioning use and the greater need to pump and treat water. Energy supply failures can also affect transportation operations, and even after electricity is restored, a significant time lag can occur until transportation services such as subway signals and traffic lights return to operation.[290] Understanding and coping with these interdependencies require cross-sector analysis and engagement by the private sector and within and across different levels of government. As a result, the connection between climate impacts, adaptation, and sustained economic development of cities is a major concern in the region.

The large number of manufacturing, distribution, and storage facilities, as well as historic structures, in the region are also vulnerable to climate shifts and extremes. For example, power plants in New York City tend to be located along the coastline for easy access to water for cooling and maritime-delivered fuel and are often located within about 16 feet (5 m) of sea level.[59] This is not unusual, as there are many power plants and petroleum storage facilities located along the Northeast coastline.[291]

The historic preservation community has begun to address the issue of climate change.[292,293] Many historic districts in cities and towns, such as Annapolis, Maryland, and Newport, Rhode Island, are at low elevations along the coast and now face the threat of rising sea levels.

Preparedness in Cities and Towns

Projected increases in coastal flooding, heavy precipitation, runoff, and extreme heat would have negative impacts on urban centers with disproportionate effects on at-risk communities. Larger cities, including Boston, MA, Burlington, VT, Hartford, CT, Newark, NJ, Manchester, NH, New York, Philadelphia, PA, Pittsburgh, PA, Portland, ME, Providence, RI, and Washington, DC, have begun to plan for climate change and in some instances have started to implement action, particularly when upgrading aging infrastructure (e.g., NYC Special Initiative for Rebuilding and Resiliency 2013, Climate Ready Boston 2016, City of Philadelphia 2016, City of Pittsburgh 2017[294,295,296,297]). Examples from municipalities of varying sizes are common (e.g., U.S. EPA 2017[33]). These cities seek to maintain the within-city and intercity connectivity that fosters growth, diversity, liveliness of urban neighborhoods, and protection of vulnerable populations, including the elderly, young, and disadvantaged. Further, city leaders hope to avoid forced migration of highly vulnerable populations and the loss of historical and cultural resources. City managers and stakeholders recognize that extreme heat events, sea level rise, and storm surge have the potential to lead to complex disasters and sustained critical infrastructure damage. Specific actions cities are taking focus largely on promoting the resilience of critical infrastructure, enhancing the social resilience of communities (especially of vulnerable populations), promoting ecosystem service hazard mitigation, and developing new indicators and monitoring systems to achieve a better understanding of climate risks and to identify adaptation strategies (see Key Message 5) (see also Ch. 11: Urban). In the Northeast region, Superstorm Sandy illustrated urban coastal flooding risk, and many localities, not just those directly impacted by the storm, have developed increased coastal resilience plans and efforts. New York City has been able to put in place a broad set of efforts in a variety of critical infrastructure sectors, including making the subway more protected from flooding (Figure 18.10).

Subway Air Vent Flood Protection

Figure 18.10: The photo shows a subway air vent with a multiuse raised flood protection grate that was installed as part of the post–Superstorm Sandy coastal resilience efforts on West Broadway in lower Manhattan, New York City. Photo credit: William Solecki.

Many Northeast cities are served by combined sewer systems that collect and treat both storm water and municipal wastewater. During heavy rain events, combined systems can be overwhelmed and release untreated sewage into local bodies of water.[298] Moderate flooding events are expected to become more frequent in most of the Northeast during the 21st century because of more intense precipitation related to climate change.[58,142] Finally, increased precipitation and high streamflows also increase streambed erosion, especially when coupled with wetter soils prior to storm events.[299,300] Erosion at bridges can cause bridge failures,[301] leading to transportation disruption, injuries, and potential fatalities.

The impacts of changes in precipitation and temperature on water supply system behavior in the Northeast are complex. Future potable water supplies are expected to be adequate to meet future demand on average across the Northeast, but the number of watersheds where demand exceeds supply is projected to increase under most climate change scenarios.[302] Studies of specific water systems in the Northeast show mixed results. The New York City reservoir system shows high resilience and reliability under different climate change scenarios.[303] Projected flows in the Potomac River, the primary water supply for the Washington, DC, metropolitan area, are lower in most climate change scenarios, with minor to major impacts on water supply.[304]

Key Message 4

Threats to Human Health

Changing climate threatens the health and well-being of people in the Northeast through more extreme weather, warmer temperatures, degradation of air and water quality, and sea level rise. These environmental changes are expected to lead to health-related impacts and costs, including additional deaths, emergency room visits and hospitalizations, and a lower quality of life. Health impacts are expected to vary by location, age, current health, and other characteristics of individuals and communities.

Health Effects of Extreme Heat

Present-day high temperatures (heat) have been conclusively linked to a higher risk of illness and death, particularly among older adults, pregnant women, and children (Ch 14: Human Health). A number of studies have replicated these findings specifically in the Northeast (see Box 18.3; e.g., Wellenius et al. 2017, Bobb et al. 2014, Hondula et al. 2012[305,306,307]). Ambient temperatures and heat-related health effects can vary significantly over small geographic areas due to local land cover (for example, due to the urban heat island effect; see Key Message 3) (see also Ch. 5: Land Changes, KM 1), topography, and the resilience of individuals and communities.[307,308] For example, older or sicker individuals and those persons who are without access to air conditioning, living in older homes, socially isolated, or working outdoors are considered particularly vulnerable to the effects of heat.[309,310,311]

Annual average temperature over the contiguous United States has increased by 1.2°F (0.7°C) over the last few decades and by 1.8°F (1.0°C) relative to the beginning of the last century. Recent decades are the warmest in at least the past 1,500 years.[312] Average annual temperatures across the Northeast have increased from less than 1°F (0.6°C) in West Virginia to about 3°F (1.7°C) or more in New England since 1901.[18,19] Although the relative risk of death on very hot days is lower today than it was a few decades ago, heat-related illness and death remain significant public health problems in the Northeast.[20,21,22,23] For example, a study in New York City estimated that in 2013 there were 133 excess deaths due to extreme heat.[24]

Annual average temperature in the contiguous United States is expected to increase by an additional 2.5°F (1.4°C) over the next few decades regardless of future greenhouse gas emissions (Ch 2: Climate).[50] By 2050, average annual temperatures in the Northeast are expected to increase by 4.0°F (2.2°C) under the lower scenario (RCP4.5) and 5.1°F (2.8°C) under the higher scenario (RCP8.5) relative to the near present (1975–2005),[50] with several more days of extreme heat occurring throughout the region each year.

These projected increases in temperature are expected to lead to substantially more premature deaths, hospital admissions, and emergency department visits due to heat across the Northeast.[23,25,26,27,28,29] For example, in the Northeast we can expect approximately 650 more excess deaths per year caused by extreme heat by 2050 under either a lower or higher scenario (RCP4.5 or RCP8.5) and 960 (under RCP4.5) to 2,300 (under RCP8.5) more excess deaths per year by 2090.[29]

The risks associated with present-day and projected future heat can be minimized by reducing greenhouse gas emissions, minimizing exposure through urban design, or increasing individual and community resilience.[23,29,313] For example, in the Northeast region, Philadelphia and New York City have been leaders in implementing policies and investing in infrastructure aimed at reducing the number of excess deaths from extreme heat.[314] Compared to the higher scenario (RCP8.5), 1,400 premature deaths from extreme temperatures could be avoided in the Northeast each year by 2090 if global greenhouse gas emissions are consistent with the lower scenario (RCP4.5), resulting in $21 billion in annual savings (in 2015 dollars).[29]

Box 18.3: Rising Temperatures and Heat-Related Emergency Room Visits in Rhode Island

Moderate and extreme heat events already pose a health risk today,[305,306,315,316] and climate change could increase this risk. Of note, days of moderate heat occur much more often compared to days of extreme heat, such that days of moderate heat may, in aggregate, be associated with a larger number of adverse health events.[315] Average summertime temperatures are projected to continue to rise through the end of the century, raising concern about the public health impact of climate change across Northeast communities. A nationwide study projected that some of the largest increases in heat-related mortality would occur in the Northeast region, with an additional 50-100 heat-related deaths per year per million people by 2050 and 120-180 additional deaths per million people by 2100 under the mid-high scenario (RCP6.0).[28] Heat health risks seem to be highest at the start of the warm weather each year[317] and among vulnerable populations such as outdoor workers, young children, and the elderly.

Box 18.3: Rising Temperatures and Heat-Related Emergency Room Visits in Rhode Island, *continued*

In the small, coastal northeastern state of Rhode Island (population of about 1 million), maximum daily temperatures in the summer have trended upwards over the last 60 years such that Rhode Islanders experienced about three more weeks of uncomfortably hot weather over 2015–2016 than in the 1950s (Figure 18.11, left panel). A recent study looking at visits to hospital emergency rooms (ERs) found that the risk of heat-related ER visits increased sharply as maximum daily temperatures climbed above 80°F (Figure 18.11, middle panel).[26] The researchers projected that with continued climate change, Rhode Islanders could experience an additional 400 (6.8% more) heat-related ER visits each year by 2050 and up to an additional 1,500 (24.4% more) such visits each year by 2095 under the higher scenario (RCP8.5; Figure 18.11, right panel). Importantly, about 1,000 fewer annual heat-related ER visits are projected for the end of the century under the lower scenario (RCP4.5) compared to the higher scenario (RCP8.5), representing the potential protective benefit of limiting greenhouse gas emissions. Such reductions would also lead to improvements in air pollution and health starting today.[318,319]

In response to the health threat from heat, local National Weather Service offices issue heat advisories and excessive heat warnings when the forecast calls for very hot weather. Based on the results of a study across multiple states,[305] the National Weather Service Northeast Region updated its heat advisory guidelines to be issued when the heat index is forecast to exceed 95°F for any amount of time on two or more days or 100°F for any amount of time on a single day. Many communities in the Northeast have implemented plans to respond to these heat alerts to better protect the public's health (for example, with the Centers for Disease Control and Prevention's Building Resilience Against Climate Effects program), although gaps in knowledge remain.[34,314] Uncertainties exist in the estimation of the cumulative impact on health of multiple aspects of weather, including heat, drought,[320] and heavy precipitation,[321,322,323] all of which have potential adverse impacts on human health.

Observed and Projected Impacts of Excess Heat on Emergency Room Visits in Rhode Island

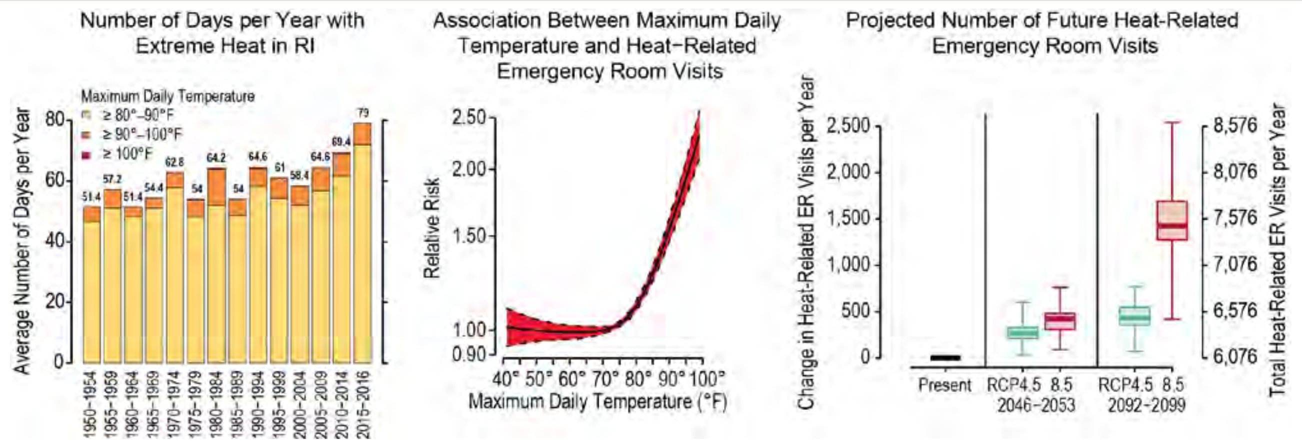


Figure 18.11: This figure shows the observed and projected impacts of excess heat on emergency room visits in Rhode Island. (left) In Rhode Island, maximum daily temperatures in the summer have trended upwards over the last 60 years, such that residents experienced about three more weeks of health-threatening hot weather over 2015–2016 than in the 1950s. (middle) A recent study looking at visits to hospital emergency rooms (ERs) found that the incidence rate of heat-related ER visits rose sharply as maximum daily temperatures climbed above 80°F. (right) The study estimates that with continued climate change, Rhode Islanders could experience an additional 400 (6.8% more) heat-related ER visits each year by 2050 and up to an additional 1,500 (24.4% more) such visits each year by 2095 under the higher scenario (RCP8.5). About 1,000 fewer annual heat-related ER visits are projected for the end of the century under the lower scenario (RCP4.5) compared to the higher scenario (RCP8.5), reflecting the estimated health benefits of adhering to a lower greenhouse gas emissions scenario. Sources: (left) Brown University; (middle, right) adapted from Kingsley et al. 2016.[26] Reproduced from Environmental Health Perspectives.

Health Effects of Air Pollution, Aeroallergens, and Wildfires

Climate change is increasing the risk of illness and death due to higher concentrations of air pollutants in many parts of the United States (Ch. 13: Air Quality). In the Northeast, climate change threatens to reverse improvements in air quality that have been achieved over the past couple of decades. For example, climate change is projected to influence future levels of ground-level ozone pollution in the Northeast by altering weather conditions and impacting emissions from human and natural sources.[324,325,326] This "climate penalty," whereby reductions in ozone precursor emissions are at least partially offset by a changing climate, is projected to lead to substantially more ozone pollution-related deaths;[324,325,327] 200–300 more excess deaths per year by 2050 compared to 2000 by one estimate.[325]

Excess deaths due to ground-level ozone pollution are projected to increase substantially under both lower (RCP4.5) and higher (RCP8.5) scenarios.[327] Reducing global emissions of greenhouse gases from a higher scenario to a lower scenario could prevent approximately 360 deaths per year due to air quality in 2090, saving approximately $5.3 billion per year (in 2015 dollars, undiscounted).[327] Moreover, many sources of the greenhouse gas emissions that contribute to climate change also contribute to degraded air quality today, with adverse effects on people's health. The adverse health risks from air pollution can be reduced in the present and in the future by addressing these common emission sources.[319]

More frequent and severe wildfires due to climate change pose an increasing risk to human health through impacts on air quality (Ch. 13: Air Quality, KM 2). Wildfire smoke can travel hundreds of miles, as occurred in 2015 when Canadian wildfire smoke caused air quality exceedance days in Baltimore, Maryland.[328]

Climate change is also expected to lengthen and intensify pollen seasons in parts of the United States, potentially leading to additional cases of allergic rhinitis (also known as hay fever) and allergic asthma episodes (Ch. 13: Air Quality, KM 3).[29,329] Among individuals with allergic asthma, exposure to certain types of pollen can result in worsening of symptoms leading to increases in allergy medication sales and emergency room visits for asthma, as already documented in New York City.[330]

Indoors, climate change is expected to bring conditions that foster mold growth, such as more dampness, and more frequent power outages that impair ventilation. Damp indoor conditions and mold are both known to be associated with respiratory illnesses including asthma symptoms and wheezing.[331] When damp conditions occur in buildings, rapid action could be warranted—remediation in a northeastern office building after the development of respiratory or severe non-respiratory symptoms by building inhabitants was not effective in reducing symptoms.[332]

Changing Ecosystems and Risk of Vector-Borne Disease

The risk posed by vector-borne diseases (those transmitted by disease-carriers such as fleas, ticks, and mosquitoes) such as Lyme disease and West Nile virus under a changing climate is also of concern in the Northeast region. These diseases, specifically tick-related Lyme disease, have been linked to climate, particularly with abundant late-spring and early-summer moisture. By 2065–2080, under the higher scenario (RCP8.5) it is projected that the period of elevated risk of Lyme disease transmission in the Northeast will begin 0.9–2.8 weeks earlier between Maine and Pennsylvania, compared to the climate observed over 1992–2007).[67] Similarly, a recent analysis estimates that there would be an additional 490 cases of West Nile neuroinvasive disease per year in the Northeast by 2090 under the higher scenario (RCP8.5) versus 210 additional cases per year under the lower scenario (RCP4.5).[29] The geographic range of suitable habitats for other mosquito vectors such as the northern house mosquito (*Culex pipiens* and *Culex restuans*, which transmit West Nile virus) and the Asian tiger mosquito (*Aedes albopictus*, which can also transmit West Nile virus and other mosquito-borne diseases) is expected to continue shifting northward into New England in the next several decades and through the end of the century as a result of climate change.[333,334]

Gastrointestinal Illness from Waterborne and Foodborne Contaminants

Another consequence of climate change is the spread of marine toxins and pathogens (Key Message 2). Some of these pathogens pose health risks through consumption of contaminated seafood. Harmful algal blooms, which can cause paralytic shellfish poisoning in humans, have become more frequent and longer lasting in the Gulf of Maine.[335] Similarly, pathogenic strains of the waterborne bacteria *Vibrio*—which are already causing thousands of foodborne illnesses per year—have expanded northward and have been responsible for increasing cases of illness in oyster consumers in the Northeast region.[336,337,338]

Combined sewer systems (where municipal wastewater and storm water use the same pipes) are particularly common in the Northeast given the older infrastructure typical of the region.[339] When runoff from heavy precipitation exceeds the capacity of these systems, combined sewer overflow containing untreated sewage is released into local waterways, potentially impacting the quality of water used for recreation or drinking. For example, a study in Massachusetts found an increased risk of gastrointestinal illness with heavy precipitation causing combined sewer overflows.[322] Increased risk of campylobacteriosis and salmonella has been documented in Maryland with increased heavy precipitation and streamflows.[340,341] Moderate flooding events are expected to become more frequent in most of the Northeast during the 21st century because of more intense precipitation related to climate change.[105,142] This could, therefore, increase the frequency of combined sewer overflows and waterborne disease. Some cities and towns are making substantial investments to reduce or eliminate the risks of combined sewer overflows (Figure 18.12).

Storm-related power outages can also pose a risk of foodborne illness.[343] Increased diarrheal illnesses from consumption of spoiled food have also been documented in New York City in 2003 following a power outage that affected millions in the Northeast (Ch. 17: Complex Systems, Box 17.5).[344]

District of Columbia Water and Sewer Authority's Clean Rivers Project

Figure 18.12: The District of Columbia Water and Sewer Authority's Clean Rivers Project[342] aims to reduce combined sewer overflows into area waterways. The Clean Rivers Project is expected to reduce overflows annually by 96% throughout the system and by 98% for the Anacostia River. In addition, the project is expected to reduce the chance of flooding in the areas it serves from approximately 50% to 7% in any given year and reduce nitrogen discharged to the Chesapeake Bay by approximately 1 million pounds per year. Photo credit: Daniel Lobo (CC BY 2.0).

Box 18.4: Role of Public Health and Healthcare Sector in Resilience and Prevention

There are numerous examples of how the public health and healthcare sectors are preparing for climate change and making energy saving changes, as highlighted in the U.S. Department of Health and Human Services' report on enhancing healthcare resilience.[345] One such example occurred in Greenwich, Connecticut, where Greenwich Hospital installed a combined heat and power system that conserves energy and provided stability in the wake of Superstorm Sandy.[346]

In June 2016, severe flooding in West Virginia resulted from a "thousand-year storm"[347] and highlighted the important role of the healthcare sector in building resilience to extreme precipitation events. A recent study of the event described the role of state and federal government working in partnership with healthcare volunteer organizations to effectively mobilize a response in the setting of such a disaster.[348] It emphasized the critical importance of healthcare professionals in providing emotional and mental health support to the response volunteers and the affected communities, as well as a need to increase capacity in these areas.[348] See Key Message 5 in this chapter and Chapter 14: Human Health, Key Message 3 for more information on additional adaptation efforts that protect health.

Figure 18.13: A Red Cross volunteer talks with a community resident after the 2016 West Virginia floods. Additionally, local medical professionals mobilized to staff temporary clinical sites. Photo credit: National Guard Bureau Public Affairs.

Mental Health and Well-Being

In addition to the adverse impacts on people's physical health, climate change is also associated with adverse impacts on mental health (Ch. 14: Human Health, KM 1). Specifically in the Northeast region, sea level rise, storm surge, and extreme precipitation events associated with climate change will contribute to higher risk of flooding in both coastal and inland areas—particularly in urban areas with large amounts of impervious surface that increases water runoff. In addition to the risks of physical injury, waterborne disease, and healthcare service disruption caused by flooding, lasting mental health consequences, such as anxiety, depression, and post-traumatic stress disorder can impact affected communities, as was observed in the wake of Superstorm Sandy in 2012 (Box 18.4).[349] Extreme weather events can have both immediate, short-term effects, as well as longer-term impacts on mental health and well-being that can last years after the specific event.

Extreme heat can also affect mental health and well-being. Higher outdoor temperatures are associated with decreases in subtle aspects of well-being such as decreased joy and happiness[350] and increased aggression and violence.[351] Underlying mental health conditions and geography also affect vulnerability. For example, a study of hospitalization for heat-related illness among people with mental health disorders showed increased risk in rural versus urban areas, possibly due to lower availability of mental health services in these rural areas.[352]

Separately, large population changes from climate-driven human migration could substantially influence both coastal and inland communities in the Northeast region (see also Key Messages 2 and 5).[285] The impacts of human migration on health and well-being depend on myriad factors, including the context of the migration.[353]

Regional Variation in Health Impacts and Vulnerability

Although climate change affects all residents of the Northeast region, risks are not experienced equally. The impact of climate change on an individual depends on the degree of exposure, the individual sensitivity to that exposure, and the individual or community-level capacity to recover (Ch. 14: Human Health, KM 2).[354] Thus, health impacts of climate change will vary across people and communities of the Northeast region depending on social, socioeconomic, demographic, and societal factors; community adaptation efforts; and underlying individual vulnerability (see Key Message 5) (see also Ch. 28: Adaptation). Particularly vulnerable groups include older or socially isolated adults, children, low-income communities, and communities of color.

Key Message 5

Adaptation to Climate Change Is Underway

Communities in the Northeast are proactively planning and implementing actions to reduce risks posed by climate change. Using decision support tools to develop and apply adaptation strategies informs both the value of adopting solutions and the remaining challenges. Experience since the last assessment provides a foundation to advance future adaptation efforts.

Communities, towns, cities, counties, states, and tribes across the Northeast are engaged in efforts to build resilience to environmental challenges and adapt to a changing climate. Developing and implementing climate adaptation strategies in daily practice often occur in collaboration with state and federal agencies (e.g., New Jersey Climate Adaptation Alliance, New York Climate Clearinghouse, Massachusetts StormSmart Coasts and Climate Action Tool, Rhode Island StormTools, EPA, CDC).[30,31,32,33,34,355,356] Advances in rural towns, cities, and suburban areas include low-cost adjustments of existing building codes and standards. In coastal areas, partnerships among local communities and federal and state agencies leverage federal adaptation tools and decision support frameworks (the National Oceanic and Atmospheric Administration's [NOAA] Digital Coast, the U.S. Geological Survey's [USGS] Coastal Change Hazards Portal, New Jersey's Getting to Resilience).

Increasingly, cities and towns across the Northeast region are developing or implementing plans for adaptation and resilience in the face of a changing climate (e.g., EPA 2017[33]). These approaches are designed to maintain and enhance the everyday life of residents and promote economic development. In some cities, adaptation planning has been used to respond to present and future challenges in the built environment. Regional efforts have recommended changes in design standards when building, replacing, or retrofitting infrastructure to account for a changing climate (Box 18.5). For example, the Port Authority of New York and New Jersey provided guidelines for engineers to account for projected changes in temperature, precipitation, and sea level rise when designing infrastructure assets.[357] The cities of Philadelphia, Pennsylvania,[296] Utica, New York,[358] and Boston, Massachusetts,[295] promote the use of green infrastructure to build resilience, particularly in response to flooding risk (Ch. 8: Coastal, Figure 8.2). In Jamaica Bay, New York, post–Superstorm Sandy efforts have fostered a set of local, regional, state, and federal actions that link resilience efforts to current climate risk, along with the potential for accelerated sea level rise and its implications for increased flood frequency (Ch. 28: Adaptation, KM 1).[359]

The issue of water security has emerged from vulnerability assessments and cuts across urban and rural communities. One example is the Washington, DC, metropolitan area's potential use of the Potomac and Occoquan estuaries as water supplies and of retired quarries as water storage facilities.[304] Adaptive reservoir operations have been implemented in the Northeast and other regions of the United States to better manage plausible future climate conditions and to meet other management goals (Ch. 3: Water, KM 3). Tribal nations have also focused on adaptation and the vulnerability of their water supplies, based on long-standing local values and traditional knowledge, including the use of water for drinking, habitat for fish and wildlife, agriculture, and cultural purposes.[97,360,361]

While resilience efforts have focused on microscale adaptations to current climate risks, communities are increasingly seeing a need for larger-scale adaptation efforts. Wide disparities in adaptive capacity exist among communities in the region. Larger, often better-resourced communities have created climate offices and programs, while response has lagged in smaller or poorer communities that are often more dependent on county- or state-level programs and expertise. The move from small-scale to larger-scale and more transformative adaptation efforts involves complex policy transition planning, social and economic development, and equity considerations (Ch. 28: Adaptation, KM 4).[362,363] This includes attention to community concerns about green gentrification—the practice of making environmental improvements in urban areas—that generally increases property values but often also drives out lower-income residents.[364]

Box 18.5: Adapting the Northeast's Cultural Heritage

A defining characteristic of the Northeast region is its rich, dense record of cultural heritage, marked by historic structures, archaeological sites, and cultural landscapes. The ability to preserve this cultural heritage is challenged by climate change. National parks and historic sites in the Northeast are already witnessing cultural resource impacts from climate change, and more impacts are expected in the future.[236] These cultural resources present unique adaptation challenges, and the region is moving forward with planning for future adaptation.

Superstorm Sandy caused substantial damage to coastal New York Harbor parks, including Gateway National Recreation Area and Statue of Liberty National Monument, where buildings and the landscape surrounding the statue and on Ellis Island were impacted and the museum collections were threatened by the loss of climate control systems that were flooded.[370,371] Sea level rise amplifies the impacts of storm events such as Superstorm Sandy, and the parks are using recovery as an opportunity to rebuild with more resilience to future storms.[371,372,373] Heating and electrical systems in historic buildings have been elevated from basement levels. Design changes, such as using non-mold-growing materials and other engineering solutions, have been made while maintaining the buildings' historic character. Following the storm, Gateway National Recreation Area added climate change vulnerability to their planning process for prioritizing historic structures between preserve, stabilize, or ruin. The recreation area has been implementing these priorities as part of the recovery process, providing examples of climate adaptation implementation.[359,374] The human community on Rockaways peninsula also responded to Sandy by using urban forestry and agricultural practices to recover and to buffer against the impact of future storms (see Building Resiliency at the Rockaways 360 tour[375]).

Decision Support Tools and Adaptation Actions

While adaptation is progressing in a variety of forms in the Northeast region, many efforts have focused on assessing risks and developing decision support tools. Many of these assessments and tools have proven useful for specific purposes. Structured decision-making is where decision-makers engage at the outset to define a problem, objectives, alternative management actions, and the consequences and tradeoffs of such actions—before making any decisions. It is being increasingly applied to design management plans, determine research needs, and allocate resources to preserve habitat and resources throughout the region.[151,365,366,367] There has been little attention devoted to evaluating and communicating the suitability and robustness of the many tools that are now available. Efforts to evaluate decision support tools and processes in a rigorous scientific manner would help stakeholders choose the best tools to answer particular questions under specific circumstances.

One significant advancement that communities and infrastructure managers have made in recent years has been the development of risk, impact, and adaptation indicators, as well as monitoring systems to measure and understand climate change and its impacts.[15] In recognizing the economic impacts of infrastructure service loss and disruption, government agencies have begun adaptation analyses to identify those infrastructure elements most critical for regional economic resilience during climate-related disruptions, as well as to identify communities most exposed to acute and chronic climate risks.[45,368,369]

Resource managers, community leaders, and other stakeholders are altering the management of coastal areas and resources in the context of climate change (Boxes 18.6 and 18.7).

Box 18.6: Building Resilience in the Chesapeake Bay Watershed

The Chesapeake Bay watershed is experiencing stronger and more frequent storms, an increase in heavy precipitation events, increasing bay water temperatures, and a rise in sea level. These trends vary throughout the watershed and over time but are expected to continue over the next century under all scenarios considered. The trends are altering both the ecosystems and mainland and island communities of the Chesapeake Bay watershed. Achieving watershed goals would require changes in policies, programs, and/or projects to achieve restoration, sustainability, conservation, and protection goals for the entire system.

To gain a better understanding of the likely impacts of climate change, as well as potential management solutions for the watershed, the 2014 Chesapeake Bay Watershed Agreement committed the NOAA Chesapeake Bay Program (CBP) Partnership to take action to "increase the resiliency of the Chesapeake Bay watershed, including its living resources, habitats, public infrastructure and communities, to withstand adverse impacts from changing environmental and climate conditions." This new Bay Agreement goal builds on the 2010 Total Maximum Daily Load (TMDL) documentation and 2009 Presidential Executive Order 13508[376,377] that called for an assessment of the impacts of a changing climate on the Chesapeake Bay's water quality and living resources. To achieve this goal and regulatory mandates, the CBP Partnership is undertaking efforts to monitor and assess trends and likely impacts of changing climatic and sea level conditions on the Chesapeake Bay ecosystem and to pursue, design, and construct restoration and protection projects to enhance resilience. The CBP Climate

Box 18.6: Building Resilience in the Chesapeake Bay Watershed, *continued*

Resiliency Workgroup's Management Strategy recognizes that it is important to build community and institutional capacity and to develop analytical capability to build cross-science disciplinary knowledge and better understanding of societal responses. A significant activity now underway is geared towards the midpoint assessment of progress towards the 2025 Chesapeake Bay TMDL goal for water quality standard attainment. As part of the TMDL midpoint assessment, the CBP Partnership has developed tools and procedures to quantify the effects of climate change on watershed flows and pollutant loads, storm intensity, increased estuarine temperatures, sea level rise, and ecosystem influences, including loss of tidal wetland attenuation with sea level rise. Current modeling efforts are underway to assess potential climate change impacts under a range of projected climate change outcomes for 2025 and 2050.[378]

Addressing climate change within the context of established watershed planning and regulatory efforts is extremely complex and requires sound climate science, climate assessments, modeling, policy development, and stakeholder engagement (Ch. 28: Adaptation, Figure 28.1). The CBP Partnership is tackling this challenge on all of these fronts, with priority directed to understanding what is needed to achieve the 2025 nutrient reduction goals and the best management practices required to achieve climate-resilient rehabilitation goals.

For example, research in Delaware is exploring the use of seashore mallow as a transitional salt-tolerant crop because of gradual wetland migration onto agricultural lands as sea levels rise.[379] Commercial and recreational fisheries and tourism depend upon living marine resources. Climate adaptation in ocean fisheries will entail coping and long-term planning responses at multiple levels of communities, industry, and management systems.[380] Fishers have traditionally switched species as needed based on ecosystem or market conditions; this will continue to be an important adaptation option, but it is increasingly constrained by regulatory approaches in fisheries.[155,178,179,202] Longer-term planning for climate adaptation has included state commissions to evaluate ocean acidification threats,[381,382] federal efforts to articulate science strategies,[383,384,385] species vulnerability assessments,[143,186] coupled social–ecological vulnerability assessments for fishing communities,[45] and planning for the potential inland migration of coastal populations due to sea level rise.[386]

The winter recreation industry has long considered snowmaking an adaptation to climate change.[387] Snowmaking improvements should assist with the viability of some Northeast ski areas,[117] while new tourism opportunities emerge.[388]

In order to sustain and advance these and other planned efforts towards climate change adaptation and resilience, decision-makers in the Northeast need to be aware of existing constraints and emerging issues. Constraints from the management, economic, and social context are highly uncertain.[389] These efforts have faced a variety of barriers and limitations, including lack of funding and jurisdictional and legal constraints.[390,391] In many cases, adaptation has been limited to coping responses that address short-term needs and are feasible within the current institutional context, whereas longer-term, more transformative efforts will likely require complex policy transition planning and frameworks that can address social and economic equality.[363] The need for solutions that support industry and community flexibility in responding to climate-related changes has also been recognized.[45,178]

Earth's changing climate is one of several stressors on human and natural systems, and it can work to exacerbate existing vulnerabilities and inequalities. Implementing resilience planning and climate change adaptation in

Box 18.7: Science for Balancing Wildlife and Human Needs in the Face of Sea Level Rise

Policymakers, agencies, and natural resource managers are under increasing pressure to manage coastal areas to meet social, economic, and natural resource demands, particularly as sea levels rise. Scientific knowledge of coastal processes and habitat use can support decision-makers as they balance these often-conflicting human and ecological needs. In collaboration with a wide network of natural resource professionals from state and federal agencies (including the U.S. Fish and Wildlife Service and National Park Service) and private conservation organizations, a research team from the U.S. Geological Survey (USGS) is conducting research and developing tools to identify suitable coastal habitats for species of concern, such as the piping plover (*Charadrius melodus*)—an ecologically important species with low population numbers—under a variety of sea level rise scenarios.

The multidisciplinary USGS team uses historical and current habitat availability and coastal characteristics to develop models that forecast likely future habitat from Maine to North Carolina.[392,393] The collaborative partners, both researchers and managers, are critical to the program: they aid in data collection efforts through the "iPlover" smartphone application[394] and help scientists focus research on specific management questions. Because these shorebirds favor sandy beaches that overwash frequently during storms, the resulting habitat maps also define current and future areas of high hazard exposure for humans and infrastructure.

Land-use planners can use results to determine optimal locations for constructing recreational facilities that minimize impacts on sensitive habitats and have a low probability of being overwashed. Alternatively, results can help resource managers proactively protect the highest-quality habitats to meet near- and long-term conservation goals and, in so doing, increase beach access for users by reducing human-bird conflicts and improving the certainty of beach availability for recreational use.

Figure 18.14: (a, b) These photographs show suitable piping plover habitat for (c) rearing chicks along the U.S. Atlantic coast. Photo credits: (a, b) Sara Zeigler, U.S. Geological Survey; (c) Josh Seibel, U.S. Fish and Wildlife Service.

order to preserve the cultural, economic, and natural heritage of the Northeast would require ongoing collaboration among tribal, rural, and urban communities as well as municipal, state, tribal, and federal agencies. The number and scope of existing adaptation plans in the Northeast show that many people in the region consider this heritage to be important.

Acknowledgments

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Traceable Accounts

Process Description

It is understood that authors for a regional assessment must have scientific and regional credibility in the topical areas. Each author must also be willing and interested in serving in this capacity. Author selection for the Northeast chapter proceeded as follows:

First, the U.S. Global Change Research Program (USGCRP) released a Call for Public Nominations. Interested scientists were either nominated or self-nominated and their names placed into a database. The concurrent USGCRP Call for Public Nominations also solicited scientists to serve as chapter leads. Both lists were reviewed by the USGCRP with input from the coordinating lead author (CLA) and from the National Climate Assessment (NCA) Steering Committee. All regional chapter lead (CL) authors were selected by the USGCRP at the same time. The CLA and CL then convened to review the author nominations list as a "first cut" in identifying potential chapter authors for this chapter. Using their knowledge of the Northeast's landscape and challenges, the CLA and CL used the list of national chapter topics that would be most relevant for the region. That topical list was associated with scientific expertise and a subset of the author list.

In the second phase, the CLA and CL used both the list of nominees as well as other scientists from around the region to build an author team that was representative of the Northeast's geography, institutional affiliation (federal agencies and academic and research institutions), depth of subject matter expertise, and knowledge of selected regional topics. Eleven authors were thus identified by December 2016, and the twelfth author was invited in April 2017 to better represent tribal knowledge in the chapter.

Lastly, the authors were contacted by the CL to determine their level of interest and willingness to serve as experts on the region's topics of water resources, agriculture and natural resources, oceans and marine ecosystems, coastal issues, health, and the built environment and urban issues.

On the due diligence of determining the region's topical areas of focus

The first two drafts of the Northeast chapter were structured around the themes of water resources, agriculture and natural resources, oceans and marine ecosystems, coastal issues, health, and the built environment and urban issues. During the USGCRP-sponsored Regional Engagement Workshop held in Boston on February 10, 2017, feedback was solicited from approximately 150 online participants (comprising transportation officials, coastal managers, urban planners, city managers, fisheries managers, forest managers, state officials, and others) around the Northeast and other parts of the United States, on both the content of these topical areas and important focal areas for the region. Additional inputs were solicited from other in-person meetings such as the ICNet workshop and American Association of Geographers meetings, both held in April 2017. All feedback was then compiled with the lessons learned from the USGCRP CLA-CL meeting in Washington, DC, also held in April 2017. On April 28, 2017, the author team met in Burlington, Vermont, and reworked the chapter's structure around the risk-based framing of interest to 1) changing seasonality, 2) coastal/ocean resources, 3) rural communities and livelihoods, 4) urban interconnectedness, and 5) adaptation.

Key Message 1

Changing Seasons Affect Rural Ecosystems, Environments, and Economies

The seasonality of the Northeast is central to the region's sense of place and is an important driver of rural economies. Less distinct seasons with milder winter and earlier spring conditions (*very high confidence*) are already altering ecosystems and environments (*high confidence*) in ways that adversely impact tourism (*very high confidence*), farming (*high confidence*), and forestry (*medium confidence*). The region's rural industries and livelihoods are at risk from further changes to forests, wildlife, snowpack, and streamflow (*likely*).

Description of evidence base

Multiple lines of evidence show that changes in seasonal temperature and precipitation cycles have been observed in the Northeast.[3,4,109,110,124,154,158] Projected increases in winter air temperatures under lower and higher scenarios (RCP4.5 and RCP8.5)[3,4] will result in shorter and milder cold seasons, a longer frost-free season,[3] and decreased regional snow cover and earlier snowmelt.[108,109,110,395,396,397] Observed seasonal changes to streamflows in response to increased winter precipitation, changes in snow hydrology,[112,138,139,140] and an earlier but prolonged transition into spring[68] are projected to continue.[105]

These changes are affecting a number of plant and animal species throughout the region, including earlier bloom times and leaf-out,[71,73,158] spawning,[164] migration,[84,166,398] and insect emergence,[74] as well as longer growing seasons,[72] delayed senescence, and enhanced leaf color change.[103] Milder winters will likely contribute to the range expansion of wildlife and insect species,[399] increase the size of certain herbivore populations[78] and their exposure to parasitism,[81,82] and increase the vulnerability of an array of plant and animal species to change.[66,103,143]

Warmer winters will likely contribute to declining yields for specialty crops[35] and fewer operational days for logging[88] and snow-dependent recreation.[115,116,118] Excess moisture is the leading cause of crop loss in the Northeast,[35] and the observed increase in precipitation amount, intensity, and persistence is projected to continue under both lower and higher scenarios.[3,4,124,125]

Major uncertainties

Warmer fall temperatures affect senescence, fruit ripening, migration, and hibernation, but are less well studied in the region[98] and must be considered alongside other climatic factors such as drought. Projections for summer rainfall in the Northeast are uncertain,[4] but evaporative demand for surface moisture is expected to increase with projected increases in summer temperatures.[3,4] Water use is highest during the warm season;[141,400] how much this will affect water availability for agricultural use depends on the frequency and intensity of drought during the growing season.[302]

Description of confidence and likelihood

There is *high confidence* that the combined effects of increasing winter and early-spring temperatures and increasing winter precipitation (*very high confidence*) are changing aquatic and terrestrial habitats and affecting the species adapted to them. The impact of changing seasonal temperature, moisture conditions, and habitats will vary geographically and impact interactions among species. It is *likely* that some will not adapt. There is *high confidence* that over the next century, some species will decline while other species introduced to the region thrive as conditions change. There is *high confidence* that increased precipitation in early spring will negatively impact farming, but the response of vegetation to future changes in seasonal temperature and moisture conditions depends on plant hardiness for *medium confidence* in the level of risk to specialty crops and forestry. A reduction in the length of the snow season by mid-century is *highly likely* under lower and higher scenarios, with *very high confidence* that the winter recreation industry will be negatively impacted by the end of the century under lower and higher scenarios (RCP4.5 and RCP8.5).

Key Message 2

Changing Coastal and Ocean Habitats, Ecosystem Services, and Livelihoods

The Northeast's coast and ocean support commerce, tourism, and recreation that are important to the region's economy and way of life. Warmer ocean temperatures, sea level rise, and ocean acidification (*high confidence*) threaten these services (*likely*). The adaptive capacity of marine ecosystems and coastal communities will influence ecological and socioeconomic outcomes as climate risks increase (*high confidence*).

Description of evidence base

Warming rates on the Northeast Shelf have been higher than experienced in other ocean regions,[39] and climate projections indicate that warming in this region will continue to exceed rates expected in other ocean regions.[48,49] Multiple lines of research have shown that changes in ocean temperatures and acidification have resulted in distribution,[7,8,10] productivity,[39,173,191,401] and phenology shifts[155,158,163,164,166] in marine populations. These shifts have impacted marine fisheries and prompted industry adaptations to changes.[155,176,200]

Research also shows that sea level rise has been[12,46,205,206] and will be higher in the Northeast with respect to the rest of the United States[12,249,250,251] due largely to vertical land movement,[207,208,209] varying atmospheric shifts and ocean dynamics,[210,211,212,213,215,252] and ice mass loss from the polar regions.[214] High tide flooding has increased[216,402] and will continue to increase,[403] and storm surges due to stronger and more frequent hurricanes[50,254,255] have been and will be amplified by sea level rise.[217,220,221,289] Climate-related coastal impacts on the landscape include greater potential for coastal flooding, erosion, overwash, barrier island breaching and disaggregation, and marsh conversion to open water,[12,216,223,226,256,257,258,259,263,279,404] which will directly affect the ability of ecosystems to sustain many of the services they provide. Changes to salt marshes in response to sea level rise have already been observed in some coastal settings in the region, although their impacts are site specific and variable.[265,266,267,268,269,270,271,405] Studies quantifying sea level rise impacts on other types of coastal settings (such as beaches) in the region are more limited; however, there is consensus on what impacts under higher rates of relative sea level rise might look like due to geologic history and modern analogs elsewhere (such as the Louisiana coast).[12,226,404] Although probabilistically low, worst-case sea level rise projections that account for ice sheet collapse[47,406] would result in sea level rise rates far beyond the rates at which natural systems are likely able to adapt,[274,275,280] affecting not only ecosystems function and services but also likely substantially changing the coastal landscape largely through inundation.[223]

Major uncertainties

Although work to value coastal and marine ecosystems services is still evolving,[6,41,281] changes to coastal ecosystem services will depend largely on the adaptability of the coastal landscape, direct hits from storms, and rate of sea level rise, which have identified uncertainties. Lower sea level rise rates are more probable, though the timing of ice sheet collapse[407] and the variability of ocean dynamics are still not well understood[210,211,215] and will dramatically affect the rate of rise.[47,406] It is also difficult to anticipate how humans will contend with changes along the coast[389] and how adjacent natural settings will respond. Furthermore, specific tipping points for many coastal ecosystems are still not well resolved[275,277,280] and vary due to site-specific conditions[224,274]

The Northeast Shelf is sensitive to ocean acidification, and many fisheries in the region are dependent on shell-forming organisms.[181,182,186] However, few studies that have investigated the impacts of ocean acidification on species biology and ecology used native populations from the region[182] or tested the effects at acidification levels expected over the next 20–40 years.[143] Moreover, there are limited studies that consider the effects of climate change in conjunction with multiple other stressors that affect marine populations.[39,40,178,408] Limited understanding of the adaptive capacity of species to environmental changes presents major uncertainties in ecosystem responses to climate change.[143,409] How humans will respond to changes in ecosystems is also not well known, yet these decisions will shape how marine industries and coastal communities are affected by climate change.[45]

Description of confidence and likelihood

Warming ocean temperatures (*high confidence*), acidification (*high confidence*), and sea level rise (*very high confidence*) will alter coastal and ocean ecosystems (*likely*) and threaten the ecosystems services provided by the coasts and oceans (*likely*) in the Northeast. There is *high confidence* that ocean temperatures have caused shifts in the distribution, productivity, and phenology of marine species and *very high confidence* that high tide flooding and storm surge impacts are being amplified by sea level rise. Because much will depend on how humans choose to address or adapt to these problems, and as there is considerable uncertainty over the extent to which many of these coastal systems will be able to adapt, there is *medium confidence* in the level of risk to traditions and livelihoods. It is *likely* that under higher scenarios, sea level rise will significantly alter the coastal landscape, and rising temperatures and acidification will affect marine populations and fisheries.

Key Message 3

Maintaining Urban Areas and Communities and Their Interconnectedness

The Northeast’s urban centers and their interconnections are regional and national hubs for cultural and economic activity. Major negative impacts on critical infrastructure, urban economies, and nationally significant historic sites are already occurring and will become more common with a changing climate. (*High Confidence*)

Description of evidence base

The urban built environment and related supply and management systems are at increased risk of disruption from a variety of increasing climate risks. These risks emerge from accelerated sea level rise as well as increased frequency of coastal and estuarine flooding, intense precipitation events, urban heating and heat waves, and drought.

Coastal flooding can lead to adverse health consequences, loss of life, and damaged property and infrastructure.[368] Much of the region's major industries and cities are located along the coast, with 88% of the region's population and 68% of the regional gross domestic product.[260] High tide flooding is also increasingly problematic and costly.[47] Rising sea level and amplified storm events can increase the magnitude and geographic size of a coastal flood event. The frequency of dangerous coastal flooding in the Northeast would more than triple with 2 feet of sea level rise.[93] In Boston, the areal extent of a 1% (1 in 100 chance of occurring in any given year) flood is expected to increase multifold in many coastal neighborhoods.[295] However, there will likely be notable variability across coastal locations. Using the 2014 U.S. National Climate Assessment's Intermediate-High scenario for sea level rise (a global rise of 1.2 meters by 2100), the median number of flood events per year for the Northeast is projected to increase from 1 event per year experienced today to 5 events by 2030 and 25 events by 2045, with significant variation within the region.[410]

Intense precipitation events can lead to riverine and street-level flooding affecting urban environments. Over recent decades, the Northeast has experienced an increase of intense precipitation events, particularly in the spring and fall.[411] From 1958 to 2016, the number of heaviest 1% precipitation events (that is, an event that has a 1% chance of occurring in any given year) in the Northeast has increased by 55%.[58] A recent study suggests that this trend began rather abruptly after 1996, though uniformly across the region.[411]

Urban heating and heat waves threaten the health of the urban population and the integrity of the urban landscape. Due to the urban heat island effect, summer surface temperatures across Northeast cities were an average of 13°F to 16°F (7°C to 9°C) warmer than surrounding rural areas over a three-year period, 2003 to 2005.[412] This is of concern, as rising temperatures increase heat- and pollution-related mortality while also stressing energy demands across the urban environment.[413] However, the degree of urban heat island intensity varies across cities depending on local factors such as whether the city is coastal or inland.[414] Recent analysis of mortality in major cities of the Northeast suggests that the region could experience an additional 2,300 deaths per year by 2090 from extreme heat under RCP8.5 (compared to an estimated 970 deaths per year under the lower scenario, RCP4.5) compared to 1989–2000.[29] Another study that considered 1,692 cities around the world suggested that without mitigation, total economic costs associated with climate change could be 2.6 times higher due to the warmer temperatures in urban versus extra-urban environments.[415]

Changes in temperature and precipitation can have dramatic impacts on urban water supply available for municipal and industrial uses. Under a higher scenario (RCP8.5), the Northeast is projected to experience cumulative losses of $730 million (discounted at 3% in 2015 dollars) due to water supply shortfalls for the period 2015 to 2099.[29] Under a lower scenario (RCP4.5), the Northeast is projected to sustain losses of $510 million (discounted at 3% in 2015 dollars).[29] The losses are largely projected for the more southern and coastal areas in the region.

Major uncertainties

Projecting changes in urban pollution and air quality under a changing climate is challenging given the associated complex chemistry and underlying factors that influence it. For example, fine particulates ($PM_{2.5}$; that is, particles with a diameter of or less than 2.5 micrometers) are affected by cloud processes and precipitation, amongst other meteorological processes, leading to considerable uncertainty in the geographic distribution and overall trend in both modeling analysis and the literature.[29] Land use can also play an unexpected role, such as planting trees as a mitigation option that may lead to increases in volatile organic compounds (VOCs), which, in a VOC-limited environment that can exist in some urban areas such as New York City, may increase ozone concentrations (however, it is noted that most of the Northeast region is limited by the availability of nitrogen oxides).[327]

Interdependencies among infrastructure sectors can lead to unexpected and amplified consequences in response to extreme weather events. However, it is unclear how society may choose to invest in the built environment, possibly strengthening urban infrastructure to plausible future conditions.

Description of confidence and likelihood

There is *high confidence* that weather-related impacts on urban centers already experienced today will become more common under a changing climate. For the Northeast, sea level rise is projected to occur at a faster rate than the global average, potentially increasing the impact of moderate and severe coastal flooding.[47]

By the end of the century and under a higher scenario (RCP8.5), Coupled Model Intercomparison Project Phase 5 (CMIP5) models suggest that annual average temperatures will increase by more than 9°F (16°C) for much of the region (2071–2100 compared to 1976–2005), while precipitation is projected to increase, particularly during winter and spring.[50]

Extreme events that impact urban environments have been observed to increase over much of the United States and are projected to continue to intensify. There is *high confidence* that heavy precipitation events have increased in intensity and frequency since 1901, with the largest increase in the Northeast, a trend projected to continue.[50] There is *very high confidence* that extreme heat events are increasing across most regions worldwide, a trend very likely to continue.[50] Extreme precipitation from tropical cyclones has not demonstrated a clear observed trend but is expected to increase in the future.[50,253] Research has suggested that the number of tropical cyclones will overall increase with future warming.[416] However, this finding is contradicted by results using a high-resolution dynamical downscaling study under a lower scenario (RCP4.5), which suggests overall reduction in frequency of tropical cyclones but an increase in the occurrence of storms of Saffir–Simpson categories 4 and 5.[50]

Key Message 4

Threats to Human Health

Changing climate threatens the health and well-being of people in the Northeast through more extreme weather, warmer temperatures, degradation of air and water quality, and sea level rise (*very high confidence*). These environmental changes are expected to lead to health-related impacts and costs, including additional deaths, emergency room visits and hospitalizations, and a lower quality of life (*very high confidence*). Health impacts are expected to vary by location, age, current health, and other characteristics of individuals and communities (*very high confidence*).

Description of evidence base

Extreme storms and temperatures, overall warmer temperatures, degradation of air and water quality, and sea level rise are all associated with adverse health outcomes from heat,[20,21,22,23,305,306,307] poor air quality,[324,325,326] disease-transmitting vectors,[67,333,334] contaminated food and water,[322,340,341,344] harmful algal blooms,[335] and traumatic stress or health service disruption.[17,349] The underlying susceptibility of populations determines whether or not there are health impacts from an exposure and the severity of such impacts.[307,308]

Major uncertainties

Uncertainty remains in projections of the magnitude of future changes in particulate matter, humidity, and wildfires and how these changes may influence health risks. For example, health effects of future extreme heat may be exacerbated by future changes in absolute or relative humidity.

Health impacts are ultimately determined by not just the environmental hazard but also the amount of exposure, size and underlying susceptibility of the exposed population, and other factors such as health insurance coverage and access to timely healthcare services. In projecting future health risks, researchers acknowledge these challenges and use different analytic approaches to address this uncertainty or note it as a limitation.[23,28,326]

In addition, there is a paucity of literature that considers the joint or cumulative impacts on health of multiple climatic hazards. Additional areas where the literature base is limited include specific health impacts related to different types of climate-related migration, the impact of climatic factors on mental health, and the specific timing and geographic range of shifting disease-carrying vectors.

Description of confidence and likelihood

There is *very high confidence* that extreme weather, warmer temperatures, degradation of air and water quality, and sea level rise threaten the health and well-being of people in the Northeast. There is *very high confidence* that these climate-related environmental changes will lead to additional adverse health-related impacts and costs, including premature deaths, more emergency department visits and hospitalizations, and lower quality of life. There is *very high confidence* that climate-related health impacts will vary by location, age, current health, and other characteristics of individuals and communities.

Key Message 5

Adaptation to Climate Change Is Underway

Communities in the Northeast are proactively planning (*high confidence*) and implementing (*medium confidence*) actions to reduce risks posed by climate change. Using decision support tools to develop and apply adaptation strategies informs both the value of adopting solutions and the remaining challenges (*high confidence*). Experience since the last assessment provides a foundation to advance future adaptation efforts (*high confidence*).

Description of evidence base

Reports on climate adaptation and resilience planning have been published by city, state, and tribal governments and by regional and federal agencies in the Northeast. Examples include the Interstate Commission on the Potomac River Basin (for the Washington, DC, metropolitan area),[304] Boston,[295] the Port Authority of New York and New Jersey,[357] the St. Regis Mohawk Tribe,[360] the U.S. Army Corps of Engineers,[368] the State of Maine,[381] and southeastern Connecticut.[417] Structured decision-making is being applied to design management plans, determine research needs, and allocate resources[365] to preserve habitat and resources throughout the region.[151,366,367]

Major uncertainties

The percentage of communities in the Northeast that are planning for climate adaptation and resilience and the percentage of those using decision support tools are not known. More case studies would be needed to evaluate the effectiveness of adaptation actions.

Description of confidence and likelihood

There is *high confidence* that there are communities in the Northeast undertaking planning efforts to reduce risks posed from climate change and *medium confidence* that they are implementing climate adaptation. There is *high confidence* that decision support tools are informative and *medium confidence* that these communities are using decision support tools to find solutions for adaptation that are workable. There is *high confidence* that early adoption is occurring in some communities and that this provides a foundation for future efforts. This Key Message does not address trends into the future, and therefore likelihood is not applicable.

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19 Southeast

Red mangrove in Titusville, Florida

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. 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. Many of these urban areas are rapidly growing and offer opportunities to adopt effective adaptation efforts to prevent future negative impacts of climate change.

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. 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.

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.

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.

Executive Summary

The Southeast includes vast expanses of coastal and inland low-lying areas, the southern portion of the Appalachian Mountains, numerous high-growth metropolitan areas, and large rural expanses. These beaches and bayous, fields and forests, and cities and small towns are all at risk from a changing climate. While some climate change impacts, such as sea level rise and extreme downpours, are being acutely felt now, others, like increasing exposure to dangerous high temperatures, humidity, and new local diseases, are expected to become more significant in the coming decades. While all regional residents and communities are potentially at risk for some impacts, some communities or populations are at greater risk due to their locations, services available to them, and economic situations.

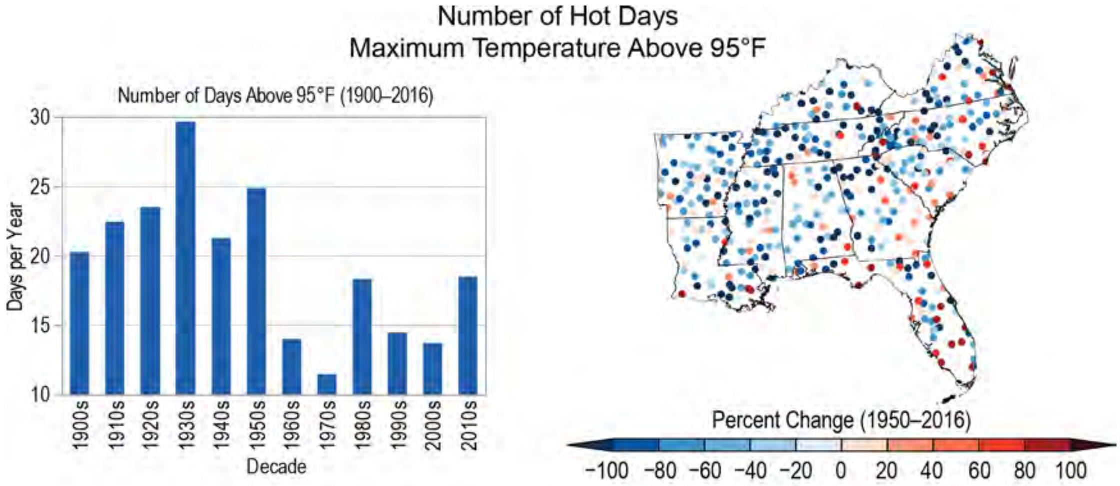
Observed warming since the mid-20th century has been uneven in the Southeast region, with average daily minimum temperatures increasing three times faster than average daily maximum temperatures. The number of extreme rainfall events is increasing. Climate model simulations of future conditions project increases in both temperature and extreme precipitation.

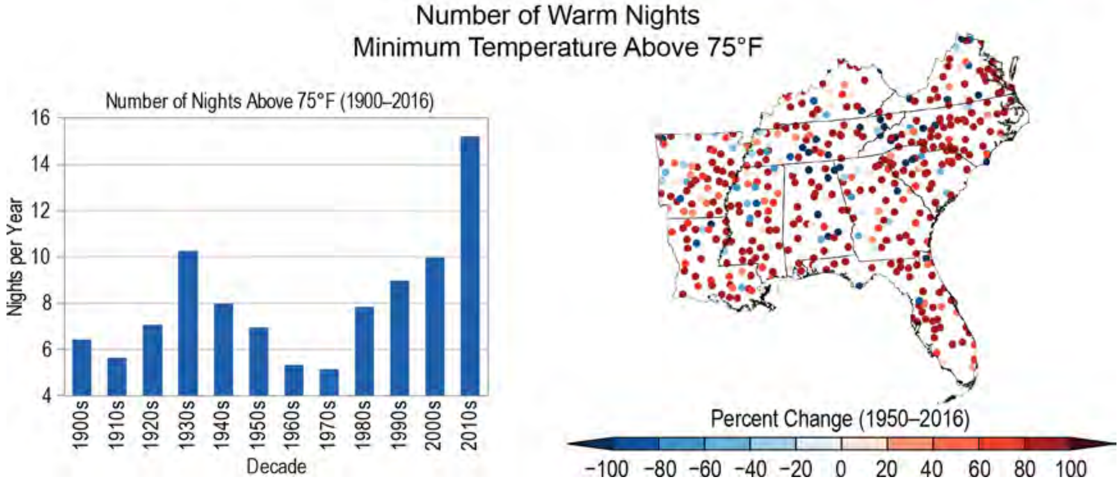
Trends towards a more urbanized and denser Southeast are expected to continue, creating new climate vulnerabilities. Cities across the Southeast are experiencing more and longer summer heat waves. Vector-borne diseases pose a greater risk in cities than in rural areas because of higher population densities and other human factors, and the major urban centers in the Southeast are already impacted by poor air quality during warmer months. Increasing precipitation and extreme weather events will likely impact roads, freight rail, and passenger rail, which will likely have cascading effects across the region. Infrastructure related to drinking water and wastewater treatment also has the potential to be compromised by climate-related events. Increases in extreme rainfall events and high tide coastal floods due to future climate change will impact the quality of life of permanent residents as well as tourists visiting the low-lying and coastal regions of the Southeast. Sea level rise is contributing to increased coastal flooding in the Southeast, and high tide flooding already poses daily risks to businesses, neighborhoods, infrastructure, transportation, and ecosystems in the region.[1,2] There have been numerous instances of intense rainfall events that have had devastating impacts on inland communities in recent years.

The ecological resources that people depend on for livelihoods, protection, and well-being are increasingly at risk from the impacts of climate change. Sea level rise will result in the rapid conversion of coastal, terrestrial, and freshwater ecosystems to tidal saline habitats. Reductions in the frequency and intensity of cold winter temperature extremes are already allowing tropical and subtropical species to move northward and replace more temperate species. Warmer winter temperatures are also expected to facilitate the northward movement of problematic invasive species, which could transform natural systems north of their current distribution. 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 practices.[3,4,5,6]

Many in rural communities are maintaining connections to traditional livelihoods and relying on natural resources that are inherently vulnerable to climate changes. Climate trends and possible climate futures show patterns that are already impacting—and are projected to further impact—rural sectors, from agriculture and forestry to human health and labor productivity. Future temperature increases are projected to pose challenges to human health. 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.[7] Rural communities tend to be more vulnerable to these changes due to factors such as demography, occupations, earnings, literacy, and poverty incidence.[8,9,10] In fact, a recent economic study using a higher scenario (RCP8.5)[11] suggests that the southern and midwestern populations are likely to suffer the largest losses from future climate changes in the United States. Climate change tends to compound existing vulnerabilities and exacerbate existing inequities. Already poor regions, including those found in the Southeast, are expected to continue incurring greater losses than elsewhere in the United States.

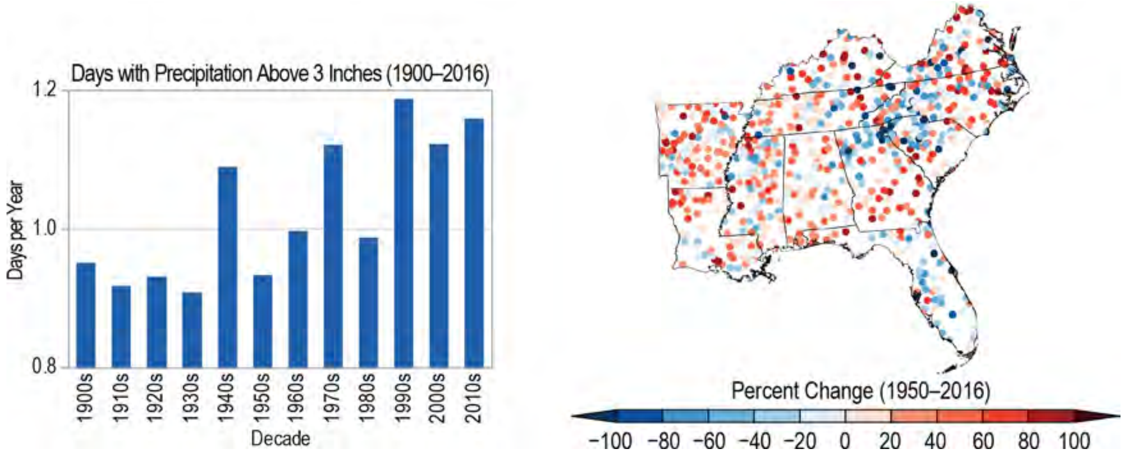
Historical Changes in Hot Days and Warm Nights


Number of Hot Days
Maximum Temperature Above 95°F


Number of Warm Nights
Minimum Temperature Above 75°F

Sixty-one percent of major Southeast cities are exhibiting some aspects of worsening heat waves, which is a higher percentage than any other region of the country.[12] Hot days and warm nights together impact human comfort and health and result in the need for increased cooling efforts. Agriculture is also impacted by a lack of nighttime cooling. Variability and change in (top) the annual number of hot days and (bottom) warm nights are shown. The bar charts show averages over the region by decade for 1900–2016, while the maps show the trends for 1950–2016 for individual weather stations. Average summer temperatures during the most recent 10 years have been the warmest on record, with very large increases in nighttime temperatures and more modest increases in daytime temperatures, as indicated by contrasting changes in hot days and warm nights. (top left) The annual number of hot days (maximum temperature above 95°F) has been lower since 1960 than the average during the first half of the 20th century; (top right) trends in hot days since 1950 are generally downward except along the south Atlantic coast and in Florida due to high numbers during the 1950s but have been slightly upward since 1960, following a gradual increase in average daytime maximum temperatures during that time. (bottom left) Conversely, the number of warm nights (minimum temperature above 75°F) has doubled on average compared to the first half of the 20th century and (bottom right) locally has increased at most stations. *From Figure 19.1 (Sources: NOAA NCEI and CICS-NC)*.

Historical Change in Heavy Precipitation



The figure shows variability and change in (left) the annual number of days with precipitation greater than 3 inches (1900–2016) averaged over the Southeast by decade and (right) individual station trends (1950–2016). The number of days with heavy precipitation has increased at most stations, particularly since the 1980s. *From Figure 19.3 (Sources: NOAA NCEI and CICS-NC)*

Background

Throughout the southeastern United States, the impacts of sea level rise, increasing temperatures, extreme heat events, heavy precipitation, and decreased water availability continue to have numerous consequences for human health, the built environment, and the natural world. This assessment builds on the above concerns described in the Third National Climate Assessment (NCA3) and includes impacts to urban and rural landscapes as well as natural systems. The impacts from these changes are becoming visible as 1) flooding increases stress on infrastructure, ecosystems, and populations; 2) warming temperatures affect human health and bring about temporal and geographic shifts in the natural environment and landscapes; and 3) wildfires and growing wildfire risk create challenges for natural resource managers and impacted communities.

The Southeast includes vast expanses of coastal and inland low-lying areas, the southern (and highest) portion of the Appalachian Mountains, numerous high-growth metropolitan areas, and large rural expanses. Embedded in these land- and seascapes is a rich cultural history developed over generations by the many communities that call this region home. However, these beaches and bayous, fields and forests, and cities and small towns are all at risk from a changing climate. These risks vary in type and magnitude from place to place, and while some climate change impacts, such as sea level rise and extreme downpours, are being acutely felt now, others, like increasing exposure to dangerously high temperatures—often accompanied by high humidity—and new local diseases, are expected to become more significant in the coming decades. While all regional residents and communities are potentially at risk for some impacts, some communities or populations are at greater risk due to their locations, services available, and economic situations. In fact, a recent economic study using a higher scenario (RCP8.5)[11] suggests that the southern and midwestern populations are likely to suffer the largest losses from projected climate changes in the United States. According to the article, "[b]ecause losses are largest in regions that are already poorer on average, climate change tends to increase preexisting inequality in the United States."[11] Understanding the demographic and socioeconomic composition of racial and ethnic groups in the region is important, because these characteristics are associated with health risk factors, disease prevalence, and access to care, which in turn may influence the degree of impact from climate-related threats.

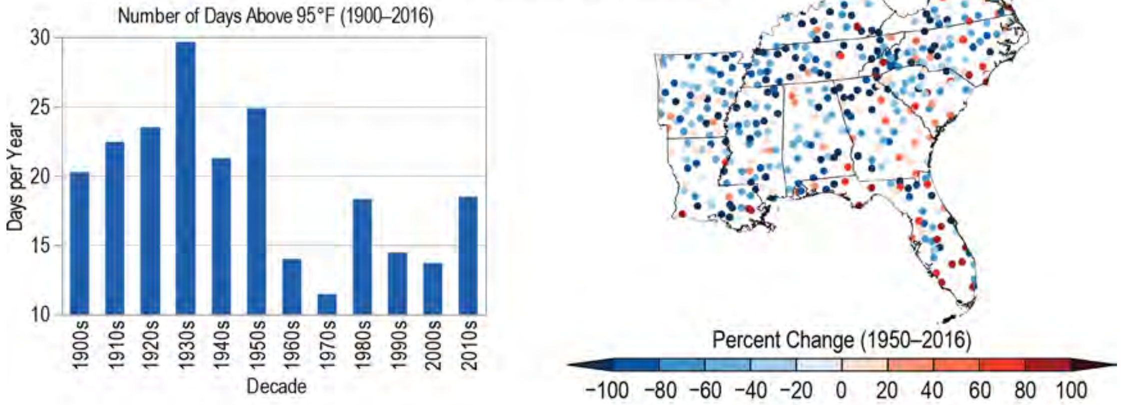
Historical Climate and Possible Future Climates

The Southeast region experienced high annual average temperatures in the 1920s and 1930s, followed by cooler temperatures until the 1970s. Since then, annual average temperatures have warmed to levels above the 1930s; the decade of the 2010s through 2017 has been warmer than any previous decade (App 5: FAQs, Figure A5.14), both for average daily maximum and average daily minimum temperature. Seasonal warming has varied. The decade of the 2010s through 2017 is the warmest in all seasons for average daily minimum temperature and in winter and spring for average daily maximum temperature. However, for average daily maximum temperature, the summers of the 1930s and 1950s and the falls of the 1930s were warmer on average. The southeastern United States is one of the few regions in the world that has experienced little overall warming of daily maximum temperatures since 1900. The reasons for this have been the subject of much research, and hypothesized causes include both human and natural influences.[13,14,15,16,17] However, since the early 1960s, the Southeast has been warming at a similar rate as the rest of the United States (Ch.

2: Climate, Figure 2.4). During the 2010s, the number of nights with minimum temperatures greater than 75°F was nearly double the long-term average for 1901–1960 (Figure 19.1), while the length of the freeze-free season was nearly 1.5 weeks greater than any other period in the historical record (Figure 19.2). These increases were widespread across the region and can have important effects on both humans and the natural environment.[18] By contrast, the number of days above 95°F has been lower since 1960 compared to the pre-1960 period, with the highest numbers occurring in the 1930s and 1950s, both periods of severe drought (Figure 19.1). The differing trends in hot days and warm nights reflect the seasonal differences in average daily maximum and average daily minimum temperature trends.

Historical Changes in Hot Days and Warm Nights

Number of Hot Days
Maximum Temperature Above 95°F



Number of Warm Nights
Minimum Temperature Above 75°F

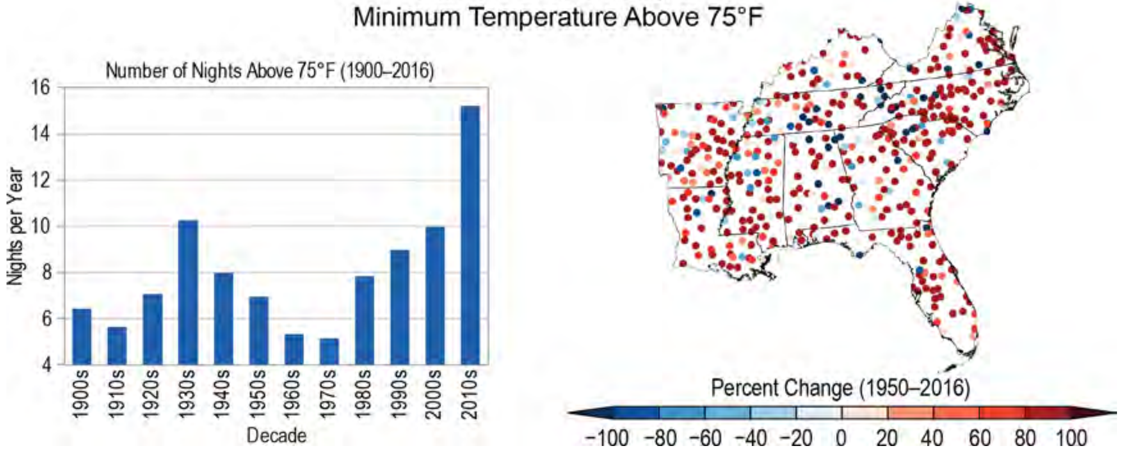


Figure 19.1: Sixty-one percent of major Southeast cities are exhibiting some aspects of worsening heat waves, which is a higher percentage than any other region of the country.[12] Hot days and warm nights together impact human comfort and health and result in the need for increased cooling efforts. Agriculture is also impacted by a lack of nighttime cooling. Variability and change in (top) the annual number of hot days and (bottom) warm nights are shown. The bar charts show averages over the region by decade for 1900–2016, while the maps show the trends for 1950–2016 for individual weather stations. Average summer temperatures during the most recent 10 years have been the warmest on record, with very large increases in nighttime temperatures and more modest increases in daytime temperatures, as indicated by contrasting changes in hot days and warm nights. (top left) The annual number of hot days (maximum temperature above 95°F) has been lower since 1960 than the average during the first half of the 20th century; (top right) trends in hot days since 1950 are generally downward except along the south Atlantic coast and in Florida due to high numbers during the 1950s but have been slightly upward since 1960, following a gradual increase in average daytime maximum temperatures during that time. (bottom left) Conversely, the number of warm nights (minimum temperature above 75°F) has doubled on average compared to the first half of the 20th century and (bottom right) locally has increased at most stations. Sources: NOAA NCEI and CICS-NC.

Historical Change in Freeze-Free Season Length

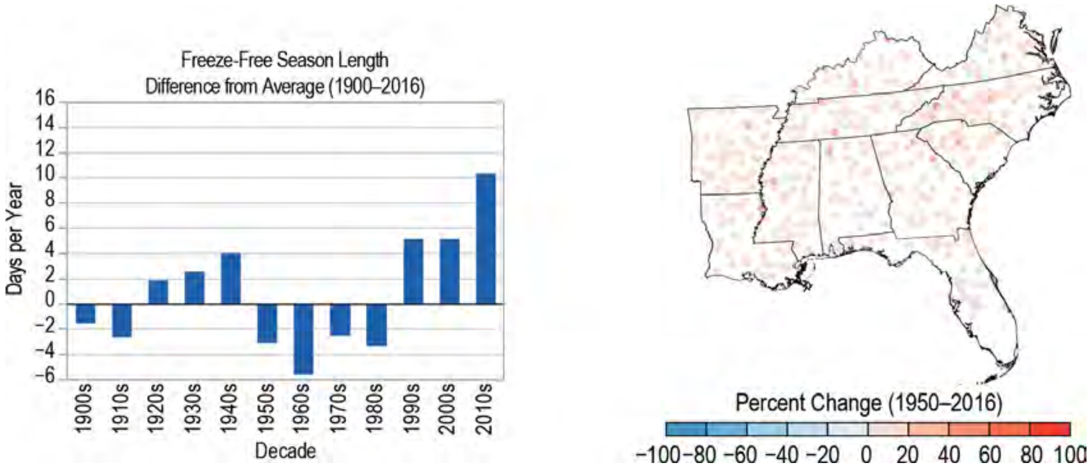


Figure 19.2: The figure shows the variability and change in the length of the freeze-free season. (left) The bar chart shows differences in the length of the freeze-free season by decade (1900–2016) as compared to the long-term average for the Southeast. (right) The map shows trends over 1950–2016 for individual weather stations. The length of the freeze-free season has increased at most stations, particularly since the 1980s. Sources: NOAA NCEI and CICS-NC.

Historical Change in Heavy Precipitation

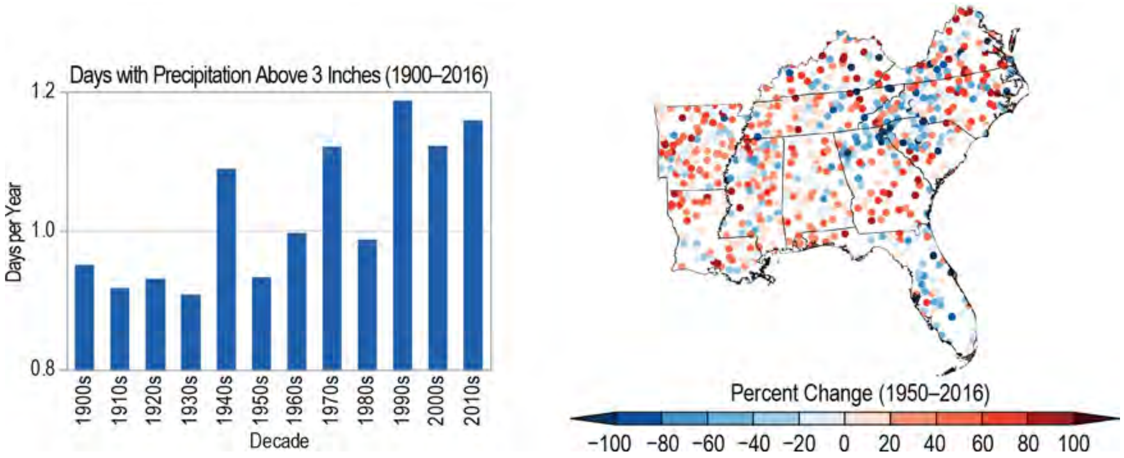


Figure 19.3: The figure shows variability and change in (left) the annual number of days with precipitation greater than 3 inches (1900–2016) averaged over the Southeast by decade and (right) individual station trends (1950–2016). The numbers of days with heavy precipitation has increased at most stations, particularly since the 1980s. Sources: NOAA NCEI and CICS-NC.

The number of extreme rainfall events is increasing. For example, the number of days with 3 or more inches of precipitation has been historically high over the past 25 years, with the 1990s, 2000s, and 2010s ranking as the decades with the 1st, 3rd, and 2nd highest number of events, respectively (Figure 19.3). More than 70% of precipitation recording locations show upward trends since 1950, although there are downward trends at many stations along and southeast of the Appalachian Mountains and in Florida (Figure 19.3).

Climate model simulations of future conditions project increases in temperature and extreme precipitation for both lower and higher scenarios (RCP4.5 and RCP8.5; see Figure 19.5).[13,19] After the middle of the 21st century, however, the projected increases are lower for the lower scenario (RCP4.5). Much larger changes are simulated by the late 21st century under the higher scenario (RCP8.5), which most closely tracks with our current consumption of fossil fuels. Under the higher scenario, nighttime minimum temperatures above 75°F and daytime maximum temperatures above 95°F become the summer norm and nights above 80°F and days above 100°F, now relatively rare occurrences, become commonplace. Cooling degree days (a measure of the need for air conditioning [cooling] based on daily average temperatures rising above a standard temperature—often 65°F) nearly double, while heating degree days (a measure of the need for heating) decrease by over a third (Figure 19.22). The freeze-free season lengthens by more than a month, and the frequency of freezing temperatures decreases substantially.[20,21]

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. 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. Many of these urban areas are rapidly growing and offer opportunities to adopt effective adaptation efforts to prevent future negative impacts of climate change.

Rapid Population Shifts and Climate Impacts on Urban Areas

While the Southeast is historically known for having a rural nature, a drastic shift toward a more urbanized region is underway. The Southeast contains many of the fastest-growing urban areas in the country, including a dozen of the top 20 fastest-growing metropolitan areas (by percentage) in 2016.[22] Metropolitan Atlanta has been swiftly growing, adding 69,200 residents in just one year.[23] At the same time, many rural counties in the South are losing population.[24] These trends towards a more urbanized and dense Southeast are expected to continue, creating new climate vulnerabilities but also opportunities to adapt as capacity and resources increase in cities (Ch. 17: Complex Systems). In particular, coastal cities in the Southeast face multiple climate risks, and many planning efforts are underway in these cities. Adaptation, mitigation, and planning efforts are emphasizing "co-benefits" (positive benefits related to the reduction of greenhouse gases or implementation of adaptation efforts) to help boost the economy while protecting people and infrastructure.

Increasing Heat

Cities across the Southeast are experiencing more and longer summer heat waves. Nationally, there are only five large cities that have increasing trends exceeding the national average for all aspects of heat waves (timing, frequency, intensity, and duration), and three of these cities are in the Southeast region—Birmingham, New Orleans, and Raleigh. Sixty-one percent of major Southeast cities are exhibiting some aspects of worsening heat waves, which is a higher percentage than any other region of the country.[12] The urban heat island effect (cities that are warmer than surrounding rural areas, especially at night) adds to the impact of heat waves in cities (Ch. 5: Land Changes, KM 1). Southeastern cities including Memphis and Raleigh have a particularly high future heat risk.[25]

The number of days with high minimum temperatures (nighttime temperatures that stay above 75ºF) has been increasing across the Southeast (Figure 19.1), and this trend is projected to intensify, with some areas experiencing more than 100 additional warm nights per year by the end of the century (Figures 19.4 and 19.5). Exposure to high nighttime minimum temperatures reduces the ability of some people to recover from high daytime temperatures, resulting in heat-related illness and death.[26] This effect is particularly pronounced in cities, many of which have urban heat islands that already cause elevated nighttime temperatures.[27] Cities are taking steps to prevent negative health impacts from heat. For example, the Louisville, Kentucky, metro government conducted an urban heat management study and installed 145,000 square feet of cool roofs as part of their goal to lessen the risk of climate change impacts.[28]

Historical Number of Warm Nights

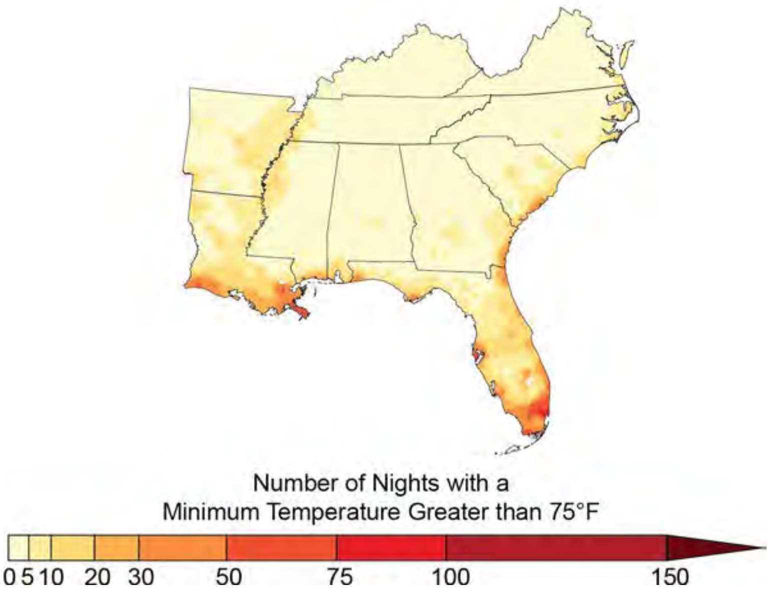


Figure 19.4: The map shows the historical number of warm nights (days with minimum temperatures above 75°F) per year in the Southeast, based on model simulations averaged over the period 1976–2005. Sources: NOAANCEI and CICS-NC.

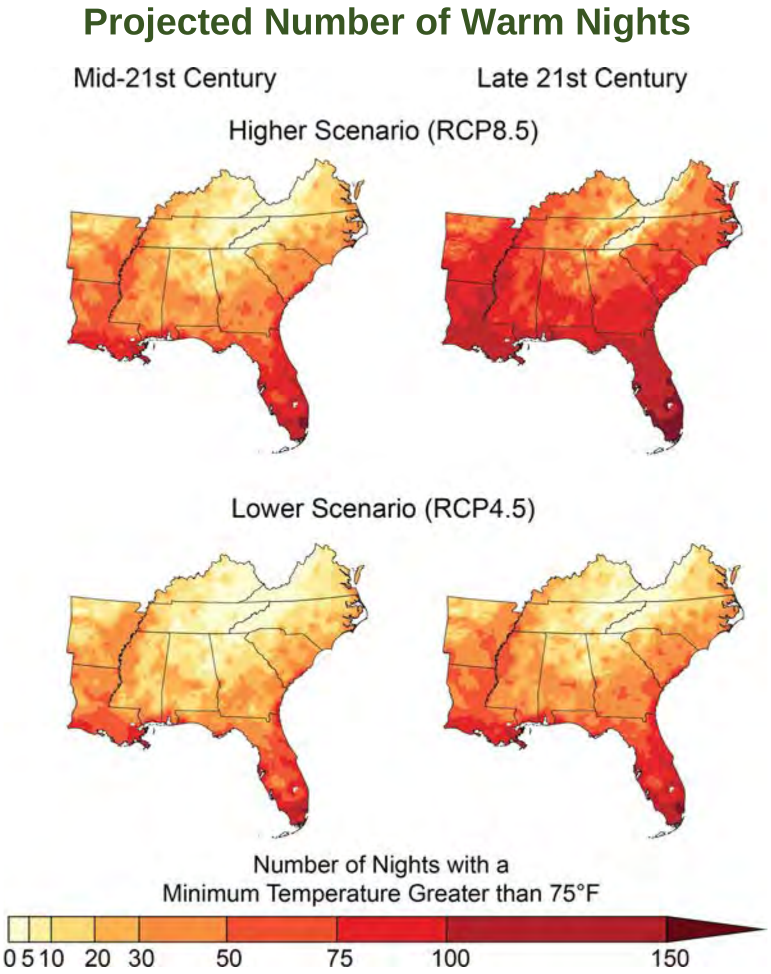


Figure 19.5: The maps show the projected number of warm nights (days with minimum temperatures above 75°F) per year in the Southeast for the mid-21st century (left; 2036–2065) and the late 21st century (right; 2070–2099) under a higher scenario (RCP8.5; top row) and a lower scenario (RCP4.5; bottom row). These warm nights currently occur only a few times per year across most of the region (Figure 19.4) but are expected to become common events across much of the Southeast under a higher scenario. Increases in the number of warm nights adversely affect agriculture and reduce the ability of some people to recover from high daytime temperatures. With more heat waves expected, there will likely be a higher risk for more heat-related illness and deaths. Sources: NOAA NCEI and CICS-NC.

Vector-Borne Disease

The transmission of vector-borne diseases, which are spread by the bite of an animal such as a mosquito or tick, is complex and depends on a number of factors, including weather and climate, vegetation, animal host populations, and human activities (Ch. 14: Human Health, KM 1). Climate change is likely to modify the seasonality, distribution, and prevalence of vector-borne diseases in the Southeast.[29] Vector-borne diseases pose a greater risk in cities than in rural areas because of higher population densities and other human factors (for example, pools of standing water in man-made structures, such as tires or buckets, are breeding grounds for some species of mosquitoes). Climatic conditions are currently suitable for adult mosquitoes of the species *Aedes aegypti*, which can spread dengue, chikungunya, and Zika viruses, across most of the Southeast from July through September (Figure 19.6), and cities in South Florida already have suitable conditions for year-round mosquito activity. The Southeast is the region of the country with the most favorable conditions for this mosquito and thus faces the greatest threat from diseases the mosquito carries.[30] Climate change is expected to make conditions more suitable for transmission of certain vector-borne diseases, including year-round transmission in southern

Florida. Summer increases in dengue cases are expected across every state in the Southeast. Despite warming, low winter temperatures may prevent permanent year-round establishment of the virus across the region.[31] Strategies such as management of urban wetlands have resulted in lower dengue fever risk in Puerto Rico.[32] Similar adaptation strategies have the potential to limit vector-borne disease in southeastern cities, particularly those cities with characteristics similar to Caribbean cities that have already implemented vector control strategies (Ch. 20: U.S. Caribbean).[33,34] The Southeast is also the region with the greatest projected increase in cases of West Nile neuroinvasive disease under both a lower and higher scenario (RCP4.5 and RCP8.5).[35,36]

Potential Abundance of Disease-Carrying Mosquito

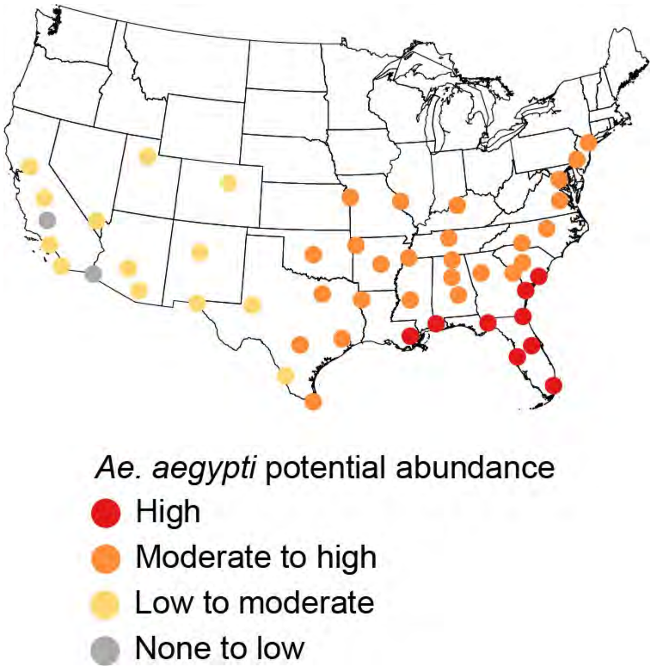


Figure 19.6: The map shows current suitability for the *Aedes aegypti* mosquito in July in 50 different cities. *Aedes aegypti* mosquitoes can spread several important diseases, including dengue fever, chikungunya, and Zika fever. The Southeast is the region of the country with the greatest potential mosquito activity. Warming temperatures have the potential to expand mosquito habitat and disease risk. Source: adapted from Monaghan et al. 2016.[30]

Air Quality and Human Health

Poor air quality directly impacts human health, resulting in respiratory disease and other ailments. In the Southeast, poor air quality can result from emissions (mostly from vehicles and power plants), wildfires, and allergens such as pollen. The major urban centers in the Southeast are already impacted by poor air quality during warmer months. The Southeast has more days with stagnant air masses than other regions of the country (40% of summer days) and higher levels of fine (small) particulate matter ($PM_{2.5}$), which cause heart and lung disease.[37] There is mixed evidence on the future health impacts of these pollutants. Ozone concentrations would be expected to increase under higher temperatures; however, a variety of factors complicate projections (Ch. 13: Air Quality, KM 1). There are many possible future wind and cloud cover conditions for the Southeast as well as the potential for continued shifts in land-use patterns, demographics and population geography, and vehicle and power plant emissions standards. Increases in precipitation and shifts in wind trajectories may reduce future health impacts of ground level ozone in the Southeast,[35] but warmer and drier autumns are expected to result in a lengthening of the period of ozone exposure.[38] Warmer August temperatures in the Southeast from 1988 to 2011 were associated with increased human sensitivity to ground-level ozone.[39]

The fast growth rate of urban areas in the Southeast contributes to aeroallergens, which are known to cause and exacerbate respiratory diseases such as asthma. Urban areas have higher concentrations of CO_2, which causes allergenic plants, such as ragweed, to grow faster and produce more pollen than in rural areas.[40] Continued rising temperatures and atmospheric CO_2 levels are projected to further contribute to aeroallergens in cities (Ch. 13: Air Quality, KM 3).

Infrastructure

Infrastructure, particularly roads, bridges, coastal properties, and urban drainage, is vulnerable to climate change and climate-related events (see Key Message 2) (see also Ch. 3: Water, KM 2; Ch. 11: Urban, KM 2; Ch. 12: Transportation, KM 1).[41] By 2050, the Southeast is the region expected to have the most vulnerable bridges.[35] An extreme weather vulnerability assessment conducted by the Tennessee Department of Transportation found that the urban areas of Memphis and Nashville had the most at-risk transportation infrastructure in the state.[42] Increasing precipitation and extreme weather events will likely impact roads, freight rail, and passenger rail, especially in Memphis, which will likely have cascading effects across the region.[43] Transit infrastructure, such as the rail lines of the Metropolitan Atlanta Rapid Transit Authority (MARTA), are also at risk. As a result, MARTA has begun to identify vulnerable assets and prioritize improvements to develop a more resilient system.[44]

Many cities across the Southeast are planning for the impacts sea level rise is likely to have on their infrastructure (see Case Study "Charleston, South Carolina, Begins Planning and Reinvesting" and Key Message 2). Flood events in Charleston, South Carolina, have been increasing, and by 2045 the city is projected to face nearly 180 tidal floods (flooding in coastal areas at high tide) per year, as compared to 11 floods per year in 2014.[45] These floods affect tourism, transportation, and the economy as a whole. The city has responded by making physical modifications, developing a more robust disaster response plan, and improving planning and monitoring prior to flood events.

Infrastructure related to drinking water treatment and wastewater treatment may be compromised by climate-related events (Ch. 3: Water, KM 2). Water utilities across the Southeast are preparing for these impacts. Tampa Bay Water, the largest wholesale water utility in the Southeast, is coordinating with groups including the Florida Water and Climate Alliance to study the impact of climate change on its ability to provide clean water in the future.[46,47] Spartanburg Water, in South Carolina, is reinforcing the ability of the utility to "cope with, and recover from disruption, trends and variability in order to maintain services."[48] Similarly, the Seminole Tribe of Florida, which provides drinking and wastewater services, assessed flooding and sea level rise threats to their water infrastructure and developed potential adaptation measures.[49] The development of "green" water infrastructure (using natural hydrologic features to manage water and provide environmental and community benefits), such as the strategies promoted in the City of Atlanta Climate Action Plan, is one way to adapt to future water management needs. Implementation of these strategies has already resulted in a reduction in water consumption in the city of Atlanta, relieving strain on the water utility and increasing resilience.[50]

There are still gaps in knowledge regarding the potential effects of climate change on cities across the Southeast. Cross-disciplinary groups such as the Georgia Climate Project (http://www.georgiaclimateproject.org) are developing research roadmaps that can help to prioritize research and action with relevance to policymakers, practitioners, and scientists.

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. 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.

Sea Level Rise Is Contributing to Increased Coastal Flooding in the Southeast

Average global sea level (or global mean sea level; GMSL) has risen about 8–9 inches since 1880, with about 3 inches of that rise occurring since 1990.[51,52] This recent increase in the rate of rise is projected to accelerate in the future due to continuing temperature increases and additional melting of land ice.[51] This recent global rate increase, combined with the local effects of vertical land motion (sinking) and oceanographic effects such as changing ocean currents, has caused some areas in the Southeast to experience even higher local rates of sea level rise than the global average.[53,54,55,56,57,58,59] Analyses at National Oceanic and Atmospheric Administration (NOAA) tide gauges show as much as 1 to 3 feet of local relative sea level rise in the past 100 years in low-lying areas of the Southeast.[54,59] This recent rise in local relative sea level has caused normal high tides to reach critical levels that result in flooding in many coastal areas in the region.

Monthly and seasonal fluctuations in high tide levels are caused by a combination of astronomical factors (sun and moon gravitational attraction) and non-astronomical factors such as geomorphology (landscape of the area), as well as meteorological (weather) conditions. The highest tides of the year are generally the perigean, or spring, tides, which occur when the moon is full or new and is closest to the Earth. These perigean tides, also known as "king tides," occur twice a year and in many cities are causing what has been called "nuisance" or "recurrent" flooding (referred to herein as high tide flooding). These floods can cause problems ranging from inconvenient to life changing. While the challenges brought on by rising perigean tides are diverse, important examples include increasingly frequent road closures, excessive water in storm water management systems, and deterioration of infrastructure such as roads and rail from saltwater. NOAA's National Weather Service (NWS) issues coastal flood advisories and warnings when water levels at tide gauges are expected to exceed flood thresholds. These thresholds correspond to discrete water levels relative to NOAA tide gauges.

Recent analyses of historical water levels at many NOAA tide gauges has shown an increase in the number of times that these warning thresholds were exceeded compared to the past. Annual occurrences of high tide coastal flooding have increased 5- to 10-fold since the 1960s in several low-lying coastal cities in the Southeast (Figure 19.7).[51,60] In 2015, several Southeast coastal cities experienced all-time records of coastal flooding occurrences, including Wilmington, NC (90 days), Charleston, SC (38 days), Mayport, FL (19 days), Miami, FL (18 days), Key West, FL (14 days), and Fernandina Beach, FL (7 days). These flooding occurrences increased more than 50% in 2015 compared to 2014.[58] In 2016, three all-time records were either tied (14 days at Key West, FL) or broken (50 days at Charleston, SC, and 38 days at Savannah, GA). The Miami area nearly matched the 2015 record of 18 days.[61] This increase in high tide flooding frequency is directly tied to sea level rise. For example, in Norfolk, Virginia, local relative sea level rise has led to a fourfold increase in the probability of exceeding NWS thresholds compared to the 1960s (Figure 19.8). High tide flooding is now posing daily risks to businesses, neighborhoods, infrastructure, transportation, and ecosystems in the Southeast.[1,2]

Global sea level is very likely to rise by 0.3–0.6 feet by 2030, 0.5–1.2 feet by 2050, and 1.0–4.3 feet by 2100 under a range of scenarios from very low (RCP2.6) to high (RCP8.5),[51,52,62] which would result in increases in both the depth and frequency of coastal flooding (Figure 19.7).[51] Under higher emissions scenarios (RCP8.5), global sea level rise exceeding 8 feet (and even higher in the Southeast) by 2100 cannot be ruled out.[51] By 2050, many Southeast cities are projected to experience more than 30 days of high tide flooding regardless of scenario.[63] In addition, more extreme coastal flood events are also projected to increase in frequency and duration.[60] For example, water levels that currently have a 1% chance of occurring each year (known as a 100-year event) will be more frequent with sea level rise. This increase in flood frequency suggests the need to consider revising flood study techniques and standards that are currently used to design and build coastal infrastructure.

Higher sea levels will cause the storm surges from tropical storms to travel farther inland than in the past, impacting more coastal properties. The combined impacts of sea level rise and storm surge in the Southeast have the potential to cost up to $60 billion each year in 2050 and up to $99 billion in 2090 under a higher scenario (RCP8.5).[35] Even under a lower scenario (RCP4.5), projected damages are $56 and $79 billion in 2050 and 2090, respectively (in 2015 dollars, undiscounted).[35] Florida alone is estimated to have a 1-in-20 chance of having more than $346 billion (in 2011 dollars) in property value (8.7%) below average sea level by 2100 under a higher scenario (RCP8.5).[64] An assessment by the Florida Department of Health determined that 590,000 people in South Florida face "extreme" or "high" risk from sea level rise, with 125,000 people living in these areas identified as socially vulnerable and 55,000 classified as medically vulnerable.[65] In addition to causing direct injury, storm surge and related flooding can impact transportation infrastructure by blocking or flooding roads and affecting access to healthcare facilities (Ch. 12: Transportation, KM 1). Marine transportation can be impacted as well. Large ports in the Southeast, such as Charleston, Savannah, and Jacksonville, and the rails and roads that link to them, are particularly vulnerable to both coastal flooding and sea level rise (Ch. 12: Transportation, KM 1; Ch. 8: Coastal, KM 1). The Port of Jacksonville provides raw material for industries, food, clothes, and essential goods to Puerto Rico, thus impacting the U.S. Caribbean region, as well (Ch. 20: U.S. Caribbean, KM 3). It is estimated that with a meter (about 3.3 feet) of sea level rise, the Southeast would lose over 13,000 recorded historic and prehistoric archaeological sites and more than 1,000 locations currently eligible for inclusion on the National Register of Historic Places.[66] This includes many historic buildings and forts in cities like Charleston, Savannah, and St. Augustine.

Annual Number of High Tide Flooding Days

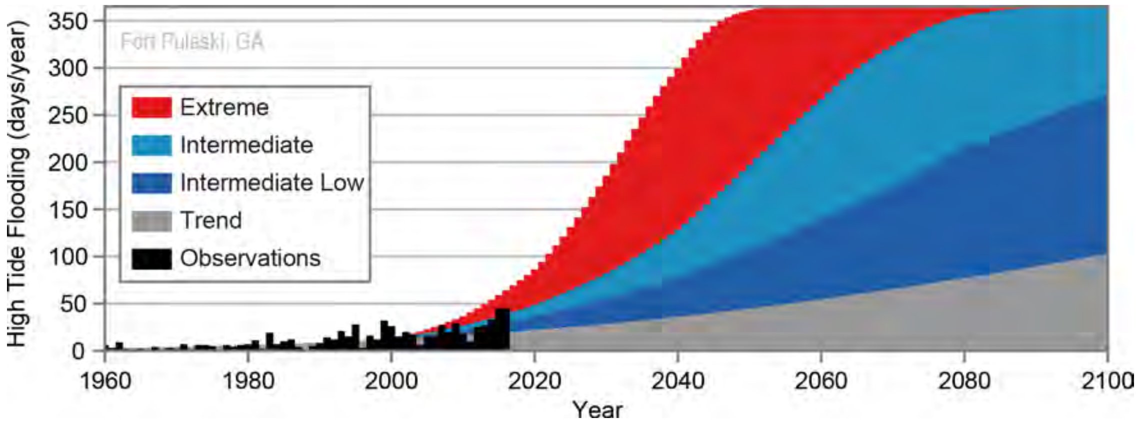


Figure 19.7: The figure shows the annual number of days experiencing high tide floods based on observations for 1960–2016 for Fort Pulaski, near Savannah, Georgia (black), and projected increases in the number of annual flood events based on four future scenarios: a continuation of the current relative sea level trend (gray) and the Intermediate-Low (dark blue), Intermediate (light blue), and Extreme (red) sea level rise scenarios. See Sweet et al. (2017)[51] and Appendix 3: Data & Scenarios for additional information on projection and trend data. Source: adapted from Sweet and Park 2014.[63]

Range of Daily Highest Water Levels in Norfolk, Virginia

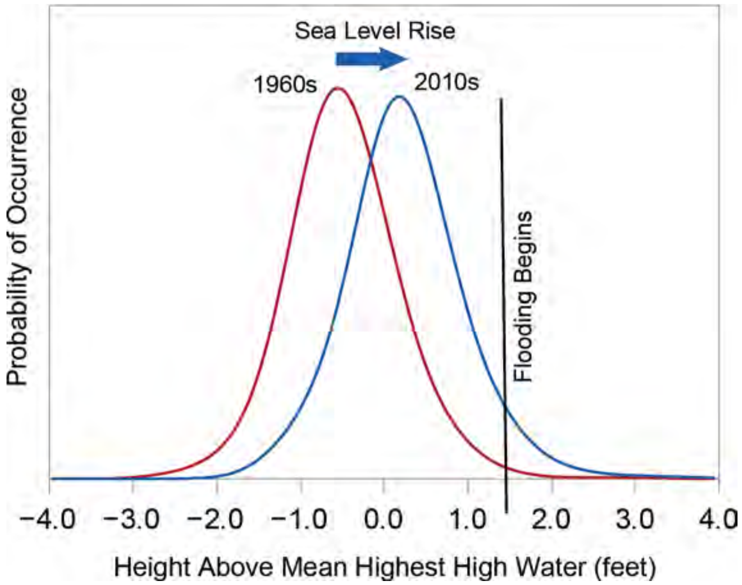


Figure 19.8: The curves in this figure show a range of daily Mean Higher High Water (MHHW) levels in Norfolk, Virginia (Sewells Point), for the 1960s and 2010s. Local sea level rise has shifted the curve closer to the point where high tide flooding begins (based on warning thresholds established by the National Weather Service). This shows why many more high tide flood events occur now than they did in the past (increase of 6 flood days per year). Source: adapted from Sweet et al. 2017.[52]