21 Midwest

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21 Midwest

Carson, Wisconsin

Key Message 1

Agriculture

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

Key Message 2

Forestry

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

Key Message 3

Biodiversity and Ecosystems

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

Key Message 4

Human Health

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

Key Message 5

Transportation and Infrastructure

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

Key Message 6

Community Vulnerability and Adaptation

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

Executive Summary

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

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

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

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

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

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

Conservation Practices Reduce Impact of Heavy Rains

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

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

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

Background

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

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

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

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

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

Energy in the Midwest

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

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

Solar Charging Stations

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

What Is New in NCA4

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

Key Message 1

Agriculture

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

Recent Agriculturally Important Trends

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

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

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

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

Projected Trends and Agricultural Impacts

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

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

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

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

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

Average Annual 5-Day Maximum Temperature

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

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

Optimum and Failure Temperatures for Vegetative Growth and Reproduction

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

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

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

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

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

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

Adaptation

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

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

Conservation Practices Reduce Impact of Heavy Rains

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

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

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

Key Message 2

Forestry

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

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

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

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

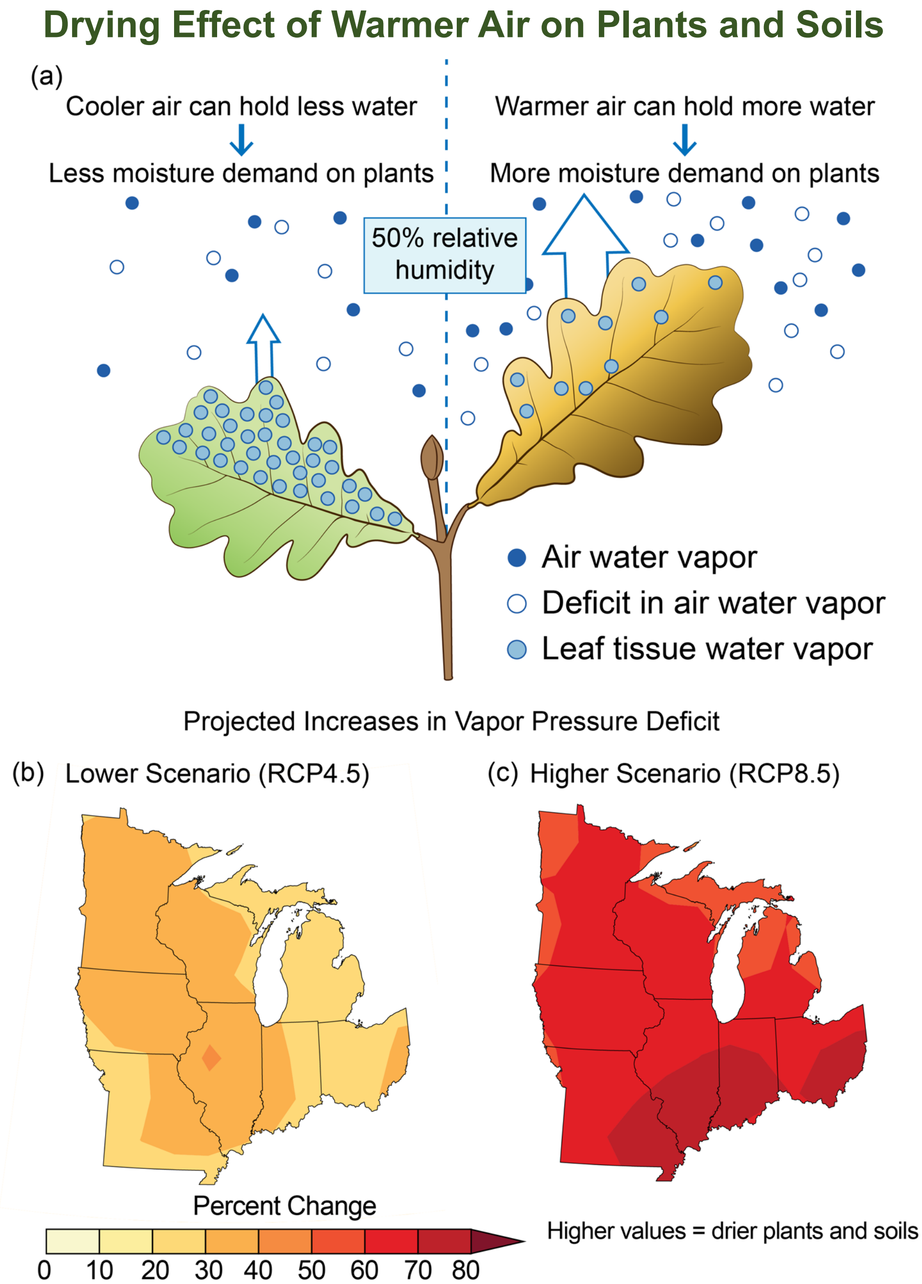


Figure 21.3: As air temperature increases in a warming climate, vapor pressure deficit (VPD) is projected to increase. VPD is the difference between how much moisture is in the air and the amount of moisture in the air at saturation (at 100% relative humidity). Increased VPD has a drying effect on plants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

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

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

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

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

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

Case Study: Adaptation in Forestry

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

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

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

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

Key Message 3

Biodiversity and Ecosystems

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

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

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

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

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

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

Climate Change Outpaces Plants' Ability to Shift Habitat Range

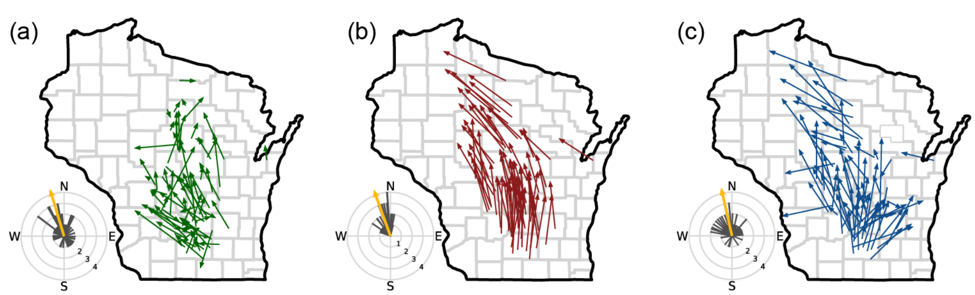


Figure 21.5: While midwestern species, such as understory plants in Wisconsin, are showing changes in range, they may not be shifting quickly enough to keep up with changes in climate. The panels here represent 78 plant species, showing (a) observed changes in the center of plant species abundances (centroids)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

Coldwater Fish at Risk

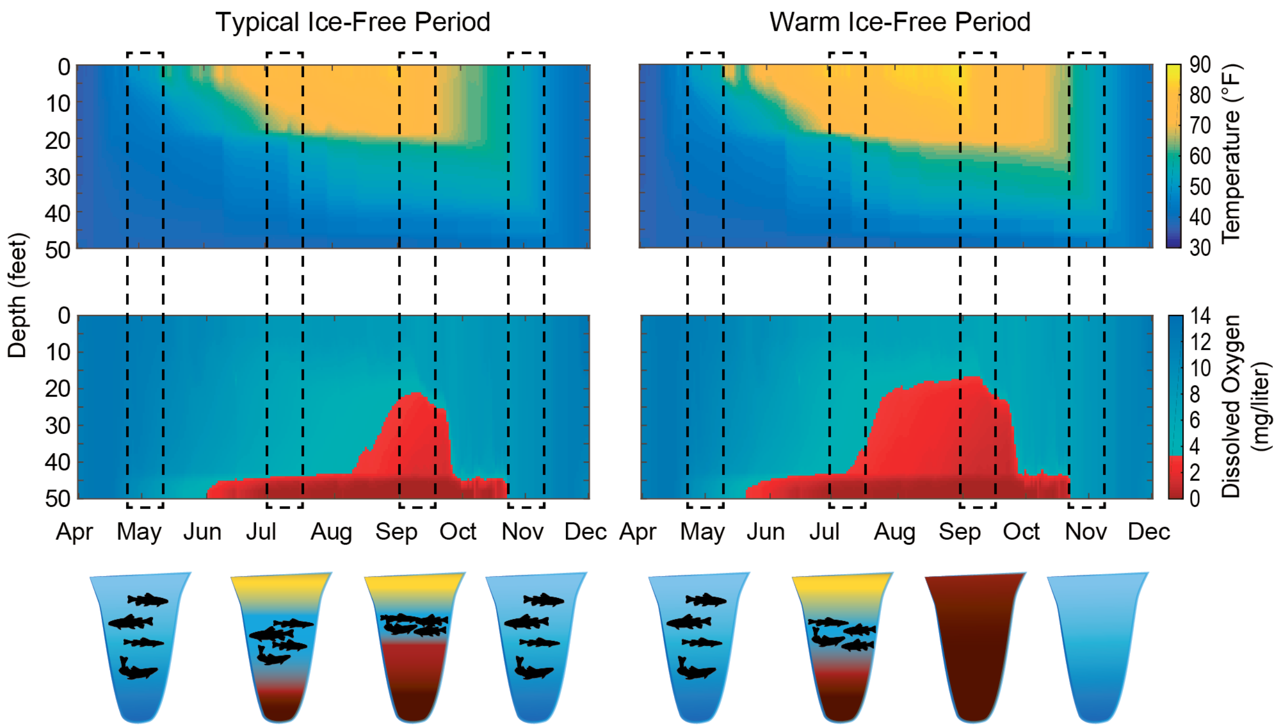


Figure 21.6: The graphic shows the oxythermal (oxygen and temperature) habitat of coldwater fish in midwestern inland lakes, illustrated by water depth under (left) a typical ice-free period and (right) a warm ice-free period (right). The top plots show water temperatures during the ice-free period,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

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

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

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

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

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

Wetland Restoration Projects Can Help Reduce Impacts

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

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

Box 21.1: Focus on the Great Lakes

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

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

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

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

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

The Changing Great Lakes

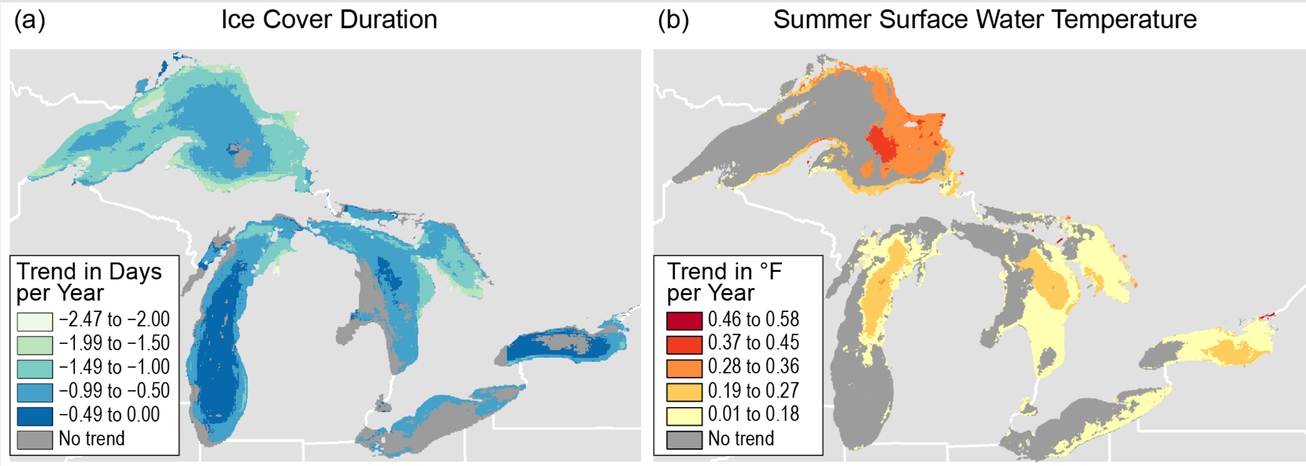


Figure 21.8: The duration of seasonal ice cover decreased in most areas of the Great Lakes between 1973 and 2013, while summer surface water temperature (SWT) increased in most areas between 1994 and 2013. (a) The map shows the rate of change in ice cover duration. The greatest rate of decrease in seasonal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

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

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

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

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

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

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

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

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

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

Key Message 4

Human Health

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

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

Air Quality

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

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

Projected Changes in Ozone-Related Premature Deaths

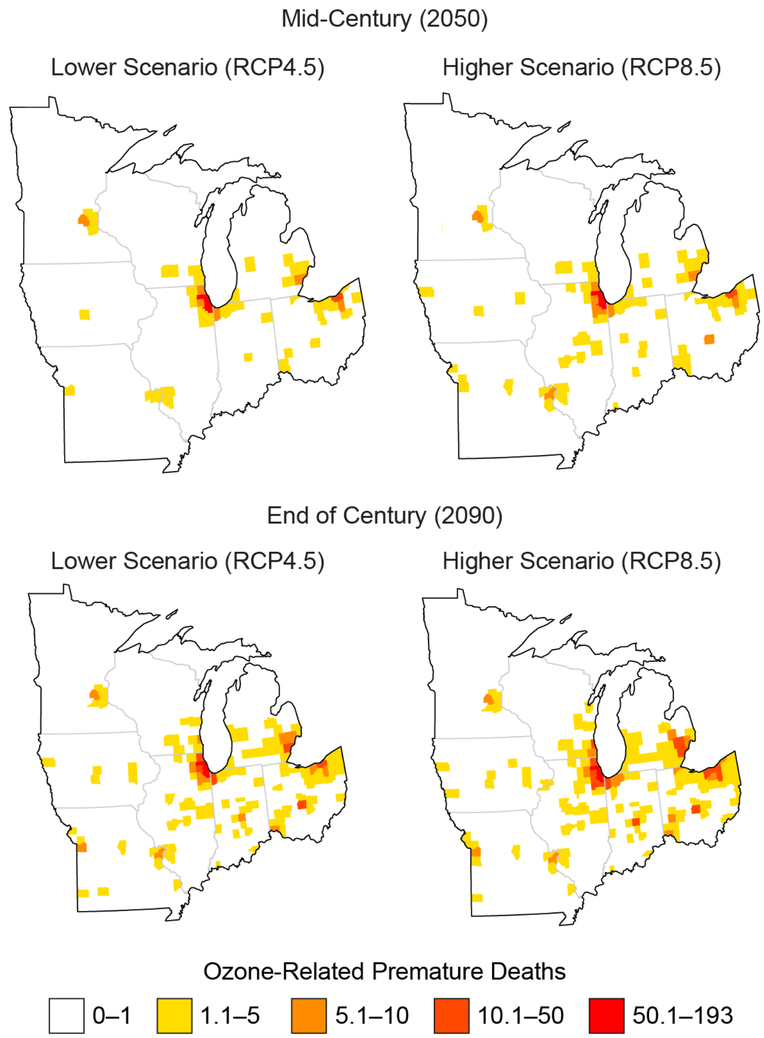


Figure 21.9: Maps show county-level estimates for the change in average annual ozone-related premature deaths over the summer months in 2050 (2045–2055) and 2090 (2085–2095) compared to 2000 (1995–2005) under the lower and higher scenarios (RCP4.5 and RCP8.5) in the Midwest. The results represent the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

Temperature

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

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

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

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

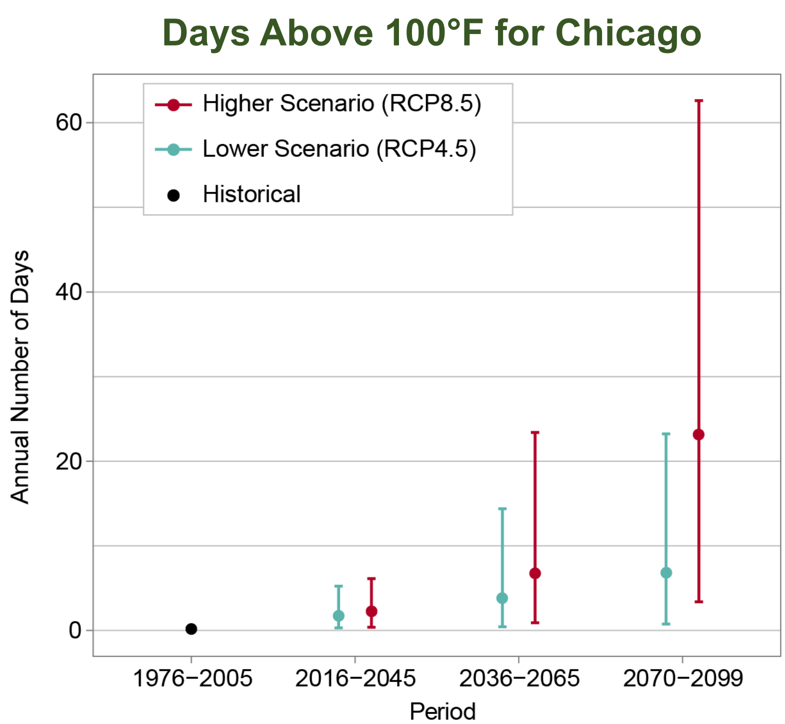


Figure 21.10: This graph shows the annual number of days above 100°F in Chicago for the historical period of 1976–2005 (black dot) and projected throughout the 21st century under lower (RCP4.5, teal) and higher (RCP8.5, red) scenarios. Increases at the higher end of these ranges would pose major heat-related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

Precipitation

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

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

Habitat Conditions

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

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

Challenges and Opportunities

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

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

Key Message 5

Transportation and Infrastructure

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

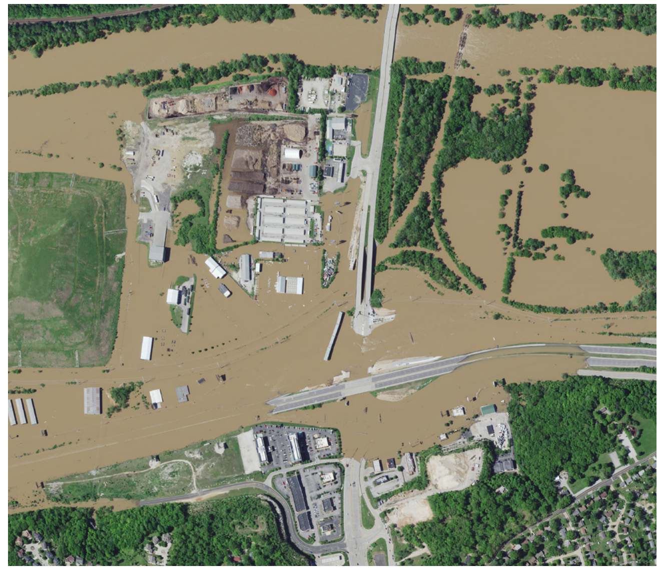
Climate change poses several challenges to transportation and storm water systems in the Midwest. Annual precipitation in the Midwest has increased by 5% to 15% from the first half of the last century (1901–1960) compared to present day (1986–2015).[193] Winter and spring precipitation are important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

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

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

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

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



River Flooding in the Midwest

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

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

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

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

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

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

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

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

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

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

Key Message 6

Community Vulnerability and Adaptation

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

Vulnerability and Adaptation

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

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

Case Study: Great Lakes Climate Adaptation Network

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

Linked Boundary Chain Model

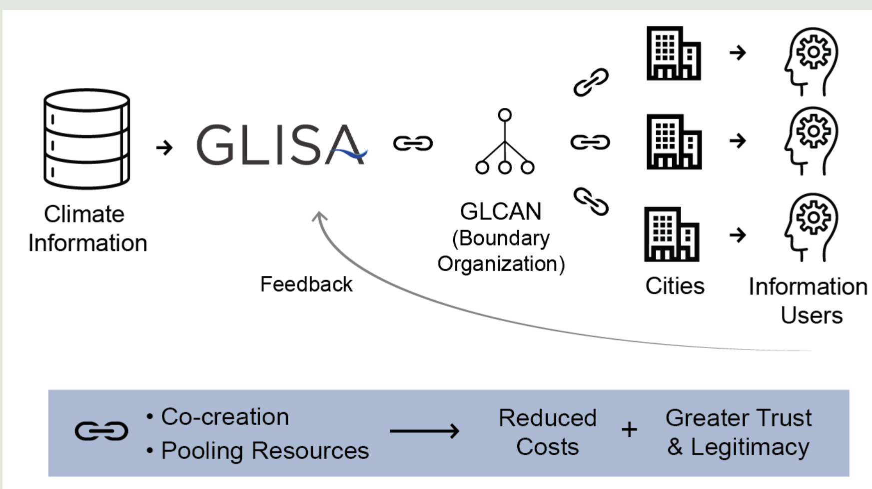


Figure 21.12: Shown here is a configuration of the boundary chain employed in the Great Lakes Climate Adaptation Network (GLCAN) Case Study. The information is tailored and moves through different boundary organizations (links in the chain) to connect science to users. By co-creating information and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

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

Collaboratively Developing Knowledge and Building Adaptive Capacity

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

Tribal Adaptation

Tribes and Indigenous communities in the Midwest have been among the first to feel the effects of climate change as it impacts their culture, sovereignty, health, economies, and ways of life.[39] The Midwest contains ceded territory—large swaths of land in Minnesota, Wisconsin, and Michigan in which Ojibwe tribes reserved hunting, fishing, and gathering rights in treaties with the United States government.[88] Climate change presents challenges to the Ojibwe tribes in co-managing these resources with other land managers; as the climate changes, various species utilized by tribes are declining and may shift entirely outside of treaty boundaries and reserved lands.[127,309,310] In certain tribal cultures, all beings (species) are important; climate adaptation efforts that favor certain beings at the detriment of others can be problematic. Adaptation to climate change might also mean giving up on something deeply embedded in tribal culture for which no substitute exists.[31] A family sugarbush (a forest stand used for maple syrup), for example, cannot be replaced culturally, spiritually, or economically if the sugar maple range were to shift outside of treaty or reservation boundaries. As the effects of climate change become more pronounced, further research can shed light on how tribal nations are being affected.

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

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

Acknowledgments

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Traceable Accounts

Process Description

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

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

Note on regional modeling uncertainties

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

Key Message 1

Agriculture

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

Description of evidence base

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

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

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

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

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

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

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

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

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

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

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

Major uncertainties

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

Description of confidence and likelihood

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

Key Message 2

Forestry

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

Description of evidence base

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

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

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

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

Major uncertainties

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

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

Description of confidence and likelihood

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

Key Message 3

Biodiversity and Ecosystems

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

Description of evidence base

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

Major uncertainties

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

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

Description of confidence and likelihood

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

Key Message 4

Human Health

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

Description of evidence base

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

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

Major uncertainties

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

Description of confidence and likelihood

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

Key Message 5

Transportation and Infrastructure

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

Description of evidence base

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

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

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

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

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

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

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

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

Major uncertainties

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

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

Description of confidence and likelihood

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

Key Message 6

Community Vulnerability and Adaptation

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

Description of evidence base

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

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

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

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

Major uncertainties

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

Description of confidence and likelihood

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

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