AN ASSESSMENT OF THE IMPACTS OF

CLIMATE CHANGE IN ILLINOIS

The Nature Conservancy


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Contents

About The Nature Conservancy

The Nature Conservancy is a global conservation organization dedicated to conserving the lands and waters on which all life depends. Creating a future where nature and people thrive hinges on curbing climate change—the greatest environmental threat of our time. Guided by science, The Nature Conservancy has integrated climate change into every aspect of our work. We are working in Illinois and across the globe to understand the impacts of climate change on communities and natural systems and to develop innovative, on-the-ground solutions.

Foreword

The Nature Conservancy's mission is to conserve the lands and waters on which all life depends, with the vision of creating a world where both people and nature thrive. Success hinges on curbing climate change—the greatest environmental and societal challenge of our time. TNC works in more than 60 countries to understand the impacts of climate change on communities and natural systems and to develop sound solutions for climate mitigation and adaptation. Climate change is integrated into every aspect of TNC's work in Illinois, including our collaboration with farmers to protect water quality and improve soil health, work with urban communities to expand access to green space, and efforts to restore floodplains and reduce flood risk across the state.

Impacts of climate change are already being felt around the world and are only expected to get worse. Illinois is experiencing a climate that is already significantly warmer and wetter than at any time in the last 120 years, and these changes can be linked directly to the overall changes in climate occurring on our planet. Without stronger, coordinated efforts to reduce greenhouse gas emissions, climate change will greatly upset the balance between human and natural systems. Changes in Illinois will likely include more frequent heat waves and warmer summer nights, increased precipitation in the winter and spring, and drier summers that will impact everything from the economy to public health.

Taking action now to reduce emissions and to build resilience is critical for combating climate change, and it can also lead to a more equitable and sustainable future. Movement toward a greener economy can bring new jobs and breathe new life into Illinois communities. Such efforts to address climate change not only benefit people, but also provide for the health and biodiversity of natural habitats and wildlife in Illinois.

Ultimately, our ability to design the most impactful strategies to combat climate change and improve local resilience in Illinois depends on understanding how climate change will affect the state. While the science is clear that climate change is happening, we are still learning more each day about how climate change will touch down in our own backyard. Better information on these local impacts can help ensure that public policy and local planning efforts fully account for climate change.

We are excited to be part of this assessment that brings together the expertise of over 40 scientists and technical experts to explain the most up-to-date information on how climate change is expected to affect Illinois. This report contains useful information on how climate change is likely to influence local and regional climate patterns, with more detailed information on how climate change could impact water resources, agriculture, public health, and nature in the state. We believe it will help Illinois communities understand climate change in a more tangible way that will empower more people to take action to address climate change and guide Illinois in a more resilient direction.

Michelle Carr
State Director, The Nature Conservancy in Illinois
nature.org/Illinois

Executive Summary

> ***"The dogmas of the quiet past are inadequate to the stormy present. The occasion is piled high with difficulty, and we must rise with the occasion. As our case is new, so we must think anew, and act anew."***
>
> *— President Abraham Lincoln, 2nd State of the Union Address, 1862*

Why Illinois? Why now?

Although it was originally used in a different context, the quote above from President Lincoln appropriately expresses the challenges from a changing climate that Illinois faces at this time. Climate, the long-term averages and statistics of weather, is changing rapidly in the state of Illinois, as well as throughout the world. For example, in Illinois, the frequency and intensity of extreme heat and heavy precipitation events are increasing, and winters are milder than they used to be. Climate change is a major environmental challenge that is likely to affect many aspects of life in Illinois, ranging from human and environmental health to the economy. Illinois is already experiencing societal impacts from the changing climate and, as climate change progresses and temperatures continue to rise, these impacts are expected to increase over time.

This assessment takes an in-depth look at how the climate is changing now in Illinois, and how it is projected to change in the future, to provide greater clarity on how climate change could affect urban and rural communities in the state. Beyond providing a general overview of anticipated climate changes, the report explores predicted effects on hydrology, agriculture, human health, and native ecosystems. These topics were selected because they touch on many aspects of people's lives and well-being in the state of Illinois.

Scientific evidence indicates it is extremely likely that human activities—which have led to drastic increases in emissions of greenhouse (heat-trapping) gases, especially from the use of fossil fuels and extensive land-use changes—are the dominant cause of global changes in climate, dating back to at least the mid-1900s. For the last century, there are no convincing alternative explanations for the observed warming that are supported by observational evidence. Natural variability or natural cycles cannot account for the observed changes in climate, nor are they the result of changes in radiation from the Sun.

The magnitude of climate change beyond the next few decades will depend primarily on the amount of greenhouse gases emitted globally and, to a limited degree, on remaining uncertainties in the sensitivity of Earth's climate to those emissions. Most of the analyses in this assessment are based on two scenarios for greenhouse gas emissions and other pollutants from human activities: a lower scenario (RCP4.5) and a higher scenario (RCP8.5). The RCP4.5 scenario assumes a rapid movement away from fossil fuels over the coming decades, while the RCP8.5 scenario corresponds to a future where carbon and methane emissions continue to rise throughout the century.

Increasing temperature

Over the past 120 years, the average daily temperature in Illinois has increased, especially the average overnight temperature. The average daily temperature has increased by 1–2°F in most areas of Illinois. Overnight minimum temperatures have increased more than daytime maximum temperatures. In some areas of the state, the increase in overnight minimum temperatures has exceeded 3°F, while the daytime maximum temperature increase has ranged between 0 and 1.5°F in most areas. This difference in trends between day and night is most prominent in summer, resulting in an increase in the number of warm summer nights. The number of freezing winter nights has decreased. By the end of the 21st century, unprecedented warming of 4–9°F under the lower scenario and 8–14°F under the higher scenario is likely in Illinois. This is likely to be accompanied by large increases in extreme high temperatures, a longer growing season, and less severe extreme cold.

Changing precipitation patterns

Illinois has gotten wetter overall in the last century. Over the last 120 years, mean precipitation has increased by 5 to 20%, varying across the state, and the number of 2-inch rain days in Illinois has increased by 40%, reflecting major regional changes in the hydrologic cycle. Over the same time period, extreme droughts have become less common.

Drought risk in Illinois is not only related to precipitation; changes in temperature also play an important role. Increased temperatures have led to more evaporation from soils, which can cause significant crop and ecosystem stress during dry conditions. Annual evapotranspiration has increased, especially in the summer months. Projections of increasing temperatures suggest evapotranspiration will continue to increase in Illinois, as will the risk for short-term droughts.

Illinois is expected to see an overall increase in precipitation in the coming decades as the climate warms, with larger increases in the north compared with the south. The projected changes in total precipitation vary widely by season. For the end of the 21st century and the higher scenario, substantial increases in precipitation are projected for winter (+10% to +20%) and spring (+5% to +25%), with small changes in the fall and decreases of around 5% projected for summer. Similar but smaller trends are projected for the lower scenario. Total seasonal snowfall is likely to decline through the 21st century, as a result of fewer snow days and more rainy days. The distribution of precipitation in Illinois is also projected to become more extreme, with increases in both heavy rains and the length of dry spells.

Intensity of weather extremes

Climate change is causing more extreme weather events across the United States. Heat waves have become more common since the 1960s, while extreme cold temperatures have generally decreased. Intense summer storms occur more often as temperatures rise.

Extreme warm days will increase in Illinois. By the end of the century, the annual hottest 5-day maximum temperature in northern Illinois is projected to increase from 92°F to a range of 96–104°F under the lower scenario and 100–110°F under the higher scenario. In central Illinois, the annual hottest 5-day maximum temperature will increase from 94°F to a range of 98–106°F under the lower scenario and 102–112°F under the higher scenario. In southern Illinois, the annual hottest 5-day maximum temperature is projected to increase from 96°F to 100–107°F under the lower scenario and to 102–114°F under the higher scenario. Projections show increases in single-day extreme temperatures as well, with projected increases in the annual number of days with a daily maximum temperature of 95°F or higher.

Meanwhile, the number of extremely cold days (with temperature less than 32°F) will decrease significantly. For the mid-21st century, the increases in temperature for the coldest days are about 4–8°F for the lower scenario and 4–10°F for the higher scenario. For the late 21st century, the increases are 6–10°F for the lower scenario and 10–16°F for the higher scenario. The freeze-free season is also projected to increase, by about 10–15 days for mid-century with the lower scenario and around 15–20 days with the higher scenario. For the late 21st century, the increases are around 15–20 days for the lower scenario and 30–45 days for the higher scenario, with somewhat greater increases in northern Illinois.

A warmer atmosphere holds more moisture, increasing the frequency and intensity of heavy rain and snow events. The number of days with 2 or more inches of precipitation are projected to increase throughout Illinois. The increase in precipitation will vary substantially with time period and scenario. Mid-21st century projections show 0–60% increase under the lower scenario and 30–90% increase under the higher scenario. Late-21st century projections show 0–60% increase and 60–150% increase in the lower and higher scenarios, respectively.

Impacts on hydrology and water resources

One of the greatest natural resources in Illinois is fresh water, both in the form of abundant precipitation and in the major rivers systems of the Mississippi, Ohio, and Illinois, as well as Lake Michigan. Although unseen, important groundwater aquifers run throughout the state, providing millions of people in Illinois with reliable water supplies. However, a changing climate poses challenges to the hydrology of the state. Most of the rivers in Illinois have already experienced increased flooding. Driven primarily by precipitation trends and land development, flooding in most Illinois rivers and streams is expected to continue to increase. An increase in intense rainfall is also expected to exacerbate flooding in urban drainage systems, which are already stressed due to aging and undersized stormwater systems, as well as land development that has altered natural drainage patterns and increased impervious surfaces.

Climate change in the form of increased precipitation and rainfall intensity tend to increase nutrient loads in rivers. However, other factors (e.g., wetland restoration) can also influence riverine nutrient loads. Combined sewer outflows (CSOs) affect water quality in urban streams and rivers and Lake Michigan in the Chicago region. Both CSOs and increased overland flooding cause environmental damage and public health hazards, such as increased exposure to infectious diseases and contaminated drinking water.

As surface water supply is often limited by low streamflow, unless it is augmented by in-channel or off-channel storages, climate change may increase risks of inadequate surface water supply in drought conditions. Projected increases in precipitation would increase recharge to shallow aquifers. This could result in higher water tables during springtime conditions, increasing basement flooding and necessitating more tile drainage in row crop areas. Conversely, more intense summer droughts could result in lower water tables during peak pumping conditions in the summer, potentially reducing the sustainability of the groundwater resource used in water supply.

Impacts on agriculture

In Illinois, agriculture forms a central pillar of the economy and a dominant part of the landscape. Illinois' fertile soils, level to gently sloping land, and favorable climate make it uniquely situated to be a major agricultural producer, especially of corn and soybeans. Yet, the favorable climate on which Illinois farmers depend is already and will continue to be impacted by climate change. Illinois is expected to face a much different climate than any experienced in the state's history, and agriculture is likely to face significant hurdles adapting to this new climate. Future agricultural production in Illinois is strongly dependent on investments made today in agricultural research and development, efforts to reduce greenhouse gas emissions, and practices to help farmers cope with climate risks.

Heat and water stress are likely to reduce corn yields by mid-century in Illinois, although the severity of loss depends on available technology and new management practices. Some yield losses could be overcome if sustained improvements in seed technology and management adaptations, such as planting date adjustments and input optimization, are able to mitigate the impact of extreme heat and drought. Increased atmospheric carbon dioxide (CO_2) is likely to benefit soybean yields in the near-term, but, as heat and water stress intensify later this century, soybean yields are expected to decline. Increased CO_2 is not expected to impact corn yields, even in the near-term.

Crops and livestock in Illinois are negatively impacted by weeds, pests, and diseases, which are expected to increase because of warmer winters, increased spring precipitation, and higher summer temperatures. Warming temperatures will also shift plant hardiness zones northward, making certain varieties of fruits, vegetables, and nuts unable to thrive in Illinois. Adopting new crop varieties, adjusting management practices, and investing in new machinery may help growers adapt.

Impacts on human health

Communities across Illinois are expected to experience adverse health impacts as a result of climate change. Rising temperatures will increase the risk of heat-related illness, such as heat exhaustion and heat stress, and exacerbate respiratory illnesses. Increasing precipitation and flooding will amplify the risk of waterborne infectious diseases, mold exposure, and flood-related injuries. The risk of vector-borne diseases will also increase as the range for disease-carrying ticks and mosquitoes expands due to more favorable climate conditions and as the length of the biting season extends. Levels of mold, pollen, and ozone pollution, which are triggers of asthma and allergies, are expected to increase and the pollen season will lengthen, resulting in more severe respiratory allergies and more frequent asthma attacks. Mental health is also likely to suffer, owing to increased stress associated with direct climate impacts, such as extreme weather events, as well as stress associated with climate change as an existential threat.

Communities that are already the most vulnerable are likely to suffer the worst health impacts from climate change. Those that currently have high rates of chronic disease, poor housing, barriers to health care access, unhealthy community design, and polluted air are expected to experience more severe health impacts from climate change than the population of Illinois overall. Thus, the issue of public health and climate change is also an issue of equity. Climate change is also expected to increase some health care costs and associated economic losses.

Impacts on ecosystems

Climate change is expected to have wide-ranging impacts on the forests, prairies, wetlands, and freshwaters of Illinois. Owing to the large number of factors involved, projecting the climate impacts on Illinois' ecosystems is difficult. In general, climate change will interact with and amplify the impacts of other stresses already affecting the state's ecosystems. A significant portion of native habitat in Illinois is fragmented and degraded due to widespread land conversion, which will reduce the ability of native flora and fauna to adapt to rapid climate changes.

Although climate change could enhance conditions for some native species, it will likely make conditions less suitable for others. For example, some tree species (e.g., sweetgum, winged elm, post oak) are expected to adapt well to a changing climate, while others are expected to fare poorly (e.g., pignut hickory, black willow, American basswood, pin oak, chinkapin oak, eastern white pine). Warmer water temperatures will alter the growth, survival, and reproduction of aquatic species, as well as predator–prey relationships, while increased precipitation and flooding may reduce important habitat availability for some species. A further expansion of non-native invasive species and pathogenic pests, which can have negative repercussions across ecosystems, is also likely.

Efforts to conserve, restore, and expand Illinois' natural areas will be critical for ensuring the survival of native flora and fauna. Conserving natural ecosystems, which are inherently more resilient to climate change than more highly managed systems (e.g., tree plantations), and restoring connections among these areas can help to safeguard native plants and wildlife and enhance their ability to adapt to changing conditions. These efforts can also help to sequester carbon, which is important for combating climate change. Because much of the state's land is in private ownership, managing natural lands effectively will require cooperation among private landowners, environmental organizations, and natural resource agencies.

Knowledge and research priorities

This assessment provides localized climate projections that can be used by lawmakers, government agencies, nonprofits, businesses, individual landowners, and farmers to develop adaptation and mitigation plans to decrease the magnitude of a wide range of adverse impacts from climate change. However, additional knowledge and research are required to decrease uncertainty and improve predictive capabilities. High-priority recommendations for research include:

Improved climate modeling. The development of climate models with very high spatial resolution would provide more robust simulations of heat waves, severe thunderstorms, and extreme precipitation. The development of integrated models of the atmosphere, land, and the Great Lakes would further enhance the utility of weather forecasts and long–term climate projections.

Water resources. Sustainable management of water supplies from surface and subsurface sources for drinking and irrigation must be guided by assessments of the availability and replenishment capacities of these sources in a changing climate. Given the high cost and long construction times for large-scale built infrastructure, it is important to develop strategies that integrate conventional stormwater infrastructure with distributed green infrastructure to mitigate local and regional flooding risks, while also maximizing co-benefits to people and nature.

Agriculture. Research is needed to understand complex plant responses associated with combined stresses (e.g., elevated CO_2, summer drought) under different management practices on crop yields and to support the development of plant traits and adaptive management practices that improve crop performance under future growing conditions. Further research would be useful to better understand the mitigation potential of farming and management practices. Social science research on the vulnerability of rural communities and effective strategies to enhance the adaptive capacity and resilience of rural communities are also needed.

Human health. Social science research is critical to improve our understanding of the vulnerability of rural and urban communities, develop strategies to enhance adaptive capacity and resilience, and overcome barriers to the adoption of improved health communication strategies. The relationship between climate change and mental health is a burgeoning field of research that needs continued support. Expanded and more comprehensive cost-benefit analyses of climate and health adaptation strategies would provide decision makers with data-driven tools to make informed decisions and take action.

Ecosystems. Baseline data collection is needed to inform natural resource management decisions, which can be achieved through ongoing trend assessments. Further research is also needed to understand how plants and animals cope with altered precipitation patterns and increasing temperatures. In particular, studies to identify the factors that contribute to successful ecological restoration of different ecosystem types will be critical to help mitigate the adverse effects of climate change on biodiversity.

CHAPTER 1

Introduction

Key Messages

1. Illinois is experiencing significant long-term changes in weather patterns, especially increases in extreme warm periods and total annual precipitation, as well as greater intensities of individual rain events. The climate of Illinois and the region is changing and changing rapidly.

2. The scientific evidence indicates it is extremely likely that human activities, which have led to drastic increases in greenhouse gas emissions from fossil fuel use and extensive land-use changes, are the dominant cause of global changes in climate, dating back to at least the mid-1900s.

3. Illinois' climate is expected to continue changing over this century, with significant impacts on urban and rural communities, including impacts on water resources, agriculture, human health, and the health of plants and animals.

Importance of understanding the impacts of climate change in Illinois

Climate, the long-term averages and statistics of weather, is changing throughout the world, including in the state of Illinois. Climate change is a major environmental challenge that is likely to affect many aspects of life in Illinois, ranging from human and environmental health to the economy. Illinois is already experiencing the effects of climate change, including more frequent heat waves, milder winters, and changing patterns of precipitation. As climate change progresses and global temperatures continue to rise, these impacts are expected to increase over time.

This report takes an in-depth look at how the climate is changing now in Illinois, and how it is projected to change in the future, to provide greater clarity on how it could affect both urban and rural communities in the state. Beyond providing a general overview of anticipated climate changes, the report explores predicted effects on hydrology, the agricultural sector and rural economy, human health, and native species. Potential impacts on the topics covered in this report—hydrology, agriculture, health, and ecosystems—were selected because these areas affect many aspects of people's lives and well-being in the state of Illinois.

Illinois has an extensive river system and a long history of flooding, which climate change is expected to exacerbate. Nearly 15% of Illinois' total area—7,400 square miles—is prone to periodic flooding, and over 250,000 buildings are located within the floodplain (IDNR n.d.). Illinois' baseline hydrology has already been significantly altered in ways that exacerbate flood risks—including the loss of wetlands, expansive cultivation, tile drainage in rural areas, and extensive impermeable surfaces in urban areas. Climate change is expected to cause a shift to warmer winters, increased winter and spring rainfall, and more intense rainfall events that further increase flood risks to agriculture, property, and people in Illinois.

Agriculture forms a major part of Illinois' economy and is particularly vulnerable to climate change. Illinois' agricultural commodities generate more than $19 billion annually (Illinois Department of Agriculture n.d.). Although corn and soybeans account for a large portion of Illinois agriculture, livestock, poultry, dairy, and specialty crops are also important economically. The agricultural sector is already experiencing impacts of climate change that are expected to continue into the future. In 2019, the fifth wettest year on record for Illinois (NOAA 2020), the state suffered from widespread flooding and major crop losses. That year, 1.2 million acres of corn and soybeans went unplanted in Illinois alone (Schnitkey 2020). This impact is in line with both observed (historical) and projected (future) trends showing increased total amounts of precipitation and intensity of precipitation events (Janssen et al. 2014).

The physical and mental well-being of Illinois' citizens is also likely to be impacted by climate change, through increased risk of heat-related illnesses, acute and chronic respiratory diseases, and vector-borne diseases. Notably, the health impacts of climate change will vary based on how particular illnesses are transmitted, as well as by geography and socio-economic conditions. Climate change exacerbates existing vulnerabilities and inequities in both rural and urban communities, meaning communities that are already more vulnerable and disadvantaged are likely to experience the worst health impacts.

This report also explores likely impacts of the changing climate on native species and habitats. Illinois contains important ecosystems that include the prairies of Central and Northern Illinois, the hardwood forests of Southern Illinois, and freshwater habitats and wetlands throughout the state. A significant portion of Illinois' original native habitat has been lost—99% of the state's original prairie has been converted (Anderson 1991) and around 90% of wetland habitats have been drained (Dahl 1990; Suloway and Hubbell 1994)—which means remaining habitats are fragmented and less resilient. Climate change will amplify existing stresses that further weaken the overall health of these remaining native ecosystems.

Fortunately, Illinois communities can take action now to mitigate and adapt to a changing climate. This assessment is intended to provide localized climate information that the state and communities can use to design programs and policies to prepare for climate impacts and respond effectively. With better information, we all benefit from the ability to plan and act accordingly. For example, we can take appropriate actions to minimize our carbon footprint and reduce emissions to levels advised by science. We can take action to minimize flood risk, adopt best management practices on farms, reduce the risks of preventable diseases and illnesses, and improve the ability of natural areas to adapt to the changing environment. Improving our knowledge of local climate change impacts provides the building blocks to create a more durable future for Illinois.

An introduction to the science of climate change and this climate assessment

This section provides an overview of the current status of climate change science and describes the scope and methodology used for the analyses contained within this assessment.

What is causing climate change?

The climate continues to change rapidly throughout the world, including the United States and in Illinois, compared with the pace of natural variations that have occurred throughout Earth's history. Trends in globally averaged temperature, sea level rise, upper-ocean heat content, land-based ice melt, Arctic sea ice, depth of seasonal permafrost thaw, and other climate variables provide consistent evidence of a warming planet. These trends are robust and have been confirmed by multiple independent observations by scientists from around the world (IPCC 2013; USGCRP 2017, 2018).

There is significant scientific consensus that climate change is the direct result of human activities. For example, the Fourth U.S. National Climate Assessment (USGCRP 2017, 2018), building upon prior assessments of the science (e.g., IPCC 2013; Melillo et al. 2014) and extensive new evidence, concludes that it is extremely likely that human activities, especially emissions of greenhouse (heat-trapping) gases from energy use and land-use change, are the dominant cause of global warming since at least the mid-20th century. As humans continue to burn fossil fuels and develop natural lands, the concentration of greenhouse gas emissions in the atmosphere rises, driving global average temperature increasingly higher. For the last century, there are no convincing alternative explanations for the observed warming that are supported by observational evidence. Natural variability or natural cycles cannot account for the amount of global warming observed over the industrial era, and radiation from the Sun has decreased slightly—not increased.

Climate change trends

Human-caused climate change has already caused global average temperatures to rise. The global annual average temperature has increased by 1.8°F (1.0°C) from 1901 through 2016, as calculated from instrumental records over both land and oceans (USGCRP 2017). Eighteen of the 19 warmest years in the measurement record (which spans >130 years) occurred in the period from 2001 to 2019—the one exception was 1998, a major El Niño year. Global average temperature for 2016 was the warmest on record, surpassing 2019, 2018, 2017, and 2015 by a small amount. These years far surpassed the sixth warmest year on record, 2014, by over 0.29°F (0.16°C), four times greater than the difference between 2014 and the next warmest year, 2010 (NCEI 2020). Similarly, annual average temperature over the contiguous United States increased by 1.8°F (1.0°C) for the period 1901–2016 and is projected to continue to rise.

Global climate is projected to continue to change over this century and beyond. The magnitude of climate change beyond the next few decades will depend primarily on the amount of greenhouse gases emitted globally and, to a limited degree, on remaining uncertainties in the sensitivity of Earth's climate to those emissions. With significant reductions in the emissions of greenhouse gases, the global annual averaged temperature rise could be limited to 3.6°F (2°C) or less, which is the goal of the Paris Agreement. Without major reductions in these emissions, the increase in annual average global temperatures relative to preindustrial times could reach 9°F (5°C) or more by the end of this century (USGCRP 2017, 2018).

Illinois is already experiencing impacts from the changing climate. For example, the frequency and intensity of extreme heat and heavy precipitation events are increasing throughout most of the world, including Illinois and the Midwest United States. The number of high temperature records set in the past two decades far exceeds the number of low temperature records. Heavy precipitation events in most parts of the United States have increased in both intensity and frequency since 1901. There are important regional differences in these trends, with the largest increases in extreme precipitation occurring in the U.S. Northeast and the Midwest, including Illinois. These trends in precipitation and temperature extremes are consistent with the expected response to a warming climate and are likely to continue, particularly without ambitious actions to curb greenhouse gas emissions (USGCRP 2017, 2018).

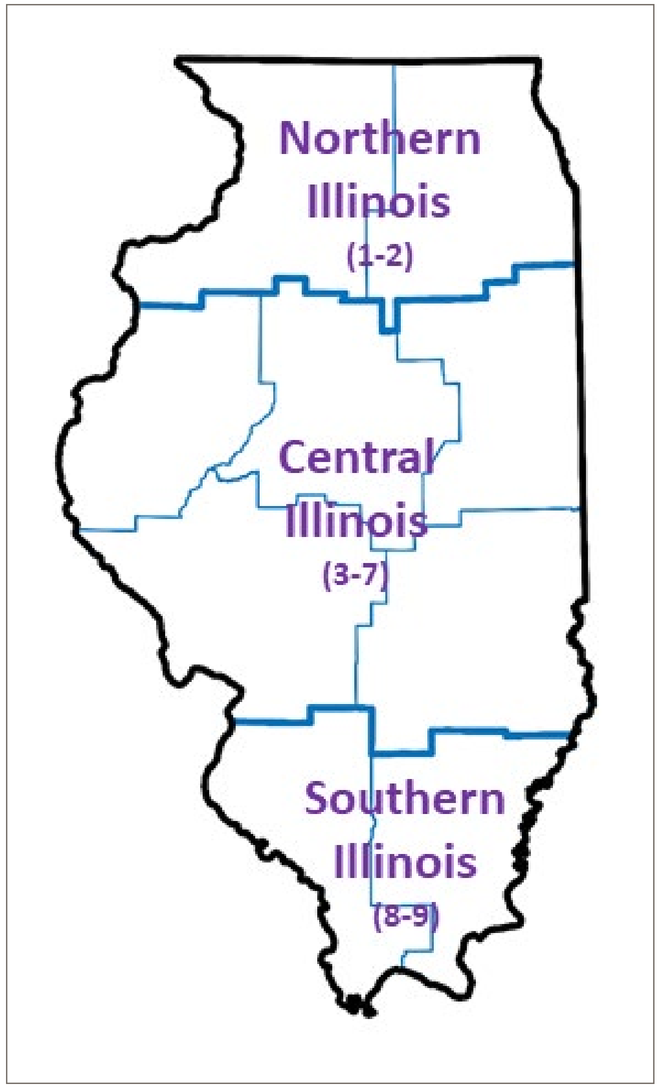

Figure 1.1 Map of Illinois regions

Illinois climate analyses

This assessment goes beyond the international IPCC assessments or the National Climate Assessments by focusing on the changes in climate and resulting impacts occurring in Illinois. For this assessment, analyses were completed to provide insight specifically into how climate change is expected to impact Illinois and the surrounding region. Chapter 2 discusses the specific changes occurring now and the future changes projected for this region, and is further broken down by Northern, Central, and Southern Illinois (Figure 1.1).

Methodology for climate change analyses in this assessment

While some of the analyses in this assessment are based on existing peer-reviewed publications or websites associated with observational datasets, some of the graphics produced for this assessment are based on model analyses or other datasets, as described in the chapters.

Analyses of the past and projected climate changes are derived based on the analyses of observational datasets for past changes and from modeling and downscaled datasets for projections produced for the Fourth National Climate Assessment for the U.S. (NCA4; USGCRP 2017, 2018). The reference periods used in these analyses are different from those used in NCA4, primarily because another three years of observational data are now available. The past changes are determined for the 30-year period 1990–2019 relative to 1896–1924. Future projections are for 2036–2065 and 2070–2099 relative to the current time period of 1990–2019. The choice of 30-year periods accounts for natural variations and provides for reasonable sampling in order to estimate likelihoods of trends in extremes; this period is consistent with the World Meteorological Organization's recommendation for climate statistics (WMO 2017).

Projections are based on global models for the CMIP5 (Coupled Model Intercomparison Project Phase 5) model dataset, using the suite of Representative Concentration Pathway (RCP) scenarios. Projections use a weighting system for global climate models, that are then statistically downscaled for temperature and precipitation at about 6-km resolution across the continental United States based on the Localized Constructed Analogs approach (LOCA; Pierce et al. 2014) that spatially matches model-simulated days, past and future, to analogs from observations.

Like NCA4 (USGCRP 2017; see Appendix B), this assessment uses model weighting for all of the global models to refine future climate change projections. In NCA4, model independence and selected global and North American model quality metrics are considered in order to determine the weighting parameters (Sanderson et al. 2017, building upon the earlier study by Knutti et al. 2017). The weighting approach takes into account the interdependence of individual climate models as well as their relative abilities to simulate the North American climate. An understanding of the calculated time history, together with the fingerprints of particular model biases, has been used to identify model pairs that are not independent. Thus, this approach considers the skill (historical accuracy) in the climatological performance of the models for the area over North America as well as the inter-dependency of models.

Most of the analyses in this assessment use one of two RCP scenarios: the lower RCP4.5 scenario or the higher RCP8.5 scenario. RCP4.5 assumes a rapid movement away from fossil fuels over the coming decades. Under the lower RCP4.5 scenario (van Vuuren et al. 2011; Thomson et al. 2011), atmospheric CO2 levels remain below 550 ppm by 2100. In contrast, the RCP8.5 scenario corresponds to a future where carbon and methane emissions continue to rise throughout the century, albeit with significant declines in emission growth rates over the second half of the century, significant reduction in aerosols, and modest improvements in energy intensity and technology (Riahi et al. 2011; USGCRP 2017). The higher emissions in the RCP8.5 scenario could occur because of continued dependence on fossil fuels or due to climate feedbacks such as increasing emissions from permafrost thaw. RCP8.5 reflects the upper range of the open literature on emissions, but this scenario is not intended to serve as an upper limit on possible emissions. Under the RCP8.5 scenario, CO_2 concentrations are projected to reach 936 ppm by 2100. Figure 1.2 illustrates the RCP8.5 and 4.5 scenarios and their impact on global temperatures.

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Don Wuebbles (lead author), James Angel, Trent Ford, Maria Lemke, Bill Miller, and Karen Petersen.

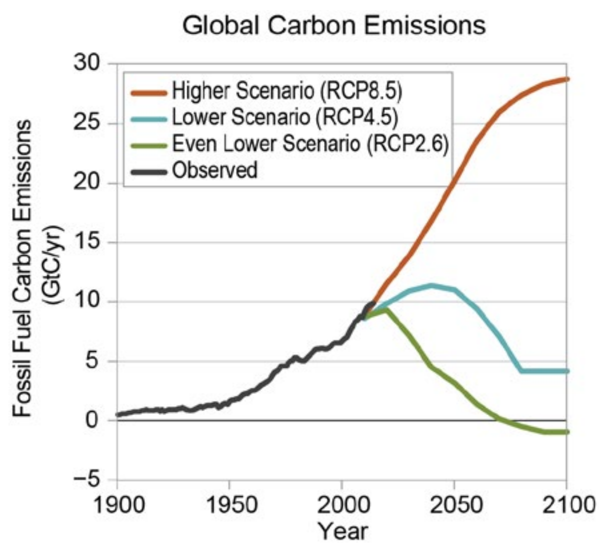

Figure 1.2 Observed and projected global carbon emissions and global temperatures. The left panel shows the observed carbon emissions (black line) and carbon emission paths out to 2100 for the lower (RCP4.5) and higher (RCP8.5) scenarios used in this study. The right panel shows the observed global temperatures (black line) and projected global temperatures out to 2100 for the RCP4.5 and RCP8.5 scenarios. The even lower scenario RCP2.6 was not considered in this study. **Source:** Figure 2.2 in the Fourth National Climate Assessment (Hayhoe et al. 2018).

CHAPTER 2

Observed and Projected Changes in Climate

Key Messages

1. Over the past 120 years, the average daily temperature in Illinois has increased, especially the average overnight temperature. Nighttime temperatures have risen about 2°F—three times the rate of daytime warming—causing an increase in the number of warm summer nights and a decrease in the number of freezing winter nights.

2. Over the last 120 years, mean precipitation has increased from 5 to 20%, varying across the state, and the number of 2-inch rain days in Illinois has increased by 40%, reflecting major regional changes in the hydrologic cycle. Over the same time period, extreme droughts have become less common.

3. By the end of the 21st century, unprecedented warming of 4–9°F under the lower pathway and 8–14°F under the higher pathway is likely in Illinois. This is likely to be accompanied by large increases in extreme high temperatures, a longer growing season, and less severe extreme cold.

4. Illinois is expected to see an overall increase in precipitation in the coming decades as the climate warms. The distribution of precipitation in Illinois is also projected to become more extreme, with increases in both heavy rains and the length of dry spells.

5. Hotter summer temperatures will increase the severity of naturally occurring droughts and, with lengthier dry spells, increase the risk of flash droughts, which start and intensify rapidly.

Introduction

The climate in Illinois and the Midwest is changing and is projected to change much more through 2100. This chapter summarizes both observed and projected changes in key climate variables, such as temperature and precipitation, for Illinois. In some cases, the analyses also capture bordering states, showing regional changes more broadly. Historical analyses show that some aspects of Illinois' climate have already started to change as a result of human activities. As explained in this chapter, Illinois is wetter and warmer than it was at the beginning of the last century. Projections of how the climate is expected to change over the next several decades show that these trends are likely to continue. The projections of how Illinois' climate could change in the future provide valuable insight into the kinds of changes we can expect to see in the state relative to whether society follows a lower or higher pathway for greenhouse gas emissions.

Methodology

As discussed in Chapter 1, the methodology used in these analyses is similar to that used in the Fourth National Climate Assessment (NCA4; USGCRP 2017). Historical changes are identified from analyses of observational datasets. Future projections are derived from modeling and downscaled datasets produced for NCA4. Data from 32 global climate models were statistically downscaled for temperature and precipitation to about 6 km resolution across the continental United States. A set of 32 model weights were computed based on the global climate models' ability to simulate key features of the global and regional climate and on their independence from one another. Then, weighted multi-model averages of the downscaled data were computed and displayed graphically.

Recent studies (e.g., Sherwood et al. 2020) have suggested that the climate sensitivity range (of about 1.5–4.5°C) should be narrowed, which could have the possible effect of eliminating some model results from consideration in assessments. Climate sensitivity is a measure of how much the Earth's climate is likely to change in response to rising atmospheric CO_2 concentrations, referring specifically to the amount of warming likely to occur when carbon dioxide in the atmosphere doubles in comparison with preindustrial levels (i.e., an increase from 280 to 560 ppm). Because the science community has not made a clear recommendation to do so, we have not modified the downscaled modeling findings developed for NCA4 and used in this assessment.

Historical air temperature changes and trends

Over the past century, Illinois has been getting warmer overall. The average daily temperature has increased by 1–2°F in most areas of Illinois over the last 100 years (Figure 2.1 center panel). Overnight minimum temperatures have increased more than daytime maximum temperatures. In some areas of the state, the increase in overnight minimum temperatures has exceeded 3°F (Figure 2.1 left panel), while the daytime maximum temperature increase has ranged between 0°F and 1.5°F in most areas (Figure 2.1, right panel). This difference in trends between day and night is most prominent in the summer (Table 2.1). Average summer daytime maximum temperatures have stayed largely the same (Figure 2.2, left panel), but average summer nighttime minimum temperatures have increased by about 2°F over the past century (Figure 2.2, right panel). Although differences in trends between day and night are most apparent in summer, the statewide minimum temperature has increased at a larger rate than maximum temperature in all seasons (Table 2.1). In winter and spring, average temperature trends are five and three times larger than that of summer, respectively (Table 2.1), signifying that statewide warming has also occurred disproportionately between December and May over the past century.

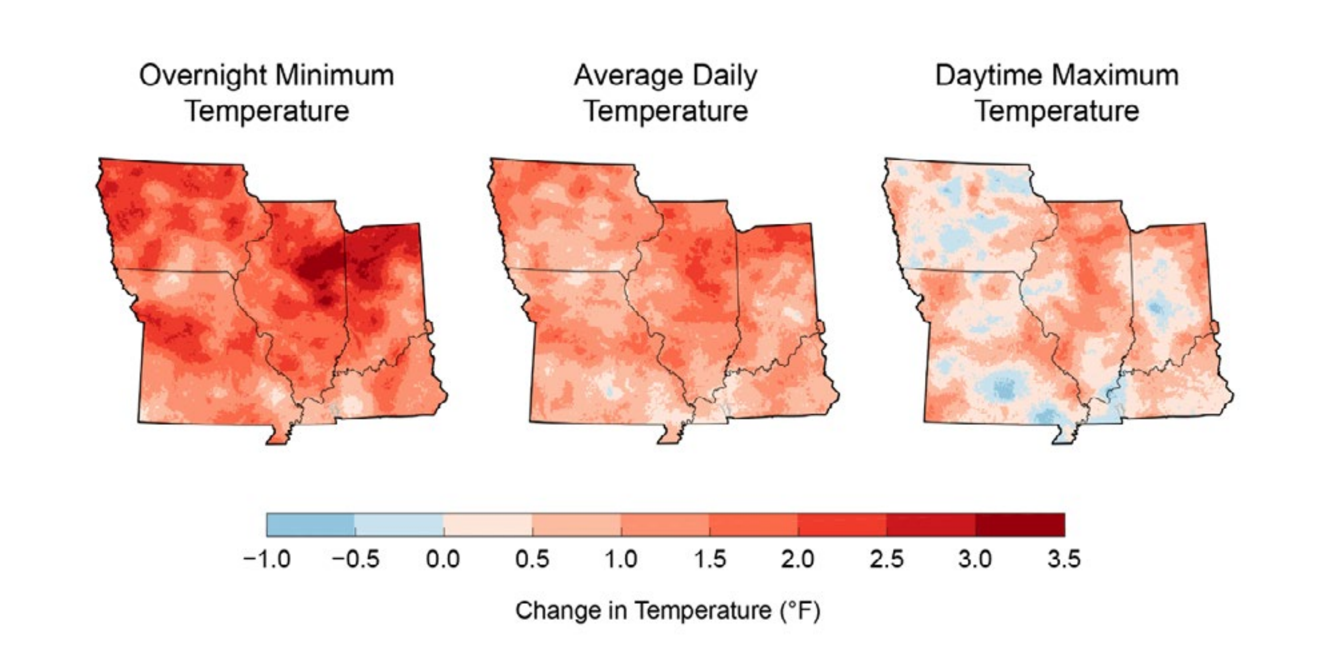

Figure 2.1 Maps of observed changes (°F) for 1990–2019 relative to 1895–1924 for average overnight minimum temperature (left panel), average daily mean temperature (middle panel), and average daytime maximum temperature (right panel) for Illinois and some bordering states. **Sources:** North Carolina Institute for Climate Studies (NCICS) and The University of Edinburgh.

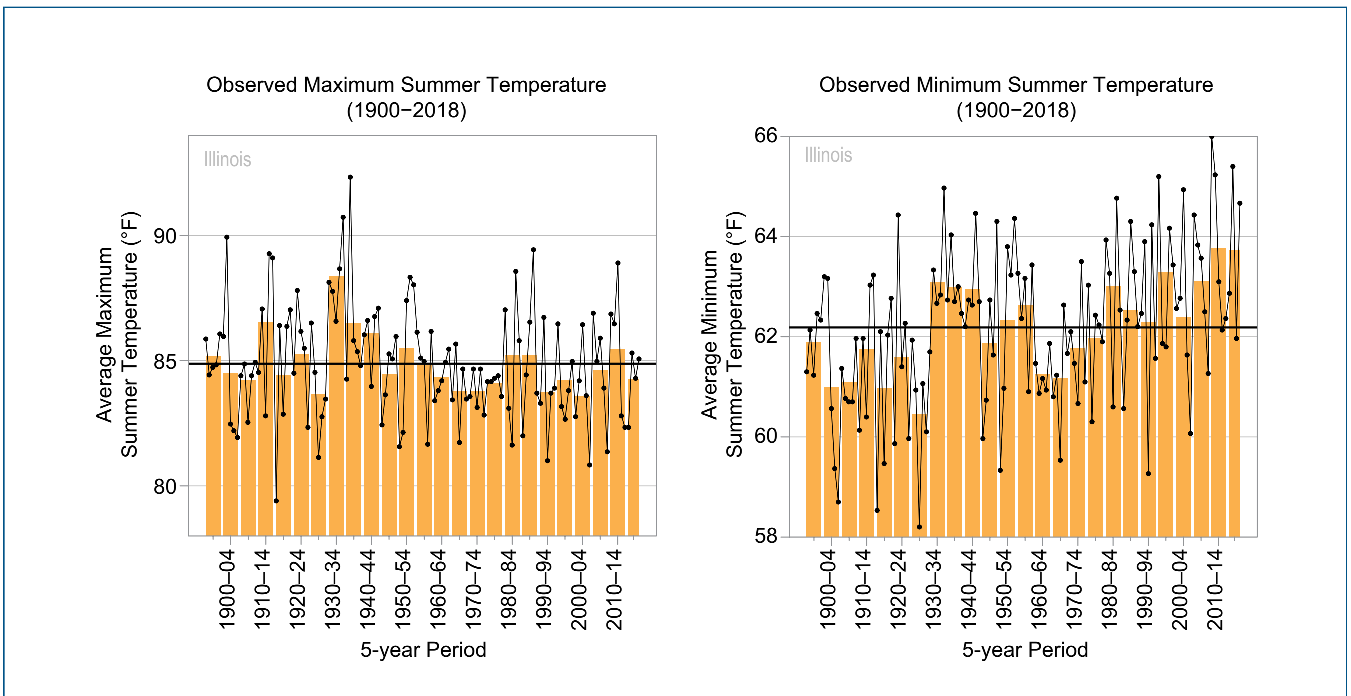

Figure 2.2 The bar graphs show the observed average daytime maximum (left panel) and average nighttime minimum (right panel) summer temperature for Illinois for 1900–2018, as averaged over 5-year periods, with the last bar representing a 4-year period (2015–2018). Dots show annual values. The horizontal black line shows the long-term averages of 84.8°F (maximum) and 62.3°F (minimum) for 1895–2018. **Source:** updated from Frankson et al. (2017).

Table 2.1 Statewide Temperature Changes for 1990–2019, Relative to 1895–1924

Season	Overnight Minimum Temperature	Average Daily Temperature	Daytime Maximum Temperature
Winter	+3.0	+2.5	+2.2
Spring	+1.8	+1.6	+1.4
Summer	+1.7	+0.5	-0.7
Fall	+1.3	+0.8	+0.4

Observed statewide temperature changes (°F) for 1990–2019 relative to 1895–1924 for average overnight minimum temperature, average daily mean temperature, and average daytime maximum temperature for Illinois. Changes are displayed by season. **Sources:** NCICS and The University of Edinburgh.

Extreme temperatures show mixed trends, consistent with the changes in precipitation and soil moisture over the last century. These mixed trends are also consistent with the observed minimum and maximum temperatures. The annual frequency of days with daytime maximum temperatures at or above 95°F was actually highest in the early half of the 20th century and exhibits no recent trends (Figure 2.3, left panel). The fact that days with daytime maximum temperatures at or above 95°F have not increased in recent decades is partly a result of concurrent increases in spring and summer precipitation. Wetter springs in Illinois have led to increased soil moisture content, which results in more of the sun's energy going to evapotranspiration than toward heating the ground and atmosphere. This effect moderates daytime maximum temperatures, resulting in fewer very hot days (Takle and Gutowski 2020).

In addition, in Illinois very hot days have historically been tied to drought, particularly in the summer, which explains why decades with high drought frequency, such as the 1930s, have coincided with some of the warmest summers. As summer precipitation has increased over the past century, the frequency of drought has decreased, also limiting the frequency of very hot days, those with a daytime maximum temperature at or above 95°F.

While the number of days with nighttime minimum temperature at or above 70°F does not exhibit an overall trend over the full period of record, it has been generally above average over the last decade (Figure 2.3, right panel). Consistent with increased winter minimum temperatures, the number of nights with temperatures at or below freezing (32°F) exhibits a decreasing trend (Figure 2.4).

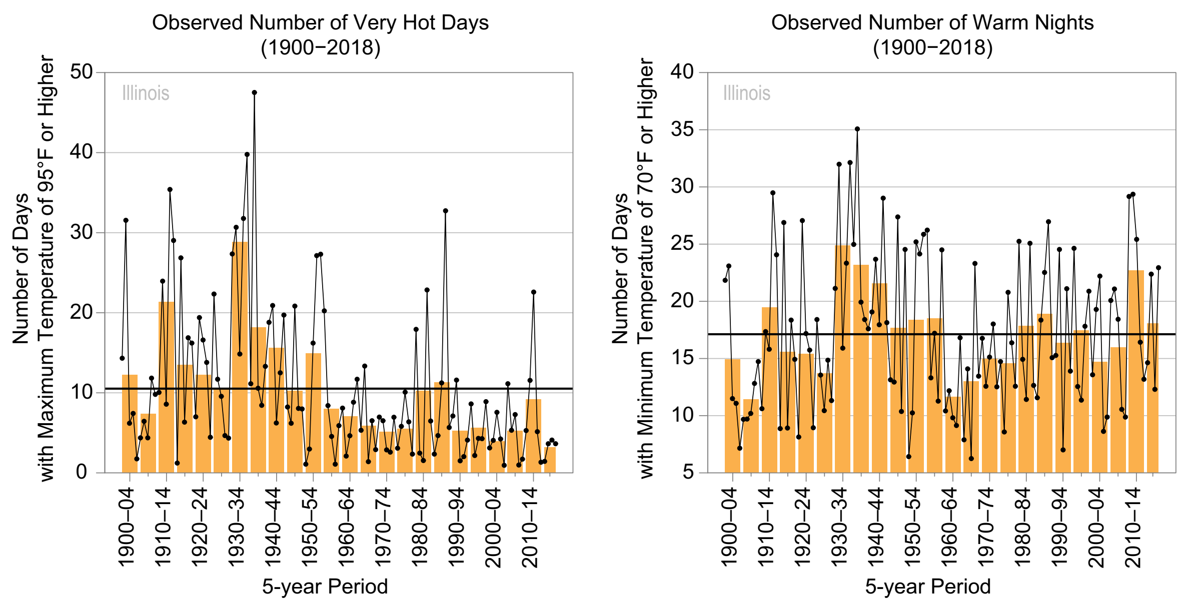

Figure 2.3 The bar graphs show the number of days with daytime maximum temperature at or above 95°F (left panel) and the number of days with nighttime minimum temperature at or above 70°F (right panel) for Illinois for 1900–2018, as averaged over 5-year periods, with the last bar representing a 4-year period (2015–2018). Dots show annual values. The horizontal black lines show the long-term (1900–2018) annual average of 11 days for very hot days and 17 days for warm nights. **Source:** updated from Frankson et al. (2017).

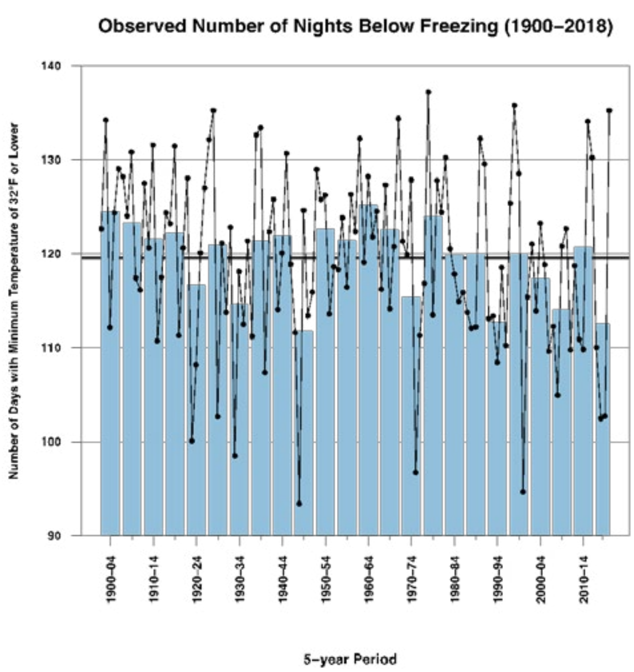

Figure 2.4 The bar graph shows the number of days with nighttime minimum temperature at or below 32°F for Illinois for 1900–2018, as averaged over 5-year periods, with the last bar representing a 4-year period (2015–2018). Dots show annual values. The horizontal black line shows the long-term annual average of 119 days for 1900–2018. **Source:** updated from Frankson et al. (2017).

Historical precipitation changes and trends

Illinois has gotten wetter overall in the past 100 years. Average annual precipitation in nearly all areas of Illinois has increased between 10% and 20% over the past century (Figure 2.5). Total precipitation has increased in all four seasons over the same time period, albeit at varying rates (Table 2.2). In particular, spring, summer, and fall total precipitation have each increased by more than one inch, relative to the 1895–1924 average, representing increases of 12.5%, 14.3%, and 15.9%, respectively. Although the overall change is smaller, winter precipitation in Illinois has still increased by 0.54 inches, or approximately 8.5%.

Table 2.2 Statewide Precipitation Changes for 1990–2019, Relative to 1895–1924

Season	Precipitation (inches)	Precipitation (% Change)
Winter	+0.54	8.5%
Spring	+1.33	12.5%
Summer	+1.55	14.3%
Fall	+1.33	15.9%

Observed seasonal average total statewide precipitation changes for 1990–2019 relative to 1895–1924 for Illinois, expressed as a total change (inches) and percent change from the 1895–1924 average. **Sources:** NCICS and The University of Edinburgh.

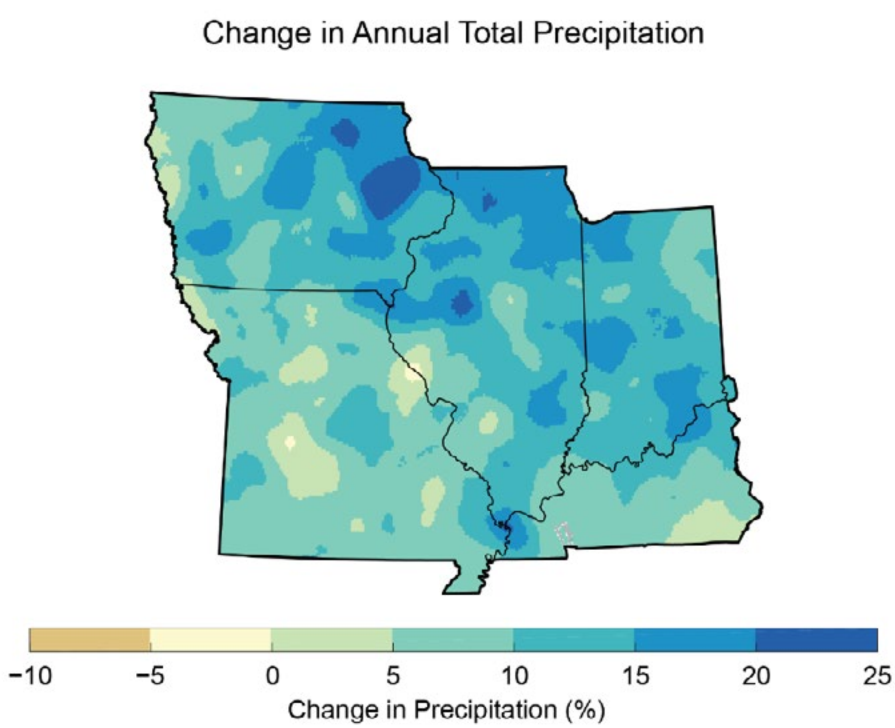

Figure 2.5 Map of observed changes (%) in annual total precipitation for 1990–2019 relative to 1895–1924 for the Midwestern United States. **Sources:** NCICS and The University of Edinburgh.

Associated with the increase in total annual and seasonal precipitation is a shift to more frequent extreme precipitation events. The number of days with precipitation exceeding 2 inches exhibits an upward trend (Figure 2.6), with an approximate 40% increase over the past century.

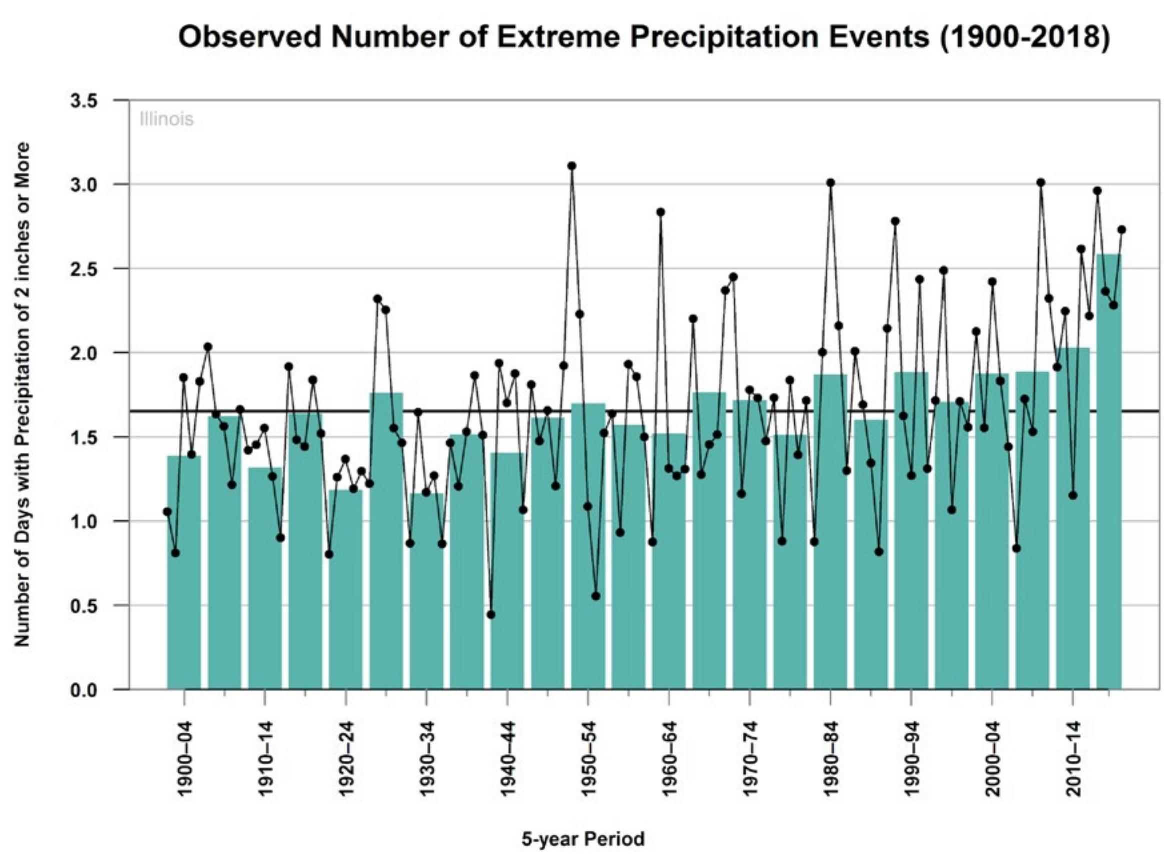

Figure 2.6 The bar graph shows the number of days with precipitation of 2 inches or greater for Illinois for 1900–2018, as averaged over 5-year periods, with the last bar representing a 4-year period (2015–2018). Dots show annual values. The horizontal black line shows the long-term annual average of approximately 1.7 events per station for 1900–2018. **Source:** updated from Frankson et al. (2017).

Historical drought changes and trends

In general, the two types of drought of concern in Illinois are agricultural and hydrologic droughts. Agricultural droughts occur when soil moisture is insufficient to support crops and are largely confined to one growing season (late spring to early fall). Hydrologic droughts generally last longer and result in below-normal streamflow, depleted reservoir storage, or shortages in groundwater supplies, typically causing severe impacts to water supplies. In Illinois, a hydrological drought usually only occurs if there has been below-normal precipitation for 6 or more months. It can last 1 to 2 years or even longer, in rare cases.

Many droughts exhibit characteristics of both types of drought. For example, although the drought Illinois experienced in 2012 began as an agricultural drought in the spring, by August the lack of rainfall had also begun to negatively impact surface and groundwater supplies. Rains in late August and September of that year provided some relief to agriculture, but the hydrologic drought persisted, affecting water supplies through the fall and winter. A similar pattern was observed in the 1988–89 drought (Angel et al. 1992).

As measured by the Palmer Drought Severity Index (PDSI), Illinois has experienced fewer extreme droughts since 1965 than during the period from 1895 to 1965, when extreme droughts were more common and more intense. The PDSI is a widely used index of drought severity based on temperature, precipitation, and soil characteristics. Values between -2 and +2 are considered near normal, while values of -2 to -2.9 indicate moderate drought, values of -3 to -3.9 indicate severe drought, and values of -4 or less indicate extreme drought. Larger positive values indicate anomalously wet conditions. The time series of monthly PDSI values averaged for the entire state for the period between 1895 to 2019 is shown in Figure 2.7. The most extreme drought statewide in Illinois occurred in 1934, reaching peak intensity in July (PDSI of -6.9). This was part of a multiyear period of dry and hot conditions, with extreme drought also in 1931 (PDSI of -6.5) and in 1936 (PDSI of -5.1). As shown in the figure, historical extreme drought events occurred in 1901–1902, 1914–1915, 1930–31, 1933–34, 1936, 1940–41, 1953–1954, 1963–1964, 1988, and 2012. Based on the historical record, such droughts would be expected to occur roughly once in 10 to 11 years, on average, but have occurred less frequently over the past 50 years.

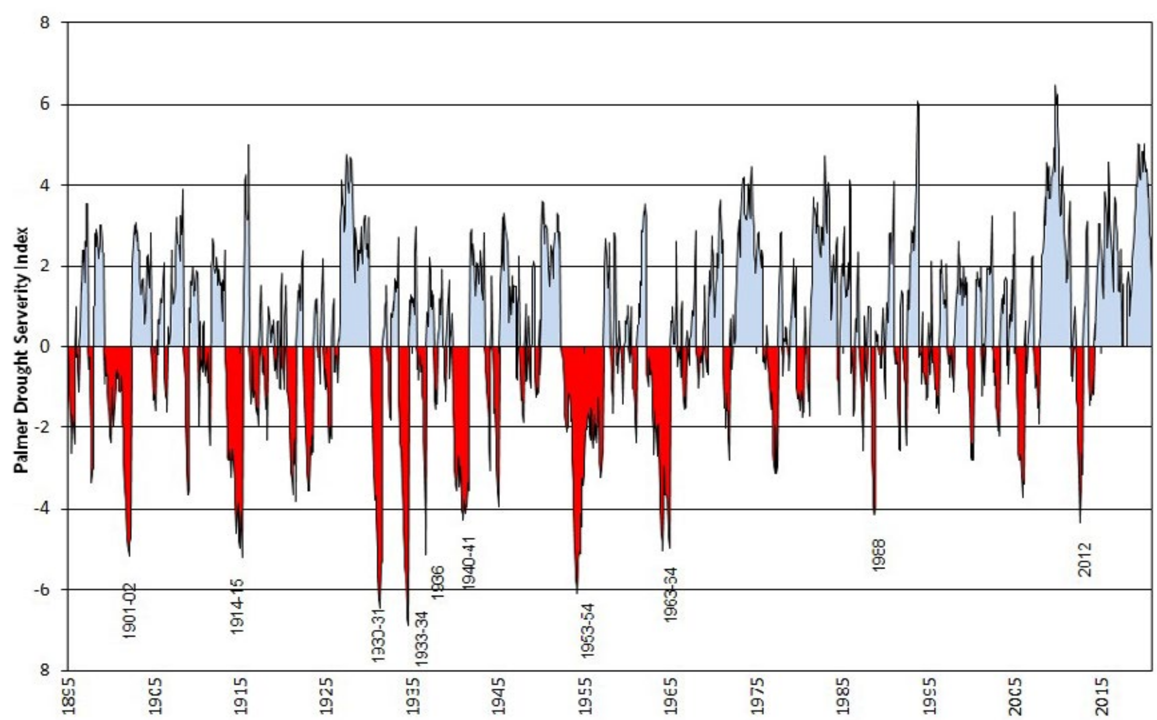

Figure 2.7 Palmer Drought Severity Index (PDSI) for Illinois from 1895 to 2019. Red indicates drier conditions while blue indicates wetter conditions. Noteworthy droughts are labeled. Extreme drought, defined as a PDSI value of −4 or less, was more common and more intense between 1895 to 1965 than droughts since 1965. Only the 1988 and 2012 drought are classified as extreme and each lasted less than a year. **Source:** Illinois State Climatologist Office.

Drought risk in Illinois is not only related to precipitation; changes in temperature also play an important role. Increased temperatures have led to more atmospheric evaporative demand, which can cause significant crop and ecosystem stress during dry conditions. For example, annual reference evapotranspiration, a measure of atmospheric evaporative demand, has increased by 0.17 inches per year since 1990 in DeKalb, Illinois (Figure 2.8). Over 50% of this change in atmospheric evaporative demand has occurred in the months of July, August, and September when soil water available to plants is at its lowest (Figure 2.8). Both the change in evaporative demand and the climatological soil moisture pattern observed in DeKalb are representative of conditions across the state. The combination of short-term dryness and very high evaporative demand can lead to depletion of soil moisture, and crop and ecosystem stress, over a relatively short period of time (e.g., 2 to 8 weeks). This can lead to a flash drought, which intensifies much more quickly than traditional, slower-evolving drought events. For example, the 2012 drought was a flash drought because of its unusually rapid intensification. Projections of increasing temperatures suggest evaporative demand will continue to increase in Illinois, as will the risk of flash drought.

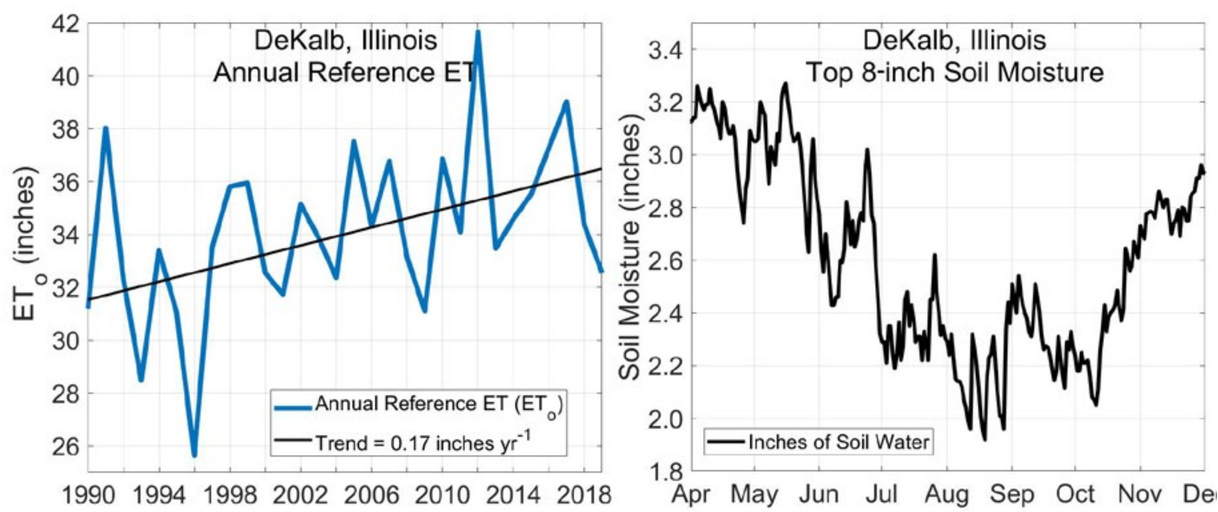

Figure 2.8 **Left panel:** Annual total reference evapotranspiration (blue line), an estimate of atmospheric evaporative demand, from 1990 to 2019 in DeKalb, Illinois. The trend line is shown in black. **Right panel:** Average daily soil moisture, in inches of water, in the top 8-inch soil column in DeKalb. **Source:** Data are from the Water and Atmospheric Resources Monitoring Program, Illinois Climate Network.

Historical snowfall changes and trends

Average annual snowfall in Illinois ranges from about 10 inches in far southern Illinois to 40 inches in the Chicago area. Illinois can feel major impacts from major winter storms. One example was the February 1–3, 2011, "Groundhog Day" storm that dropped up to 27 inches of snow in northeastern Illinois. In this event, more than 9.8 million Illinois residents were in areas with 12 or more inches of snow. The statewide average snowfall since 1902 (Figure 2.9) shows no long-term trends. However, some decades were snowier than others, such as the 1910s, 1960s, and 1970s. In fact, the 1970s were the snowiest decade on record with an average snowfall of 27.2 inches. Snowfall amounts dropped steeply with less year-to-year variability for much of the 1980s and into the early 2000s. However, snowfall amounts in the last 10 winters have been more variable, with the winter of 2014 being about as snowy as the winters of late 1970s. On the other hand, the two lowest snowfall totals were from the winter of 2011–12 with 9.2 inches and the winter of 2016–17 with 9.6 inches. The only trend found in the snowfall data was that the snowfall season has decreased by about two weeks since the 1970s.

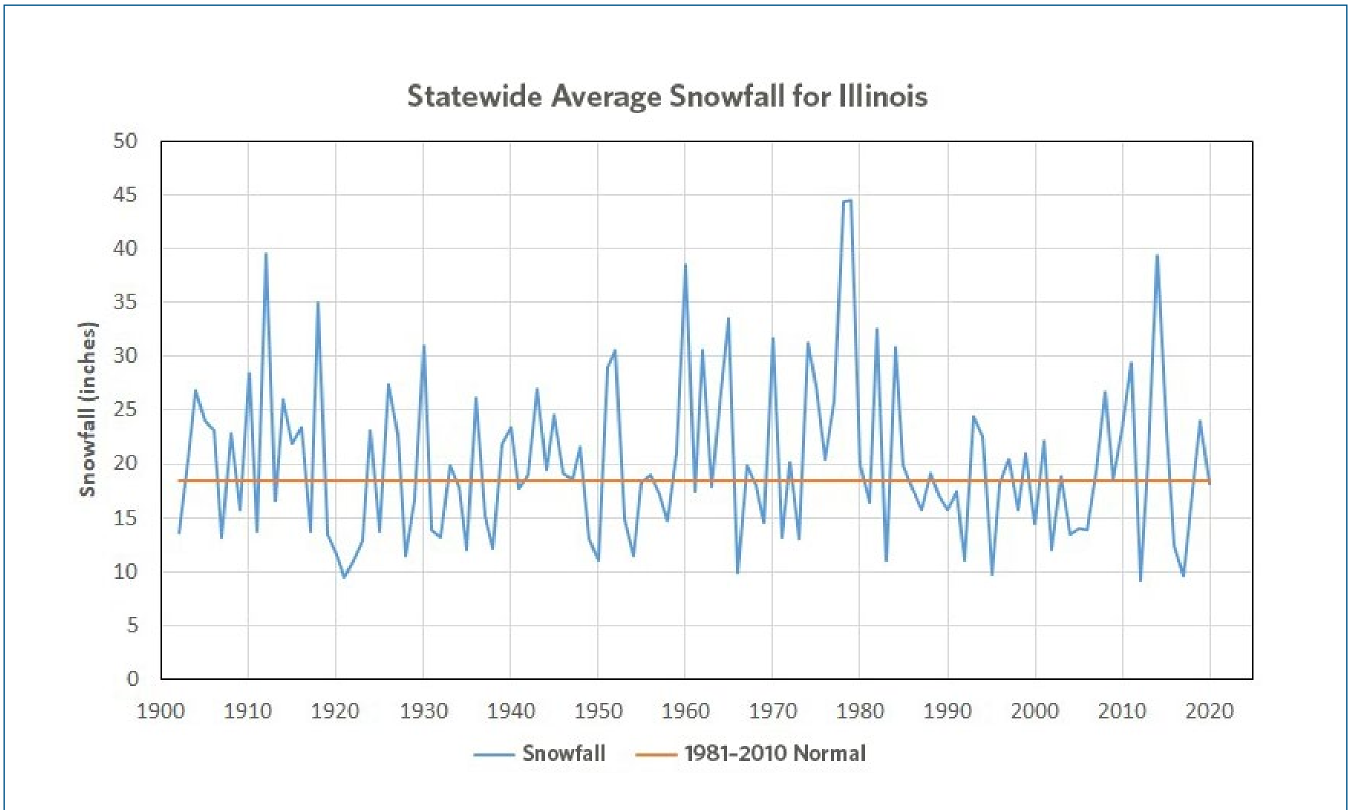

Figure 2.9 Average winter season (September–May) snowfall for Illinois from 1903 to 2020. **Source:** Illinois State Climatologist Office.

Projected temperature changes

Recent historical warming is projected to continue into the middle and late 21st century (Figure 2.10). In general, small spatial variations are expected; the projected temperature changes are slightly larger in northern Illinois than in southern Illinois. However, the projected temperature changes vary substantially depending on the RCP scenario (i.e., a lower or higher scenario). For an explanation of the lower and higher scenarios, please see Chapter 1. Annual average temperatures are projected to increase by 3 to 4°F under the lower scenario (RCP4.5) and by 4 to 5°F under the higher scenario (RCP8.5) by the mid-21st century. The disparity between scenarios further increases with time. By the late 21st century, temperatures are projected to increase by 4 to 5°F for the lower scenario and 8 to 9°F for the higher scenario. The magnitude of future temperature change is contingent on emissions now and to the end of the century.

The dependence of temperature change on scenario, as well as the range of model projections and regional behavior, are shown in Figure 2.11. Temperature increases are consistent between northern, central, and southern Illinois, and model projection spread increases with time. By the end of the century, the average temperature in northern Illinois is projected to increase from 49°F to 52–58°F (an increase of 3–9°F) under the lower scenario (RCP4.5) and to 57-63°F (an increase of 4–14°F) under the higher scenario (RCP8.5; Figure 2.11). In central Illinois, the projected increases are from 52°F to 56–62°F under the lower scenario (RCP4.5) and to 60–66°F under the higher scenario (RCP8.5; Figure 2.11). In southern Illinois, the projected increases are from 56°F to 60–64°F under the lower scenario (RCP4.5) and to 63–69°F under the higher scenario (RCP8.5; Figure 2.11).

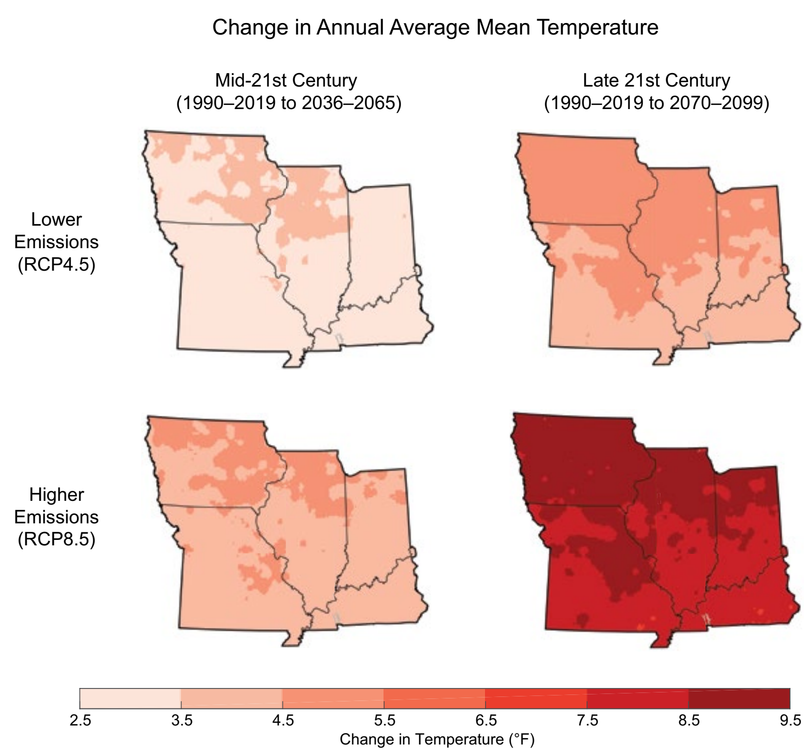

Figure 2.10 The maps show projected changes (°F) in the annual mean temperature for mid-21st century (left column) and late 21st century (right column) under a lower (RCP4.5) scenario (top row) and a higher (RCP8.5) scenario (bottom row) for the Midwestern United States. All projected values are shown as changes compared with 1990–2019 averages. **Sources:** NCICS and The University of Edinburgh.

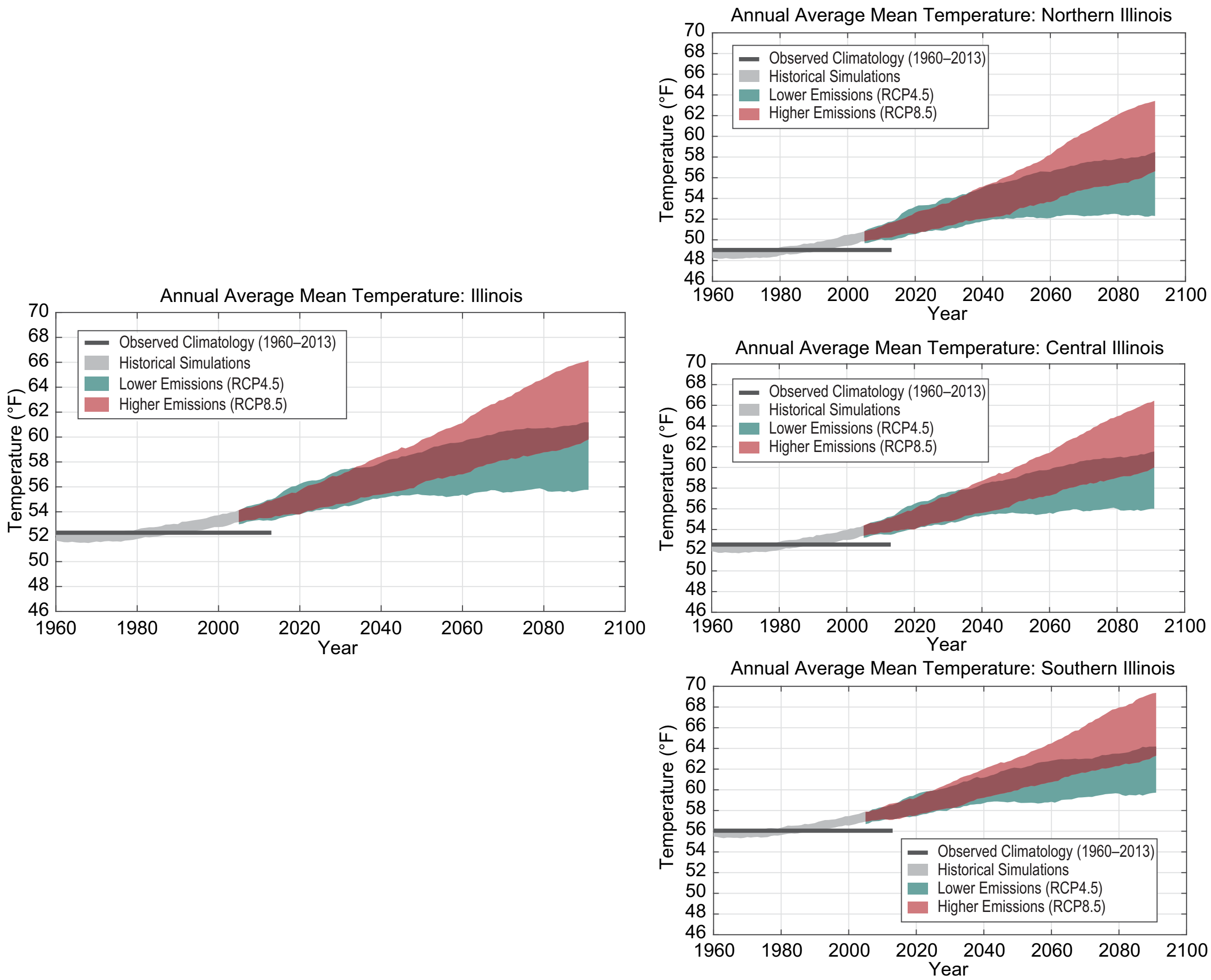

Figure 2.11 These time series (1960–2100) show the simulated historical and projected annual average mean temperature (°F) for the state of Illinois (left panel), northern Illinois (upper right panel), central Illinois (middle right panel), and southern Illinois (lower right panel). The observed climatological values averaged for the period 1960–2013 are shown (black line). Historical simulations (gray shading) are shown for 1960–2005. Projected changes for 2006–2100 are shown for a higher scenario (RCP8.5; red shading) and a lower scenario (RCP4.5; teal shading). The shaded ranges indicate the 10% to 90% confidence intervals of 20-year running averages from the set of climate models. **Sources:** NCICS and The University of Edinburgh.

Precipitation projections

Projections indicate increases in total annual precipitation everywhere in Illinois (Figure 2.12), with larger increases in the north than in the south, especially for late 21st century. Like temperature, the increases vary substantially with time period and scenario. Increases in precipitation range from 0%–4% and 3%–6% for the lower and higher scenarios, respectively, by the mid-21st century. For the late 21st century, the increases are 2%–6% for the lower scenario and 4%–10% for the higher scenario.

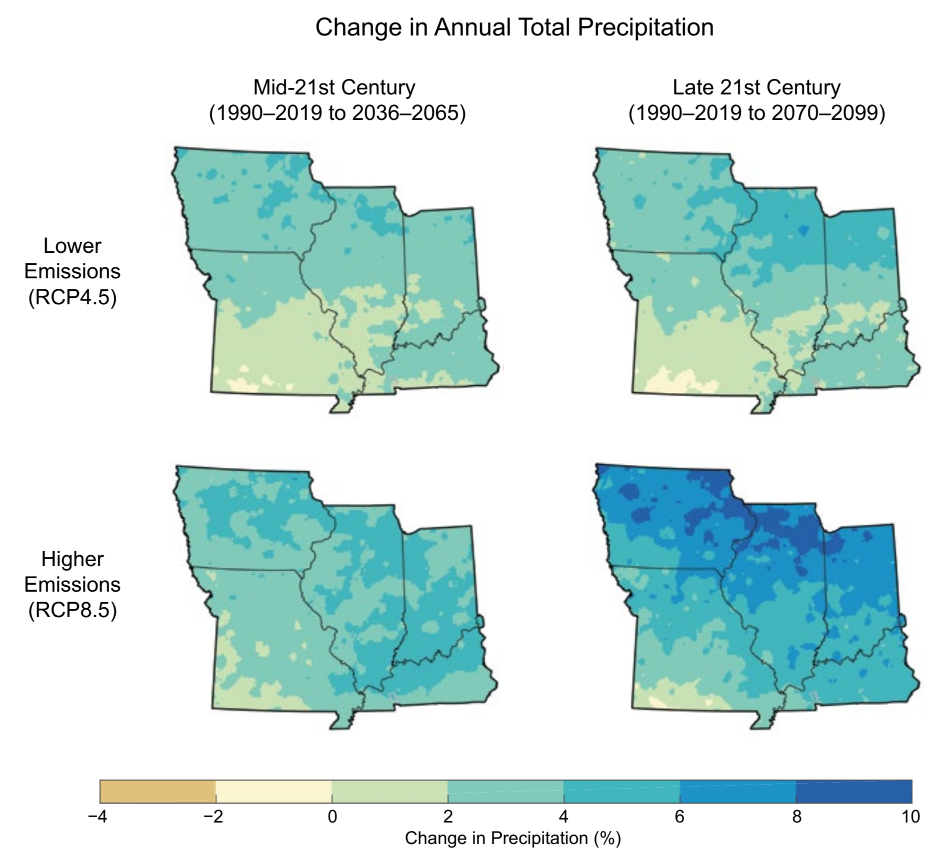

Figure 2.12 The maps show projected changes (%) in the annual total precipitation for the mid-21st century (left column) and late 21st century (right column) under a lower (RCP4.5) scenario (top row) and a higher (RCP8.5) scenario (bottom row) for the Midwestern United States. All projected values are shown as changes compared with 1990–2019 averages. **Sources:** NCICS and The University of Edinburgh.

The graphs in Figure 2.13 illustrate the large ranges between models of precipitation projections in Illinois, a feature that is apparent for all three regions. Although most models project increases, consistent with Figure 2.12, some models project no change or small decreases. Comparing the period 2070–2099 with the recent historical period of 1990–2019, the annual total precipitation in northern Illinois is projected to change from 35 inches to 34–40 inches under the lower scenario (RCP4.5) and to 34–42 inches under the higher scenario (RCP8.5; Figure 2.13). In central Illinois, the projected changes are from 37 inches to 37–42 inches under the lower scenario (RCP4.5) and to 37–45 inches under the higher scenario (RCP8.5; Figure 2.13). In southern Illinois, the projected changes are from 43 inches to 40–48 inches under the lower scenario (RCP4.5) and to 40–52 inches under the higher scenario (RCP8.5; Figure 2.13).

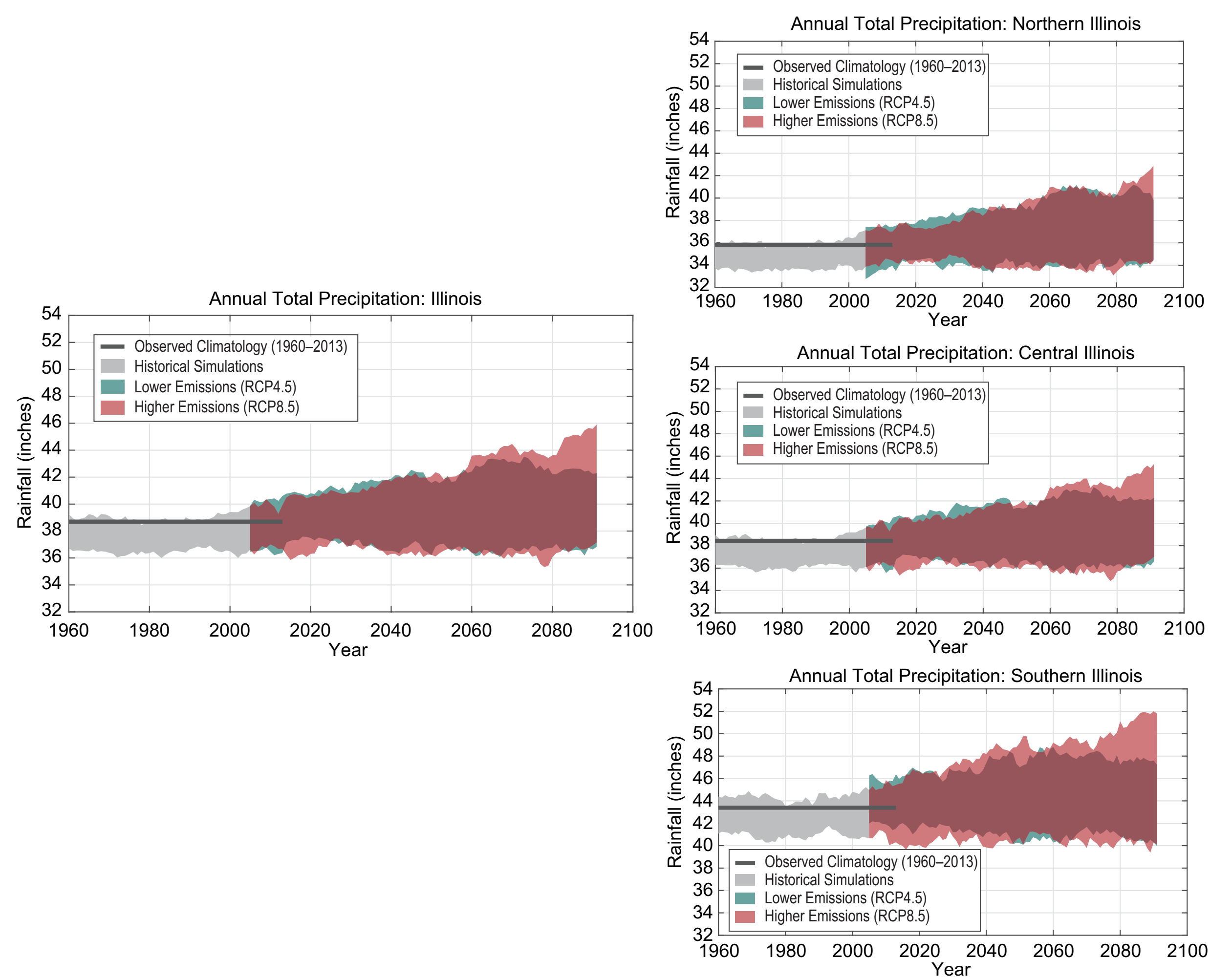

Figure 2.13 These time series (1960–2100) show the simulated historical and projected annual average total precipitation (inches) for the state of Illinois (left panel), northern Illinois (upper right panel), central Illinois (middle right panel), and southern Illinois (lower right panel). The observed climatological values averaged for the period 1960–2013 are shown (black line). Historical simulations (gray shading) are shown for 1960–2005. Projected changes for 2006–2100 are shown for a higher scenario (RCP8.5; red shading) and a lower scenario (RCP4.5; teal shading). The shaded ranges indicate the 10% to 90% confidence intervals of 20-year running averages from the set of climate models. **Sources:** NCICS and The University of Edinburgh.

The projected changes in total precipitation vary widely by season. Using the late 21st century under the higher (RCP8.5) scenario (Figure 2.14) to illustrate, substantial increases in precipitation are projected for winter (+10% to +20%) and spring (+5% to +25%), including snowfall as melted equivalent rainfall. By contrast, changes are small in the fall, and decreases of around 5% are projected for summer. The temporal behavior, as well as the range of model projections, is shown in Figure 2.15. As with total annual precipitation, the ranges of projected changes in precipitation are large, particularly for summer. By the end of the century, the statewide-average winter precipitation is projected to change from 6 inches to 7–8 inches under the lower scenario (RCP4.5) and to 7–9 inches under the higher scenario (RCP8.5; Figure 2.15). Statewide-average spring precipitation is projected to change from 11 inches to 11–14 inches under the lower scenario (RCP4.5) and to 12–14 inches under the higher scenario (RCP8.5; Figure 2.15). Statewide-average summer precipitation is projected to change from 11 inches to 9–13 inches under the lower scenario (RCP4.5) and to 8–13 inches under the higher scenario (RCP8.5; Figure 2.15). Statewide-average fall precipitation is projected to change from 9 inches to 8–10 inches under the lower scenario (RCP4.5) and to 9–10 inches under the higher scenario (RCP8.5; Figure 2.15).

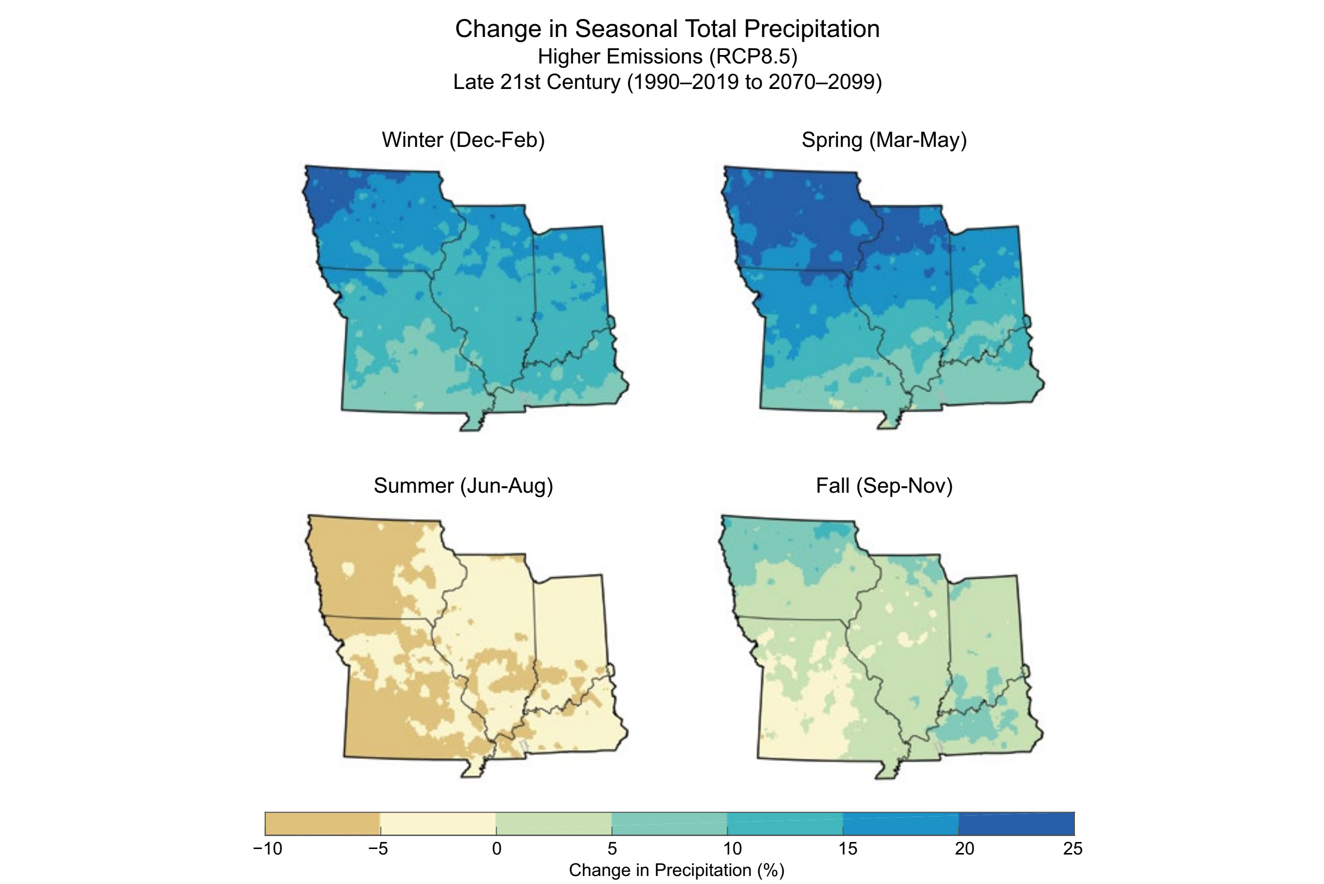

Figure 2.14 The maps show projected changes (%) in the seasonal total precipitation for late 21st century under a higher (RCP8.5) scenario for the Midwestern United States. for winter (upper left), spring (upper right), summer (lower left), and fall (lower right). All projected values are shown as changes compared with 1990–2019 averages. **Sources:** NCICS and The University of Edinburgh.

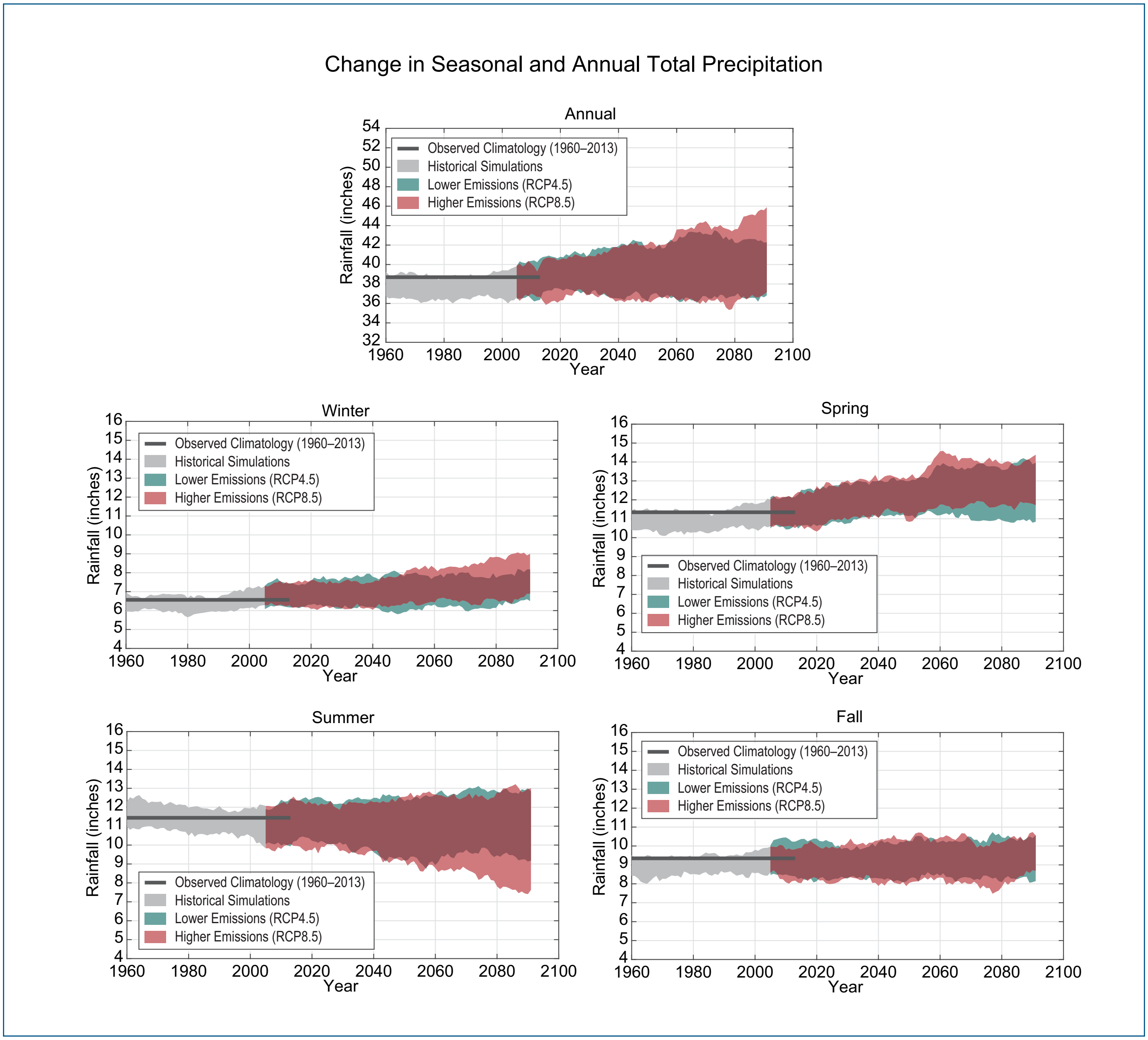

Figure 2.15 These time series (1960–2100) show the simulated historical and projected average total precipitation (inches) for the state of Illinois for annual (top panel), winter (middle left panel), spring (middle right panel, summer (lower left panel), and fall (lower right panel). The observed climatological values averaged for the period 1960–2013 are shown (black line). Historical simulations (gray shading) are shown for 1960–2005. Projected changes for 2006–2100 are shown for a higher scenario (RCP8.5; red shading) and a lower scenario (RCP4.5; teal shading). The shaded ranges indicate the 10% to 90% confidence intervals of 20-year running averages from the set of climate models.
Sources: NCICS and The University of Edinburgh.

Drought projections

Illinois' annual precipitation increased by 4.75 inches from 1895–1924 to 1990–2019. Overall, annual precipitation is expected to continue to increase in the future, with the largest increase by late century under the higher scenario, which might suggest an overall diminishing drought risk. However, there are three points of concern moving forward. First, the expected increases in temperature will drive up evapotranspiration rates throughout the year, leading to drier soils and potentially increasing demand for irrigation. Second, summer precipitation is projected to decrease, especially by late century under the higher scenario (Figure 2.14), which will likely increase the risk of short-term drought. Finally, this chapter presents strong evidence that the distribution of precipitation will change over time, with more heavy rain events and a possible increase in the maximum number of consecutive dry days. These factors suggest that drought is likely to be a concern in Illinois in some years even if annual precipitation increases as projected.

Also, many of Illinois' past droughts have been triggered by other global and interregional climate factors, highlighting the important role that broader climate interactions play in drought development beyond just the impacts that human-induced climate change is projected to have locally. For example, the droughts in the 1930s were likely caused by La Niña conditions in the Pacific Ocean, combined with the effects of poor land management practices (Cook et al. 2009). More recently, Hoerling et al. (2014) suggested that the 2012 drought was likely triggered by "a reduction in atmospheric moisture transport into the Great Plains from the Gulf of Mexico." Therefore, the risk of significant future drought in Illinois remains, despite the expected shift toward overall wetter conditions.

Snow projections

Projections of future snowfall were beyond the scope of the analysis here. However, Demaria et al. (2016) provide insights into future snowfall in the warmer, wetter winters that Illinois and the Midwest are likely to experience. They found that despite an increase in winter season (November–April) precipitation, the water content contained in the total seasonal snowfall showed a significant decline through the 21st century as a result of fewer snow days and more rain days. Meanwhile, snow cover is likely to migrate northward in the future as winter temperatures warm. The loss of snow cover will be most pronounced at the beginning and ending of the snowfall season, specifically in November, March, and April. Declines in snow cover will become more pronounced in the second half of this century, especially for the warmer RCP8.5 scenario. In fact, the results indicate a strong possibility that Illinois could be snow-free by 2100, according to Demaria et al. (2016).

Projections of extreme events

Extreme heat

Beyond an increase in mean temperature, projections also show increases in extreme temperatures across the state. Similar to annual average temperature projections, the projected changes in annual hottest 5-day maximum temperature (Figure 2.16) for Illinois show rather small spatial variations but vary substantially with time period and scenario. The annual hottest 5-day maximum temperature is projected to increase between 3.5–5.0°F for the lower scenario and 5.0–6.5°F for the higher scenario by the mid-21st century. By the late 21st century, the increases are 3.5–5.0°F for the lower scenario and 9.5–11.5°F for the higher scenario.

The temporal and regional behavior, as well as the range of model projections, are shown in Figure 2.17. By the end of the century, the annual hottest 5-day maximum temperature in northern Illinois is projected to increase from 92°F to 96–104°F under the lower scenario (RCP4.5) and to 100–110°F under the higher scenario (RCP8.5; Figure 2.17). In central Illinois, the projected increases are from 94°F to 98–106°F under the lower scenario (RCP4.5) and to 102–112°F under the higher scenario (RCP8.5; Figure 2.17). In southern Illinois, the projected increases are from 96°F to 100–107°F under the lower scenario (RCP4.5) and to 102–114°F under the higher scenario (RCP8.5; Figure 2.17).

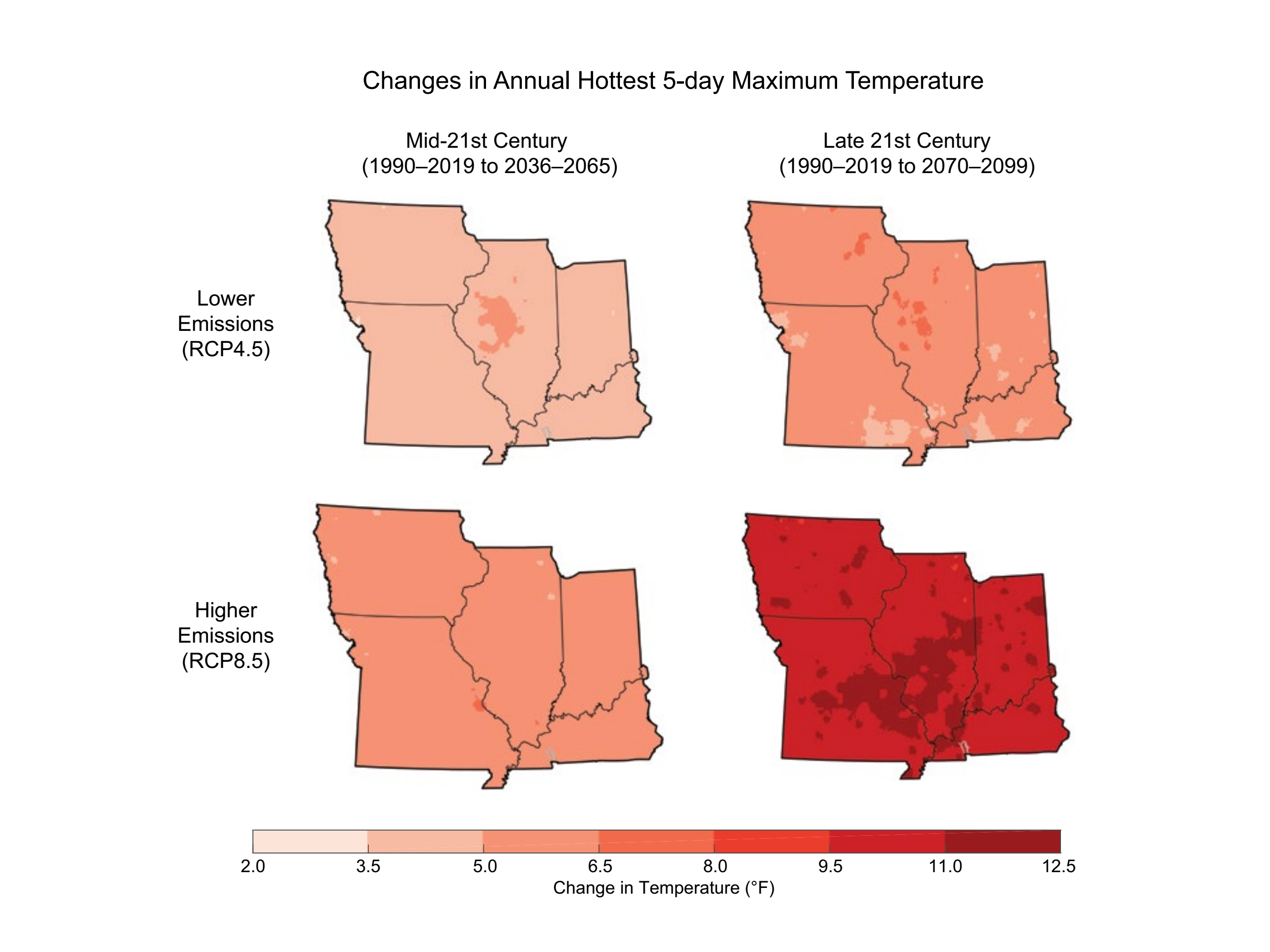

Figure 2.16 The maps show projected changes (°F) in the annual hottest 5-day maximum temperature for the mid-21st century (left column) and late 21st century (right column) under a lower (RCP4.5) scenario (top row) and a higher (RCP8.5) scenario (bottom row) for the Midwestern United States. All projected values are shown as changes compared with 1990–2019 averages. **Sources:** NCICS and The University of Edinburgh.

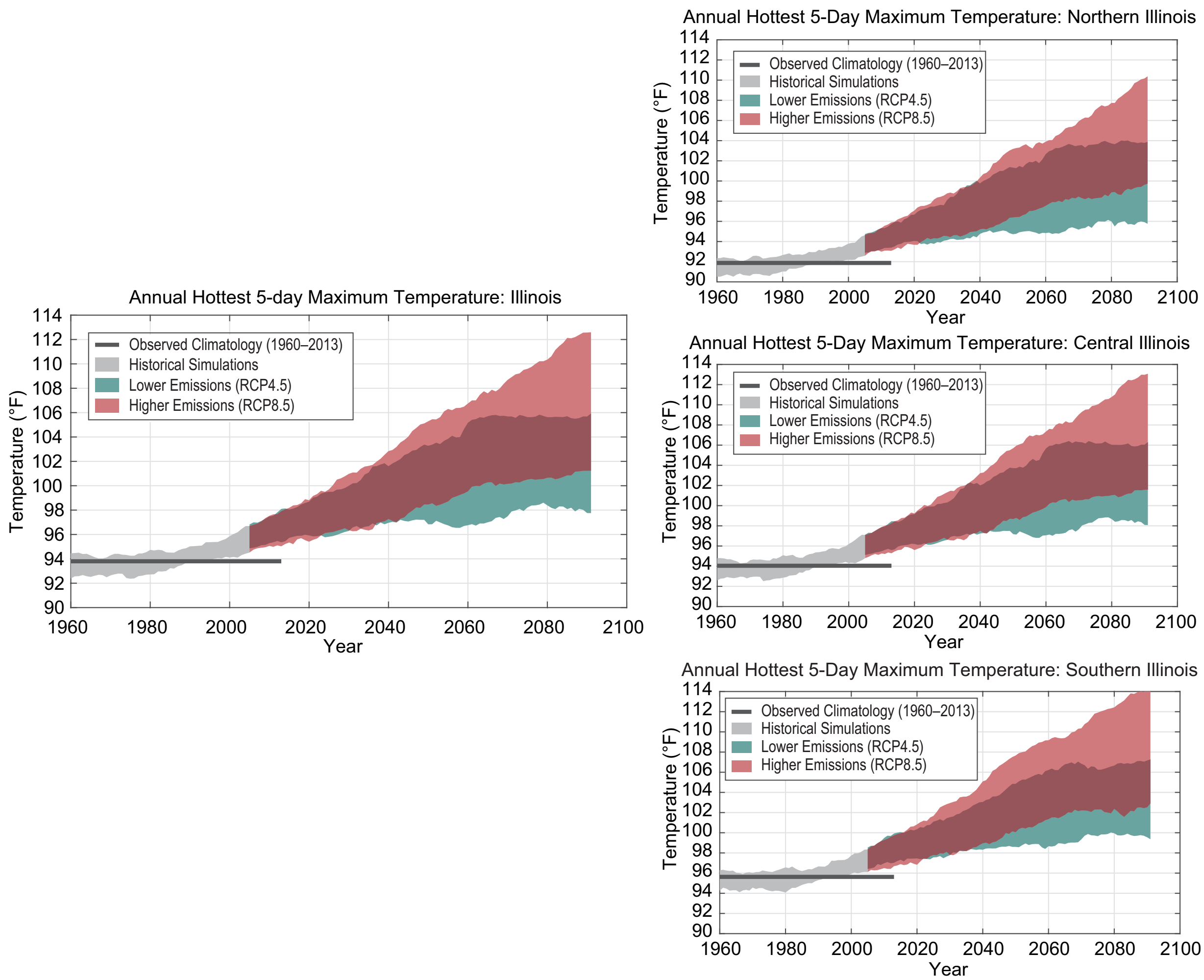

Figure 2.17 These time series (1960–2100) show the simulated historical and projected annual hottest 5-day maximum temperature (°F) for the state of Illinois (left panel), northern Illinois (upper right panel), central Illinois (middle right panel), and southern Illinois (lower right panel). The observed climatological values averaged for the period 1960–2013 are shown (black line). Historical simulations (gray shading) are shown for 1960–2005. Projected changes for 2006–2100 are shown for a higher scenario (RCP8.5; red shading) and a lower scenario (RCP4.5; teal shading). The shaded ranges indicate the 10% to 90% confidence intervals of 20-year running averages from the set of climate models.
Sources: NCICS and The University of Edinburgh.

Projections show increases in single-day extreme temperatures as well, with projected increases in the annual number of days with a daily maximum temperature of 95°F or higher (Figure 2.18). Increases in very hot days are somewhat larger in southern Illinois compared with northern Illinois; however, projections indicate increased frequency of very hot days everywhere in the state. Like average temperature projections, very hot day frequency projections also vary substantially with time period and scenario. Mid-21st century projections show 8–32 additional very hot days under the lower scenario and 8–40 additional very hot days under the higher scenario. Late 21st century projections show between 16–40 additional very hot days under the lower scenario and between 40–72 additional very hot days under the higher scenario.

The temporal and regional behavior, as well as the range of model projections, are shown in Figure 2.19. By the end of the century, the number of days with a daily maximum temperature of 95°F or higher in northern Illinois is projected to increase from fewer than 5 days to 15–60 days under the lower scenario (RCP4.5) and to 25–90 days under the higher scenario (RCP8.5; Figure 2.19). In central Illinois, the projected increases are from fewer than 10 days to 20–80 days under the lower scenario (RCP4.5) and to 30–110 days under the higher scenario (RCP8.5; Figure 2.19). In southern Illinois, the projected increases are from fewer than 15 days to 30–80 days under the lower scenario (RCP4.5) and to 50–120 days under the higher scenario (RCP8.5; Figure 2.19).

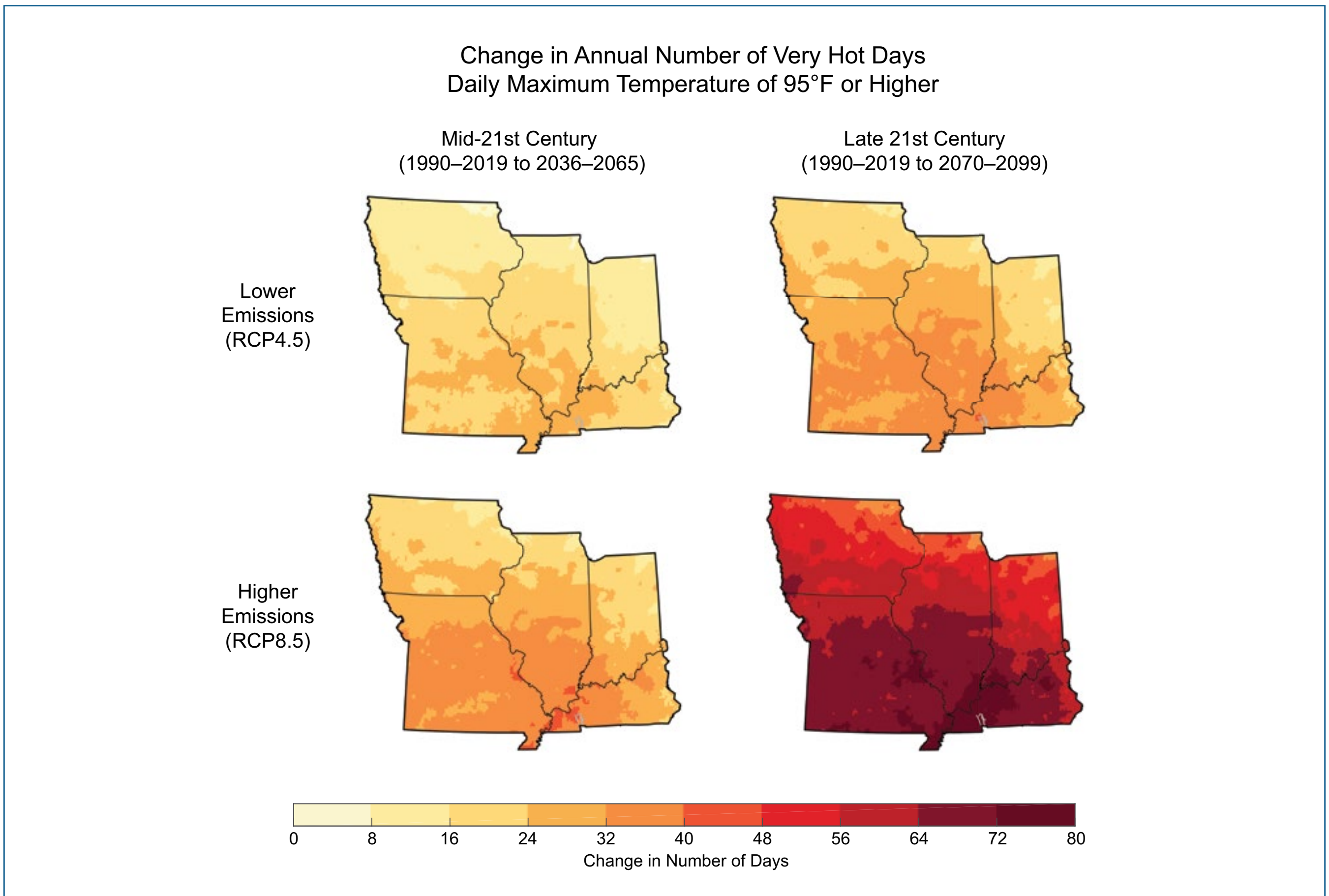

Figure 2.18 The maps show projected changes in the number of very hot days (maximum temperature of 95°F or higher) for the mid-21st century (left column) and late 21st century (right column) under a lower (RCP4.5) scenario (top row) and a higher (RCP8.5) scenario (bottom row) for the Midwestern United States. All projected values are shown as changes compared with 1990–2019 averages. **Sources:** NCICS and The University of Edinburgh.

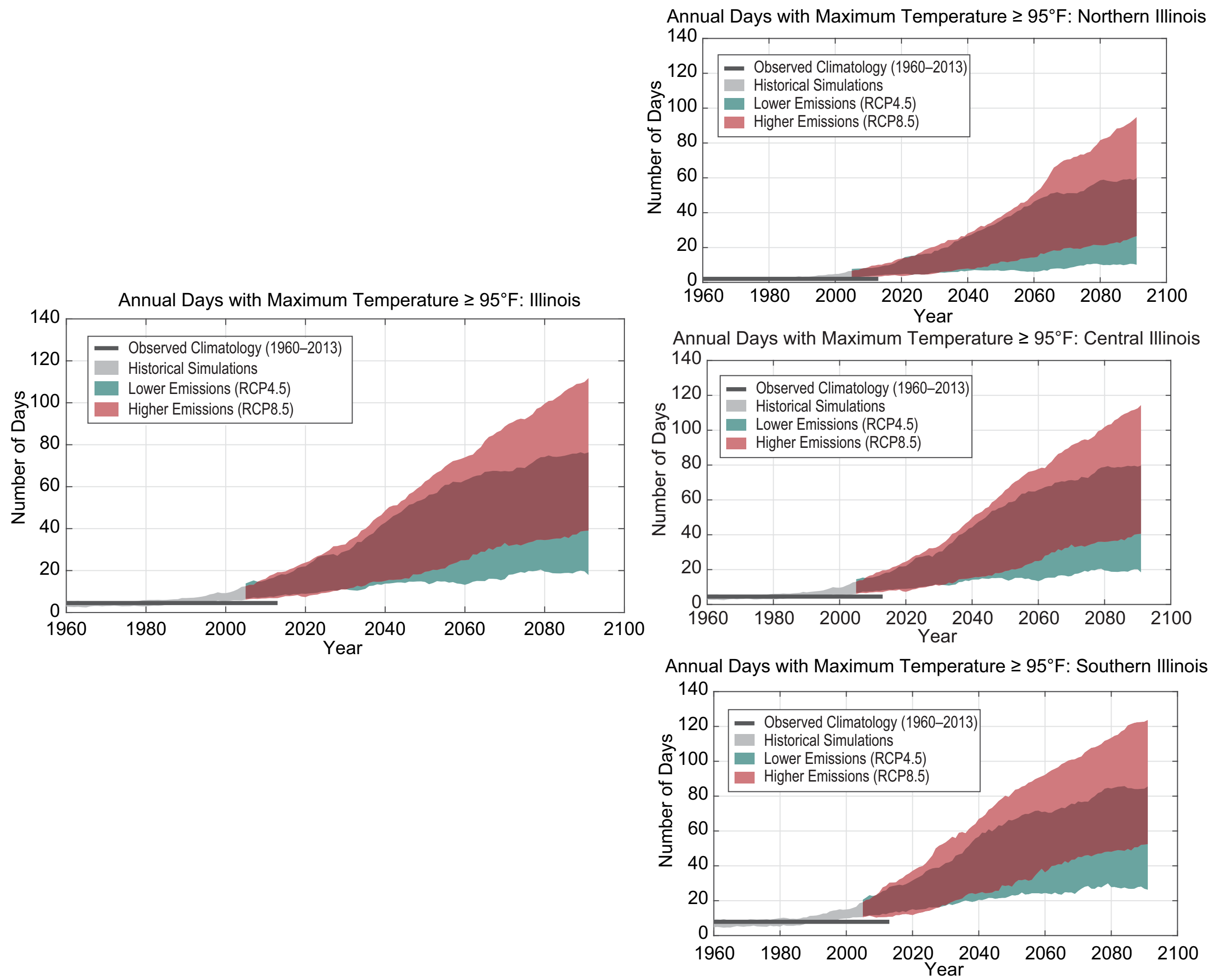

Figure 2.19 These time series (1960–2100) show the simulated historical and projected annual number of days with daily maximum temperature of 95°F or higher for the state of Illinois (left panel), northern Illinois (upper right panel), central Illinois (middle right panel), and southern Illinois (lower right panel). The observed climatological values averaged for the period 1960–2013 are shown (black line). Historical simulations (gray shading) are shown for 1960–2005. Projected changes for 2006–2100 are shown for a higher scenario (RCP8.5; red shading) and a lower scenario (RCP4.5; teal shading). The shaded ranges indicate the 10% to 90% confidence intervals of 20-year running averages from the set of climate models. **Sources:** NCICS and The University of Edinburgh.

Projections also show increases in the annual number of days with a daily maximum temperature of 100°F or higher (Figure 2.20). Mid-21st century projections show 0–12 additional extremely hot days under the lower scenario and 6–18 additional extremely hot days under the higher scenario. Late-21st century projections show between 6 and 18 additional extremely hot days under the lower scenario and between 18 and 48 additional extremely hot days under the higher scenario.

Increases in extremely hot days are somewhat larger in southern Illinois than in northern Illinois, although increases are projected everywhere in the state. The temporal and regional behavior, as well as the range of model projections, are shown in Figure 2.21. By the end of the century, the number of days with a daily maximum temperature of 100°F or higher in northern Illinois is projected to increase from less than 1 day to 1–25 days under the lower scenario (RCP4.5) and to 5–65 days under the higher scenario (RCP8.5; Figure 2.21). In central Illinois, the projected increases are from less than 1 day to 5–40 days under the lower scenario (RCP4.5) and to 13–90 days under the higher scenario (RCP8.5; Figure 2.21). In southern Illinois, the projected increases are from less than 1 day to 5–55 days under the lower scenario (RCP4.5) and to 15–100 days under the higher scenario (RCP8.5; Figure 2.21).

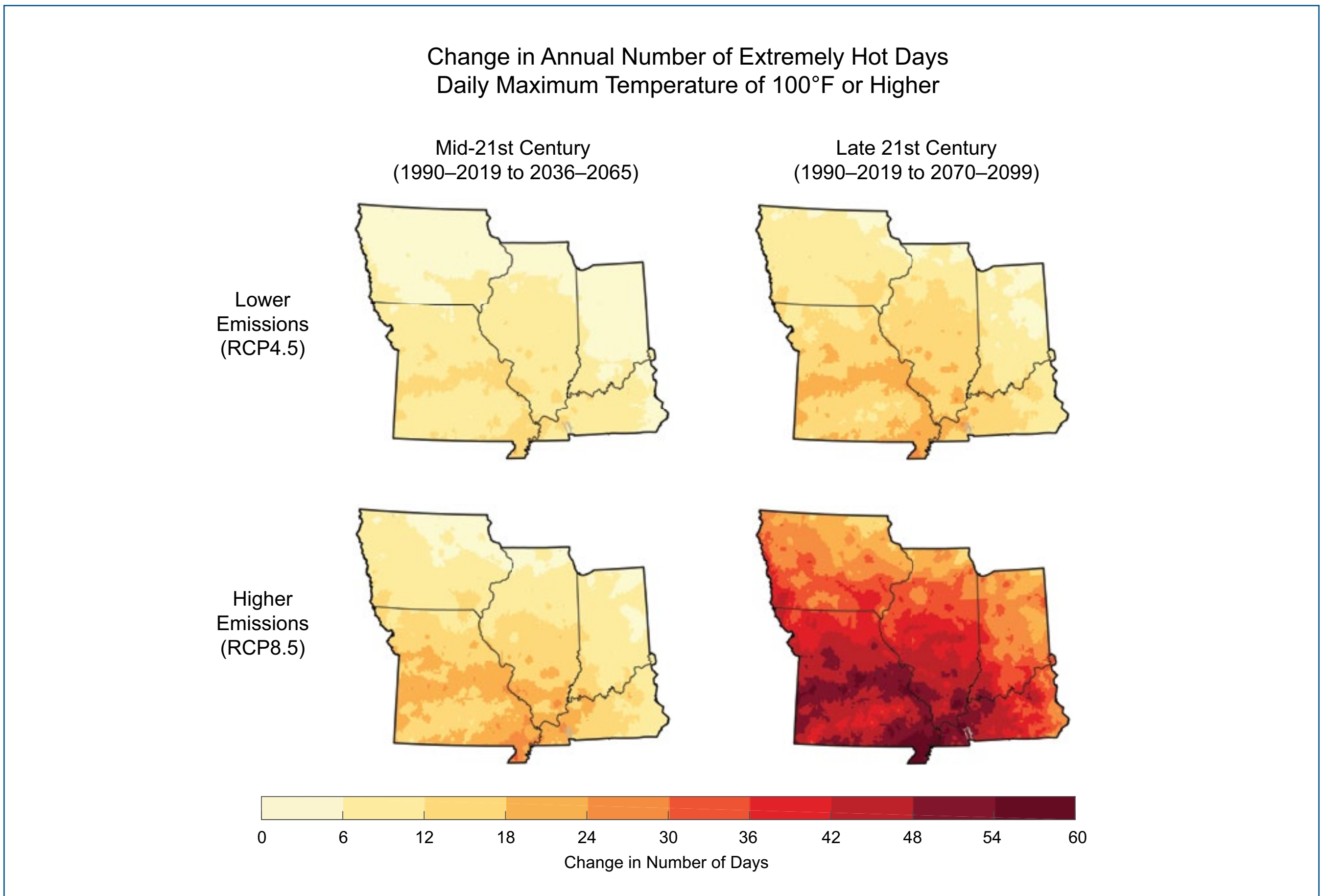

Figure 2.20 The maps show projected changes in the number of extremely hot days (maximum temperature of 100°F or higher) for mid-21st century (left column) and late 21st century (right column) under a lower (RCP4.5) scenario (top row) and a higher (RCP8.5) scenario (bottom row) for the Midwestern United States. All projected values are shown as changes compared with 1990–2019 averages. **Sources:** NCICS and The University of Edinburgh.

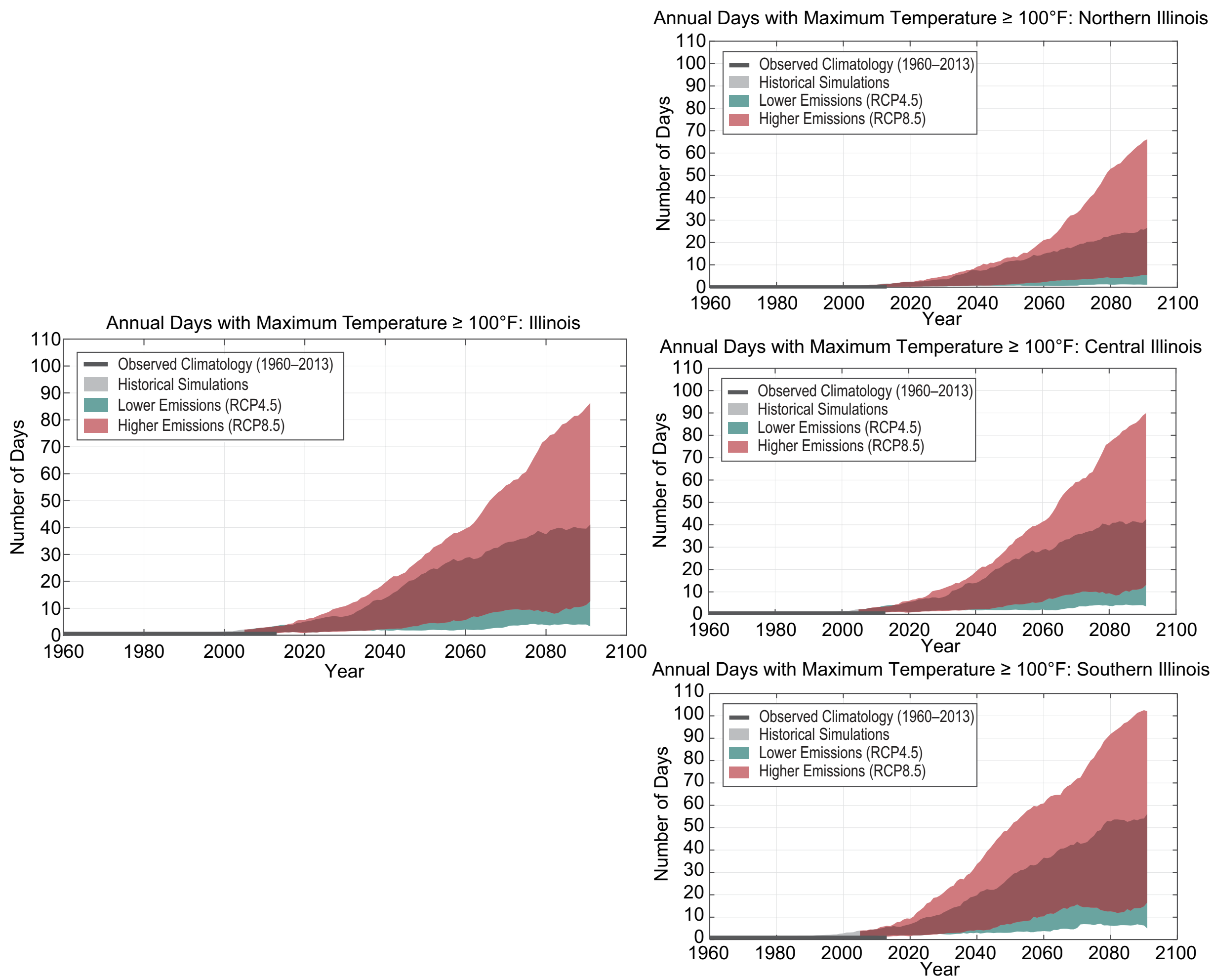

Figure 2.21 These time series (1960–2100) show the simulated historical and projected annual number of days with a daily maximum temperature of 100°F or higher for the state of Illinois (left panel), northern Illinois (upper right panel), central Illinois (middle right panel), and southern Illinois (lower right panel). The observed climatological values averaged for the period 1960–2013 are shown (black line). Historical simulations (gray shading) are shown for 1960–2005. Projected changes for 2006–2100 are shown for a higher scenario (RCP8.5; red shading) and a lower scenario (RCP4.5; teal shading). The shaded ranges indicate the 10% to 90% confidence intervals of 20-year running averages from the set of climate models. **Sources:** NCICS and The University of Edinburgh.

The annual frequency of warm nights, with a nighttime minimum temperature of 70°F or higher, is also projected to increase (Figure 2.22). For the mid-21st century, the increases are about 16–32 days for the lower scenario and 16–40 days for the higher scenario. For the late 21st century, the increases are 16–40 days for the lower scenario and 40–72 days for the higher scenario.

Consistent with other temperature trends for Illinois, somewhat larger increases in warm nights are projected for the south compared with the north. The temporal and regional behavior, as well as the range of model projections, are shown in Figure 2.23.

By the end of the century, the number of days with a daily minimum temperature of 70°F or higher in northern Illinois is projected to increase from 10 days to 20–60 days under the lower scenario (RCP4.5) and to 45–95 days under the higher scenario (RCP8.5; Figure 2.23). In central Illinois, the projected increases are from 15 days to 30–75 days under the lower scenario (RCP4.5) and to 60–110 days under the higher scenario (RCP8.5; Figure 2.23). In southern Illinois, the projected increases are from 25 days to 50–85 days under the lower scenario (RCP4.5) and to 85–125 days under the higher scenario (RCP8.5; Figure 2.23).

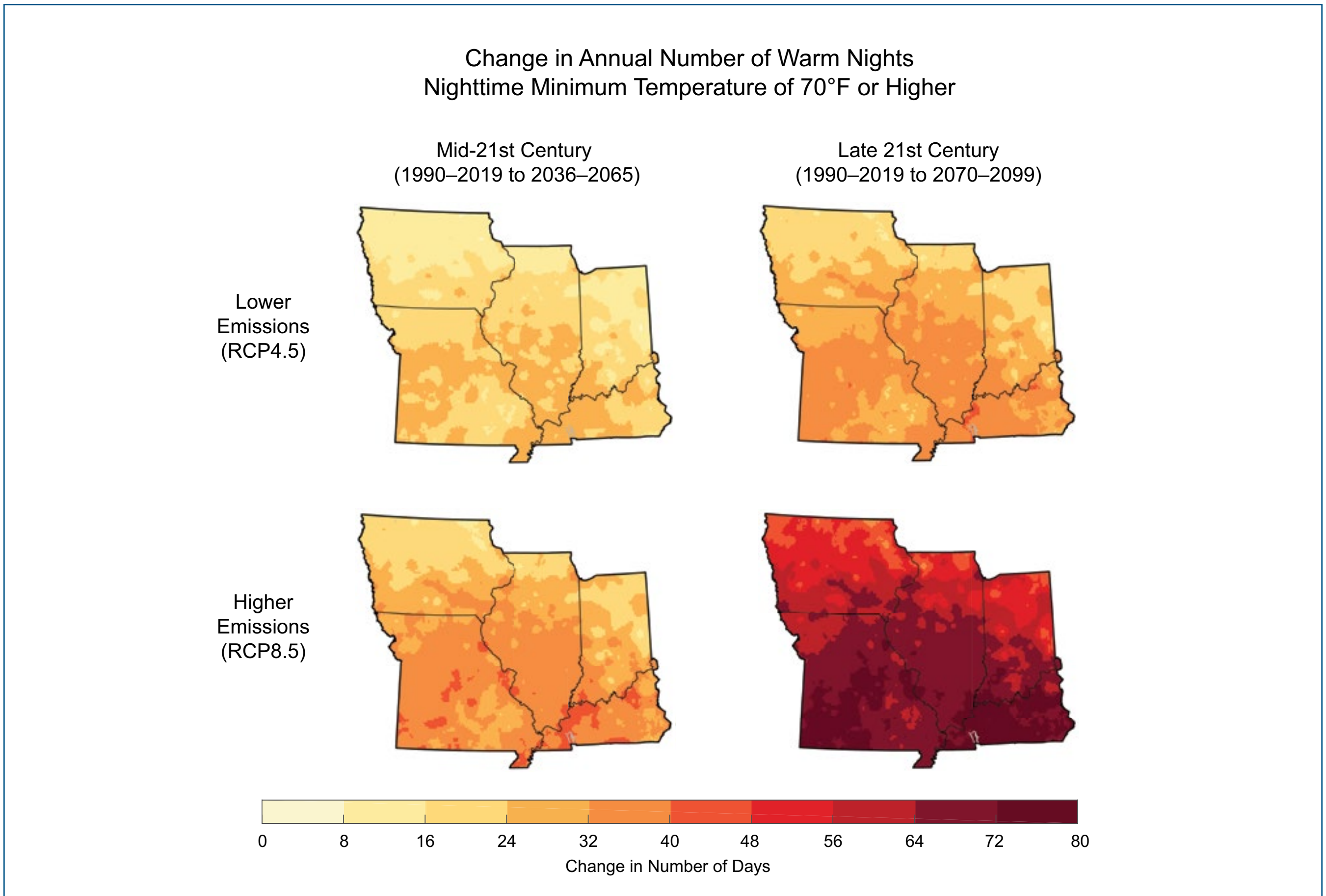

Figure 2.22 The maps show projected changes in the number of warm nights (nighttime minimum temperature of 70°F or higher) for the mid-21st century (left column) and late 21st century (right column) under a lower (RCP4.5) scenario (top row) and a higher (RCP8.5) scenario (bottom row) for the Midwestern United States. All projected values are shown as changes compared with 1990–2019 averages. **Sources:** NCICS and The University of Edinburgh.

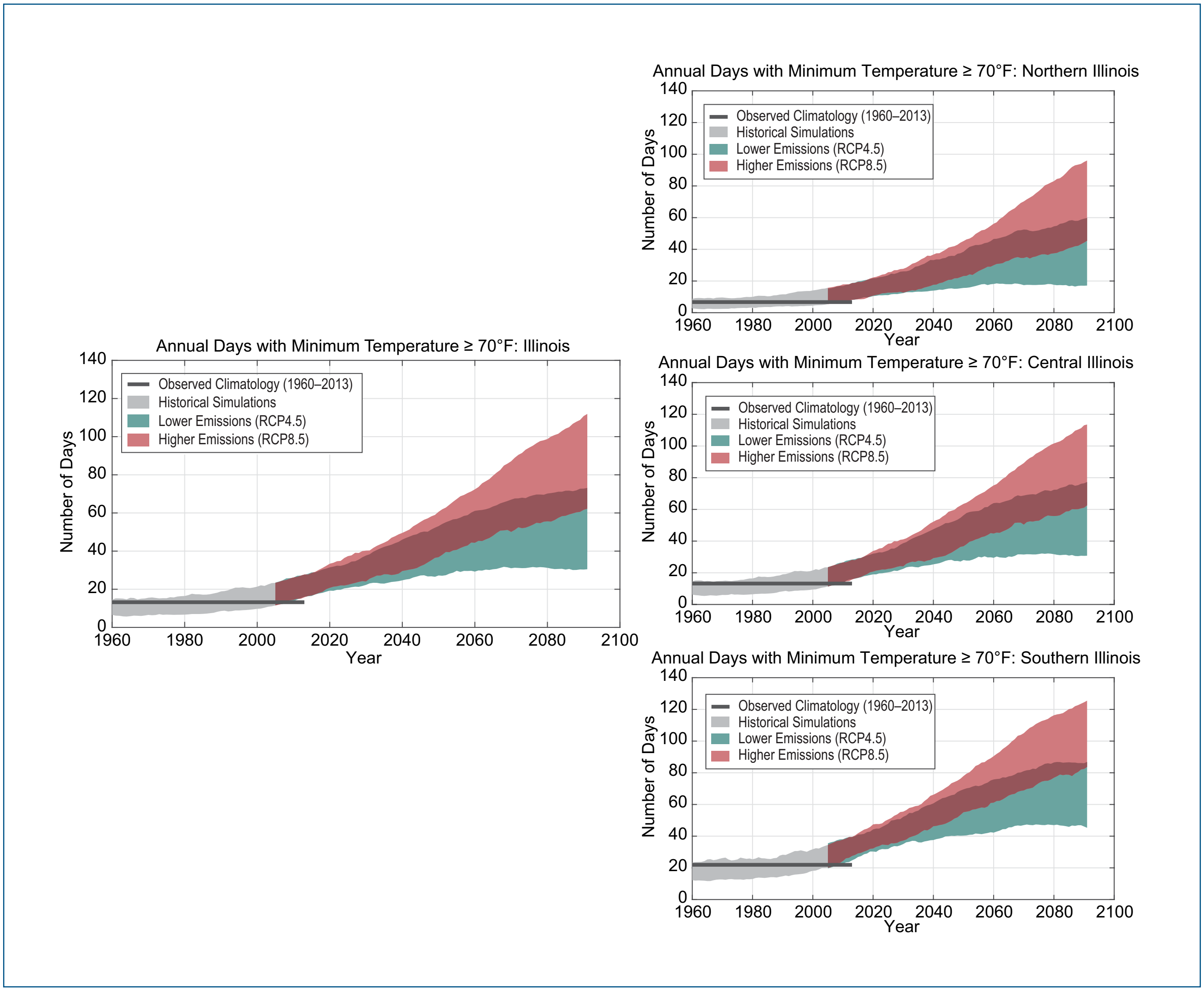

Figure 2.23 These time series (1960–2100) show the simulated historical and projected annual number of days with a daily minimum temperature of 70°F or higher for the state of Illinois (left panel), northern Illinois (upper right panel), central Illinois (middle right panel), and southern Illinois (lower right panel). The observed climatological values averaged for the period 1960–2013 are shown (black line). Historical simulations (gray shading) are shown for 1960–2005. Projected changes for 2006–2100 are shown for a higher scenario (RCP8.5; red shading) and a lower scenario (RCP4.5; teal shading). The shaded ranges indicate 10% to 90% confidence intervals of 20-year running averages from the set of climate models. **Sources:** NCICS and The University of Edinburgh.

Projections also indicate consistent increases in the annual frequency of even warmer nights, with a nighttime minimum temperature of 80°F or higher, which occur only very rarely in the current climate. For the mid-21st century, the increases are about 0–2 days for the lower scenario and 0–6 days for the higher scenario. For the late 21st century, the increases are 0–6 days for the lower scenario and 2–20 days for the higher scenario.

The temporal and regional behavior, as well as the range of model projections, are shown in Figure 2.25. By the end of the century, the number of days with a daily minimum temperature of 80°F or higher in northern Illinois is projected to increase from near zero to 0–3 days under the lower scenario (RCP4.5) and to 2–25 days under the higher scenario (RCP8.5; Figure 2.25). In central Illinois, the projected increases are from near zero to 0–6 days under the lower scenario (RCP4.5) and to 3–38 days under the higher scenario (RCP8.5; Figure 2.25). In southern Illinois, the projected increases are from near zero to 0–8 days under the lower scenario (RCP4.5) and to 7–47 days under the higher scenario (RCP8.5; Figure 2.25).

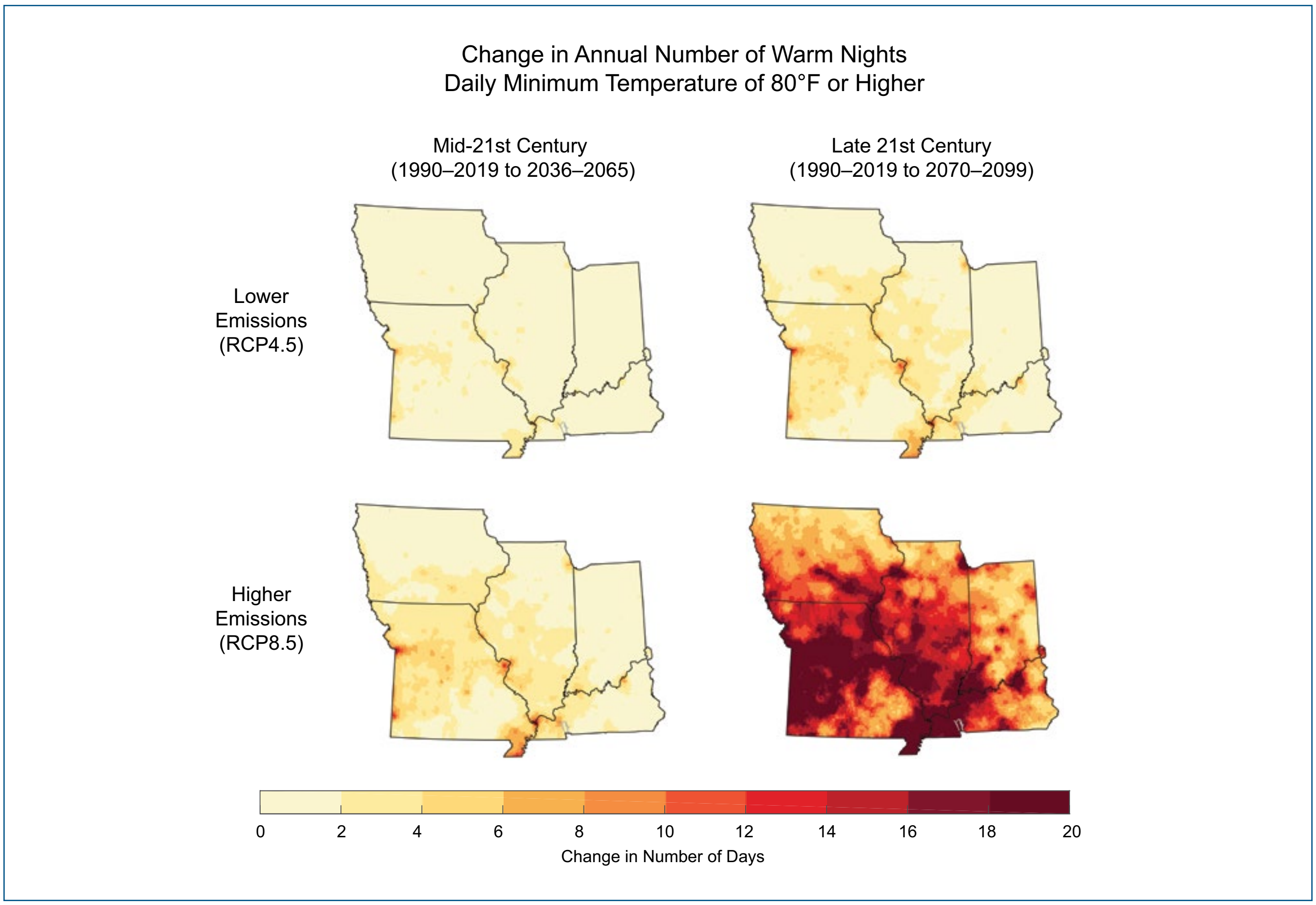

Figure 2.24 The maps show projected changes in the number of very warm nights (nighttime minimum temperature of 80°F or higher) for the mid-21st century (left column) and late 21st century (right column) under a lower (RCP4.5) scenario (top row) and a higher (RCP8.5) scenario (bottom row) for the Midwestern United States. All projected values are shown as changes compared with 1990–2019 averages. **Sources:** NCICS and The University of Edinburgh.

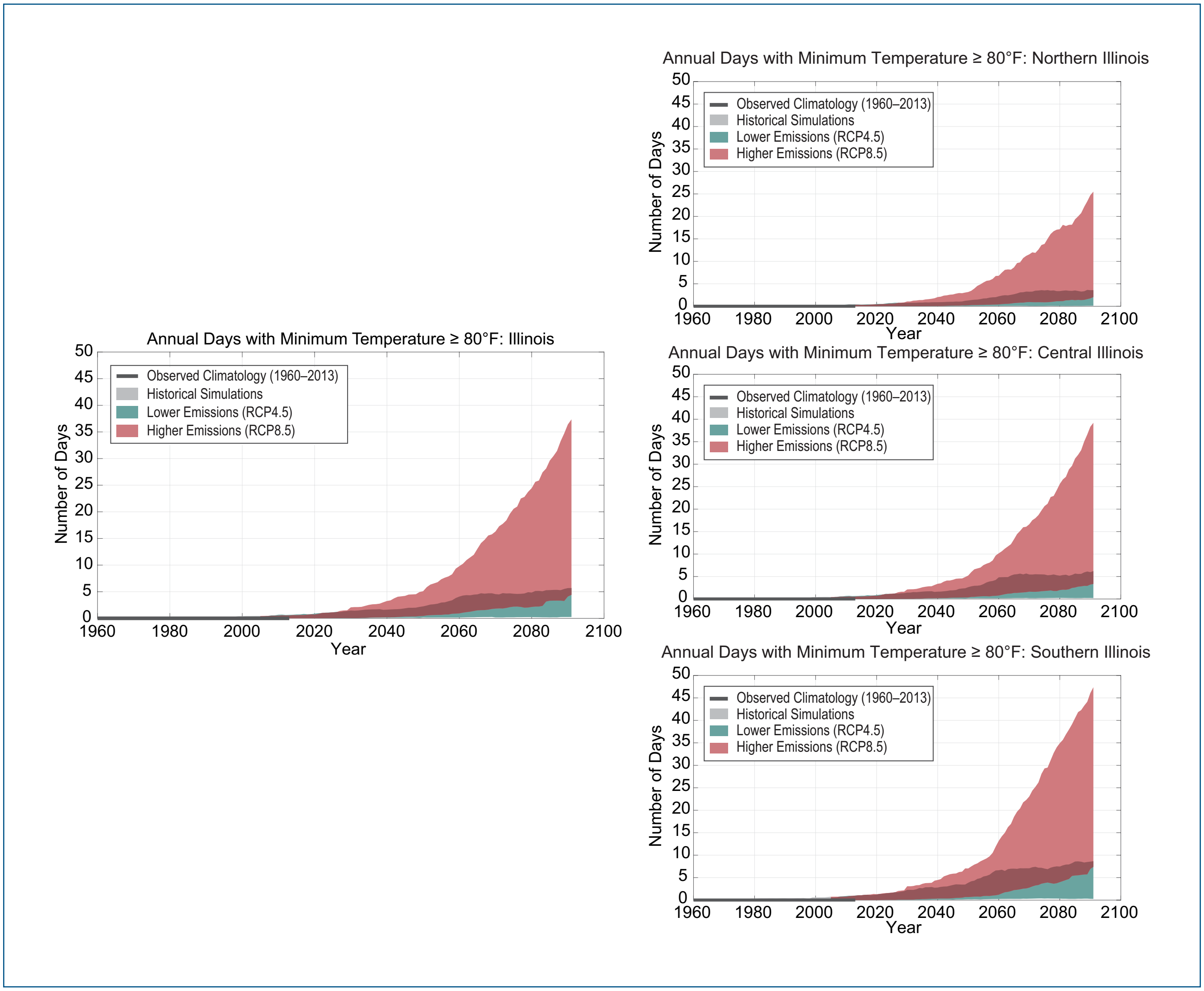

Figure 2.25 These time series (1960–2100) show the simulated historical and projected annual number of days with a daily minimum temperature of 80°F or higher for the state of Illinois (left panel), northern Illinois (upper right panel), central Illinois (middle right panel), and southern Illinois (lower right panel). The observed climatological values averaged for the period 1960–2013 are shown (black line). Historical simulations (gray shading) are shown for 1960–2005. Projected changes for 2006–2100 are shown for a higher scenario (RCP8.5; red shading) and a lower scenario (RCP4.5; teal shading). The shaded ranges indicate 10% to 90% confidence intervals of 20-year running averages from the set of climate models. **Sources:** NCICS and The University of Edinburgh.

The physiological stress of high temperature conditions on humans is exacerbated by high humidity. The effectiveness of sweating, one of the body's primary adaptive responses to high heat, is reduced because high humidity decreases the rate of evaporation of sweat, which cools the skin. The heat index is a metric that incorporates humidity and represents what the temperature "feels like," known as the apparent temperature. The National Weather Service uses this metric to issue heat alerts. In Illinois, an excessive heat warning is issued when the heat index is expected to exceed 110°F (hereafter referred to as "dangerous"), representing a high-risk situation for human health. Climate change is projected to increase the annual number of days with a daily maximum heat index of 110°F or higher across the state (Figure 2.26). Mid-21st century projections show 0–10 additional dangerous heat index days under the lower scenario and 0–20 additional dangerous heat index days under the higher scenario.

Late 21st century projections show between 0 and 20 additional dangerous heat index days under the lower scenario and between 10 and 50 additional dangerous heat index days under the higher scenario.

The temporal and regional behavior of the simulated historical heat index, as well as the range of model projections, are shown in Figure 2.27. By the end of the century, the number of days with a daily maximum heat index of 110°F or higher in northern Illinois is projected to increase from less than 1 day to 2–15 days under the lower scenario (RCP4.5) and to 10–49 days under the higher scenario (RCP8.5; Figure 2.27). In central Illinois, the projected increases are from less than 1 day to 3–25 days under the lower scenario (RCP4.5) and to 18–70 days under the higher scenario (RCP8.5; Figure 2.27). In southern Illinois, the projected increases are from about 1 day to 5–35 days under the lower scenario (RCP4.5) and to 25–88 days under the higher scenario (RCP8.5; Figure 2.27).

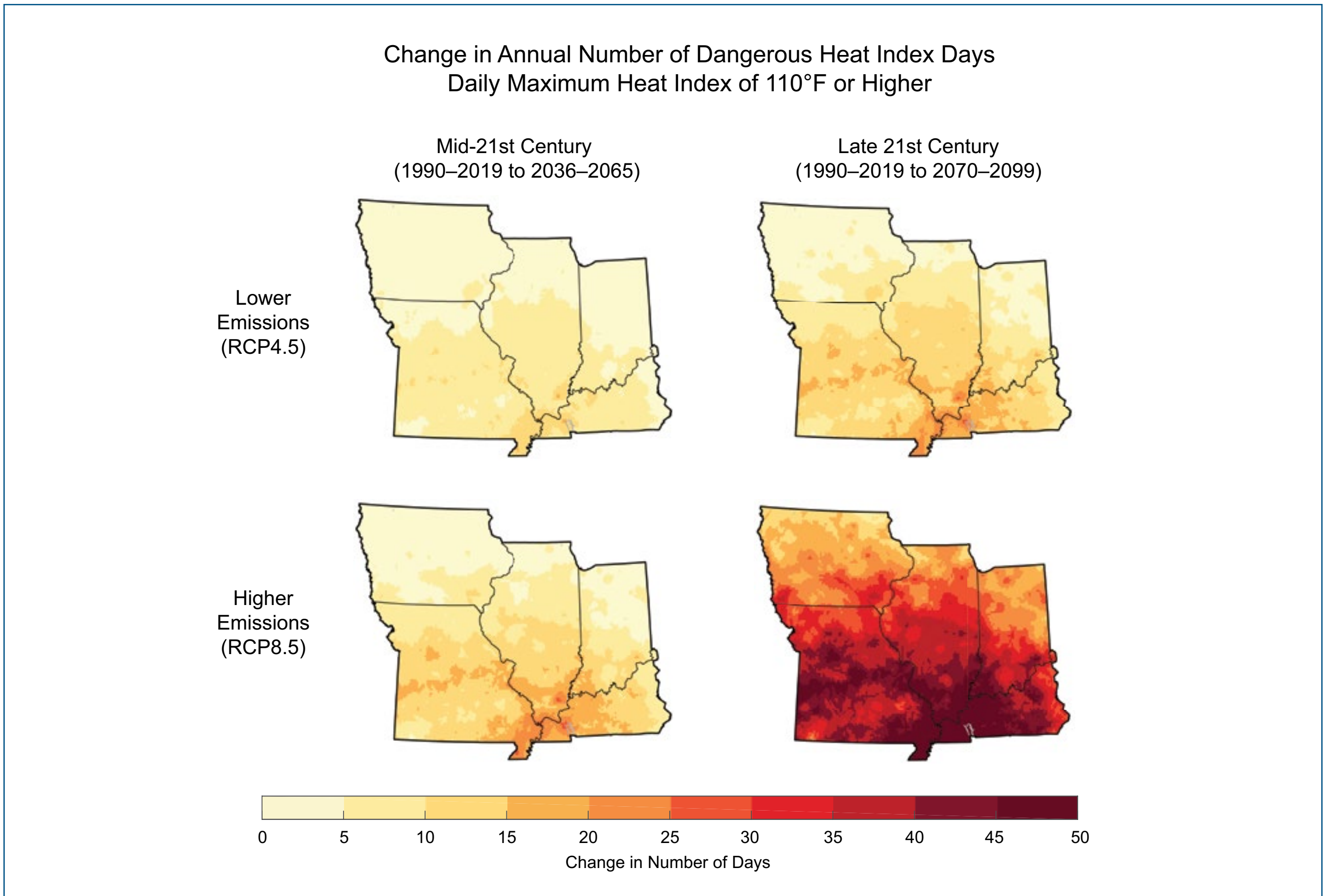

Figure 2.26 The maps show projected changes in the number of dangerous heat index days (maximum heat index of 110°F or higher) for the mid-21st century (left column) and late 21st century (right column) under a lower (RCP4.5) scenario (top row) and a higher (RCP8.5) scenario (bottom row) for the Midwestern United States. All projected values are shown as changes compared with 1990–2019 averages. **Sources:** NCICS and The University of Edinburgh.

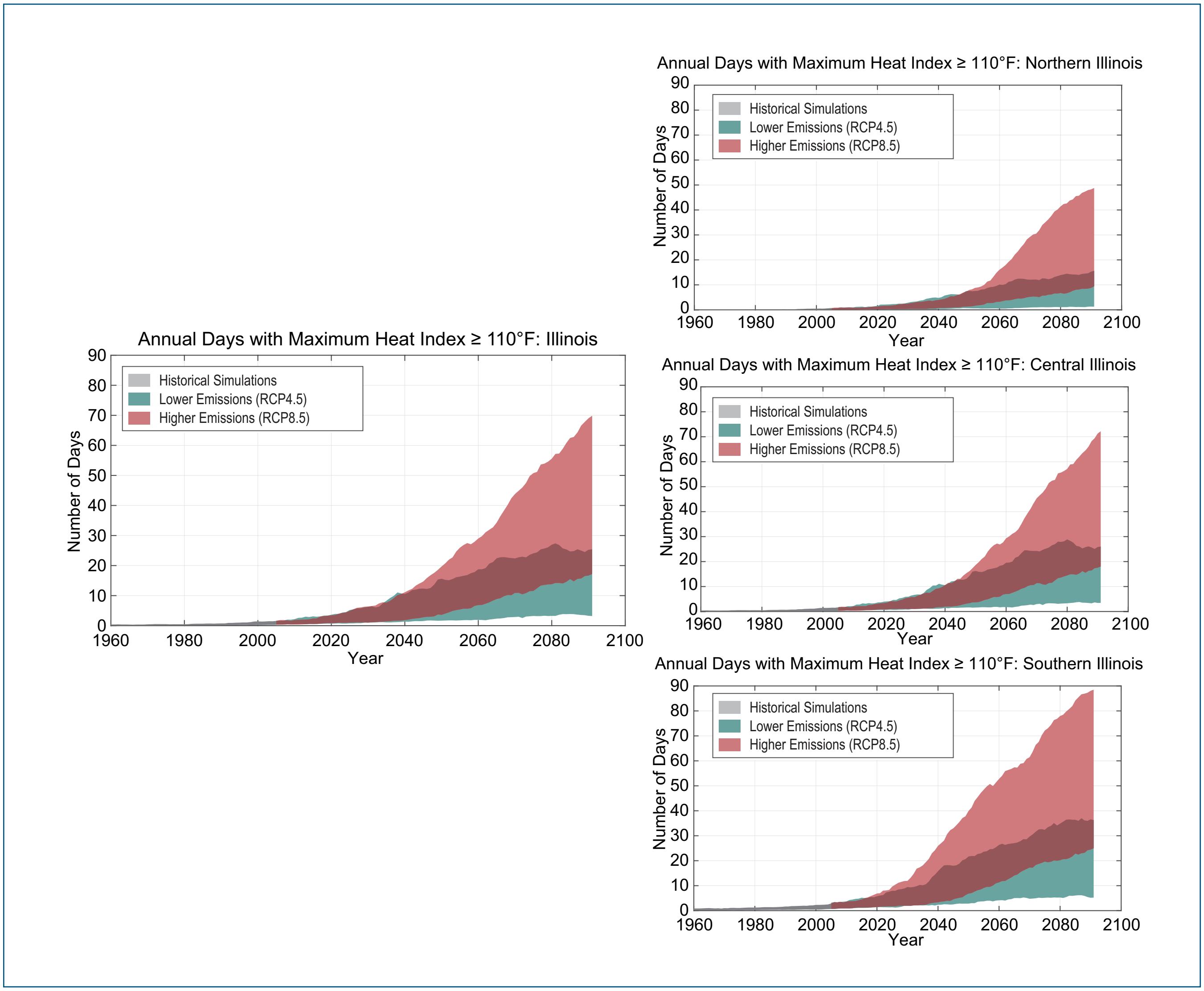

Figure 2.27 These time series (1960–2100) show the simulated historical and projected annual number of days with daily maximum heat index of 110°F or higher for the state of Illinois (left panel), northern Illinois (upper right panel), central Illinois (middle right panel), and southern Illinois (lower right panel). Historical simulations (gray shading) are shown for 1960–2005. Projected changes for 2006–2100 are shown for a higher scenario (RCP8.5; red shading) and a lower scenario (RCP4.5; teal shading). The shaded ranges indicate the 10% to 90% confidence intervals of 20-year running averages from the set of climate models. **Sources:** NCICS and The University of Edinburgh.

Similar to the annual warmest 5-day maximum temperatures, projections show a warming of the annual coldest 5-day minimum temperature (Figure 2.28). For mid-21st century, the increases are about 4–8°F for the lower scenario and 4–10°F for the higher scenario. For the late 21st century, the increases are 6–10°F for the lower scenario and 10–16°F for the higher scenario.

The projected changes in annual coldest 5-day minimum temperature for Illinois show more warming in the north than in the south. The temporal and regional behavior, as well as the range of model projections, are shown in Figure 2.29. By the end of the century, the annual coldest 5-day minimum temperature in northern Illinois is projected to increase from -6°F to 0–10°F under the lower scenario (RCP4.5) and to 7–17°F under the higher scenario (RCP8.5; Figure 2.29). In central Illinois, the projected increases are from -2°F to 5–12°F under the lower scenario (RCP4.5) and to 10–20°F under the higher scenario (RCP8.5; Figure 2.29). In southern Illinois, the projected increases are from 5°F to 10–17°F under the lower scenario (RCP4.5) and to 15–22°F under the higher scenario (RCP8.5; Figure 2.29).

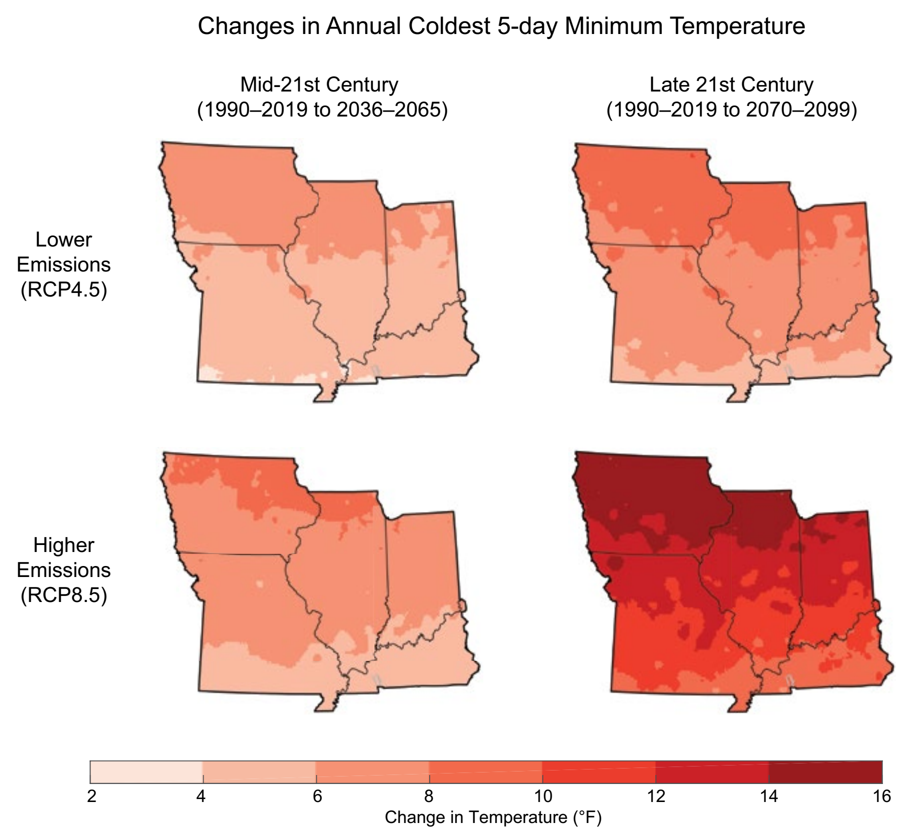

Figure 2.28 The maps show projected changes (°F) in the annual coldest 5-day minimum temperature for the mid-21st century (left column) and late 21st century (right column) under a lower (RCP4.5) scenario (top row) and a higher (RCP8.5) scenario (bottom row) for the Midwestern United States. All projected values are shown as changes compared with 1990–2019 averages. **Sources:** NCICS and The University of Edinburgh.

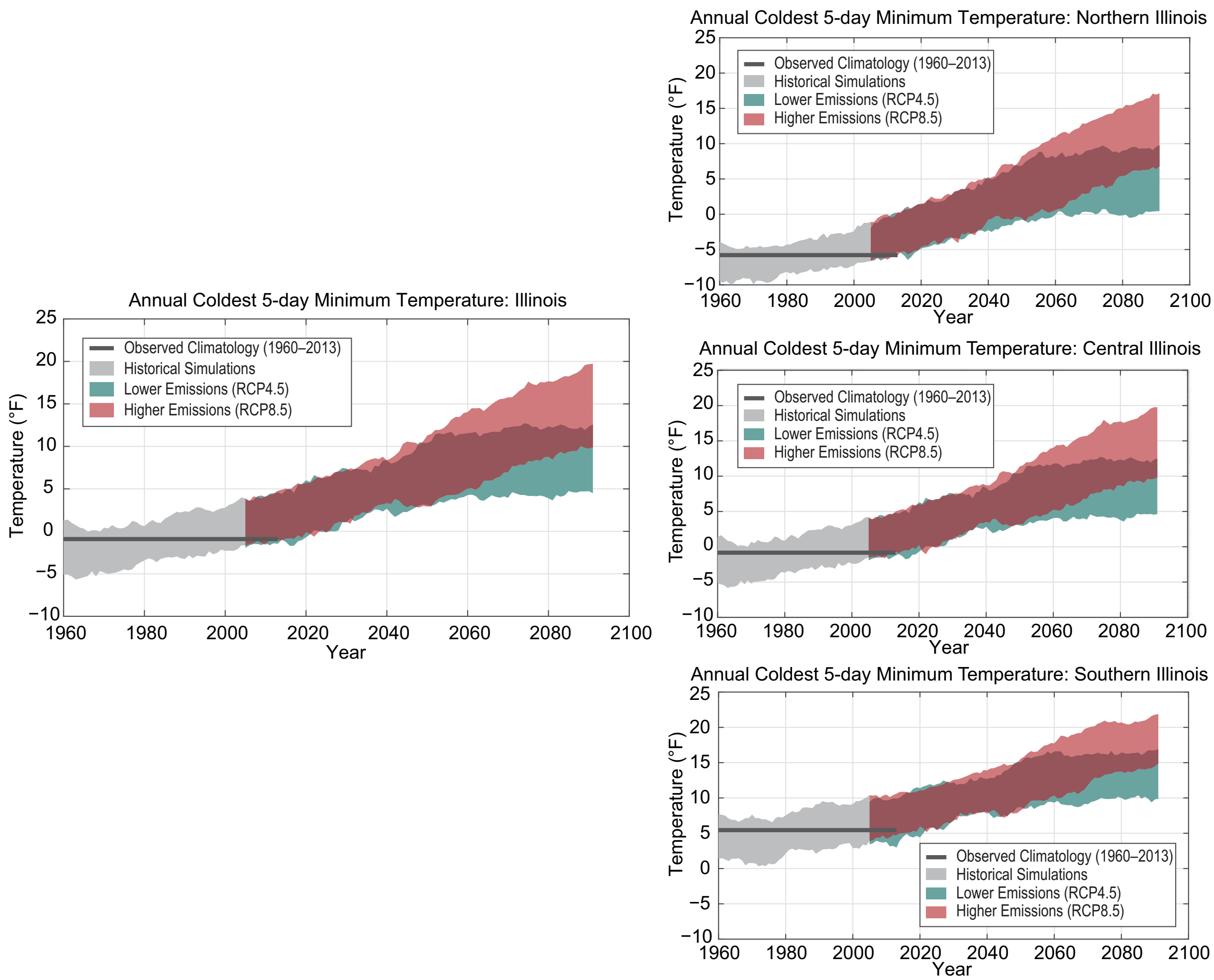

Figure 2.29 These time series (1960–2100) show the simulated historical and projected annual coldest 5-day minimum temperature (°F) for the state of Illinois (left panel), northern Illinois (upper right panel), central Illinois (middle right panel), and southern Illinois (lower right panel). The observed climatological values averaged for the period 1960–2013 are shown (black line). Historical simulations (gray shading) are shown for 1960–2005. Projected changes for 2006–2100 are shown for a higher scenario (RCP8.5; red shading) and a lower scenario (RCP4.5; teal shading). The shaded ranges indicate the 10% to 90% confidence intervals of 20-year running averages from the set of climate models.
Sources: NCICS and The University of Edinburgh.

The frequency of cold nights, with a nighttime minimum temperature of 32°F or lower, is projected to decrease (Figure 2.30). Mid-21st century projections show 15–20 fewer cold nights in the lower scenario, and 15–25 fewer cold nights in the higher scenario. Late-21st century projections show 20–25 fewer cold nights and 35–50 fewer cold nights in the lower and higher scenarios, respectively.

The projections for Illinois show rather small spatial variations, although there are somewhat larger decreases in the frequency of cold nights in the north than in the south by the end of the 21st century under the higher scenario. The temporal and regional behavior, as well as the range of model projections, are shown in Figure 2.31. By the end of the century, the number of days with a nighttime minimum temperature of 32°F or lower in northern Illinois is projected to decrease from 135 days to 95–120 days under the lower scenario (RCP4.5) and to 60–100 days under the higher scenario (RCP8.5; Figure 2.31). In central Illinois, the projected decreases are from 115 days to 80-100 days under the lower scenario (RCP4.5) and to 50–85 days under the higher scenario (RCP8.5; Figure 2.31). In southern Illinois, the projected decreases are from 90 days to 60–75 days under the lower scenario (RCP4.5) and to 40–60 days under the higher scenario (RCP8.5; Figure 2.31).

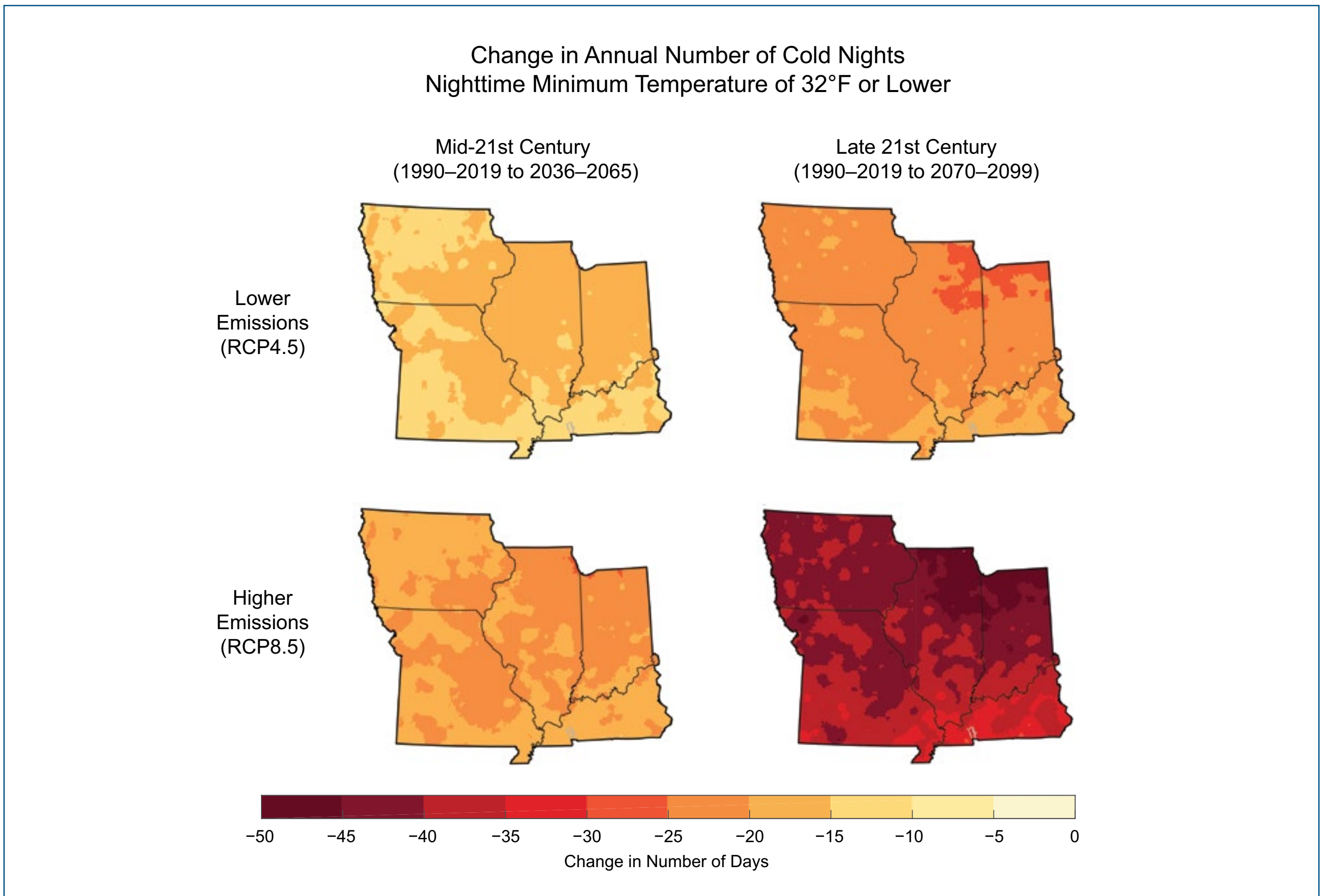

Figure 2.30 The maps show projected changes in the number of cold nights (minimum temperature of 32°F or lower) for the mid-21st century (left column) and late 21st century (right column) under a lower (RCP4.5) scenario (top row) and a higher (RCP8.5) scenario (bottom row) for the Midwestern United States. All projected values are shown as changes compared with 1990–2019 averages. **Sources:** NCICS and The University of Edinburgh.

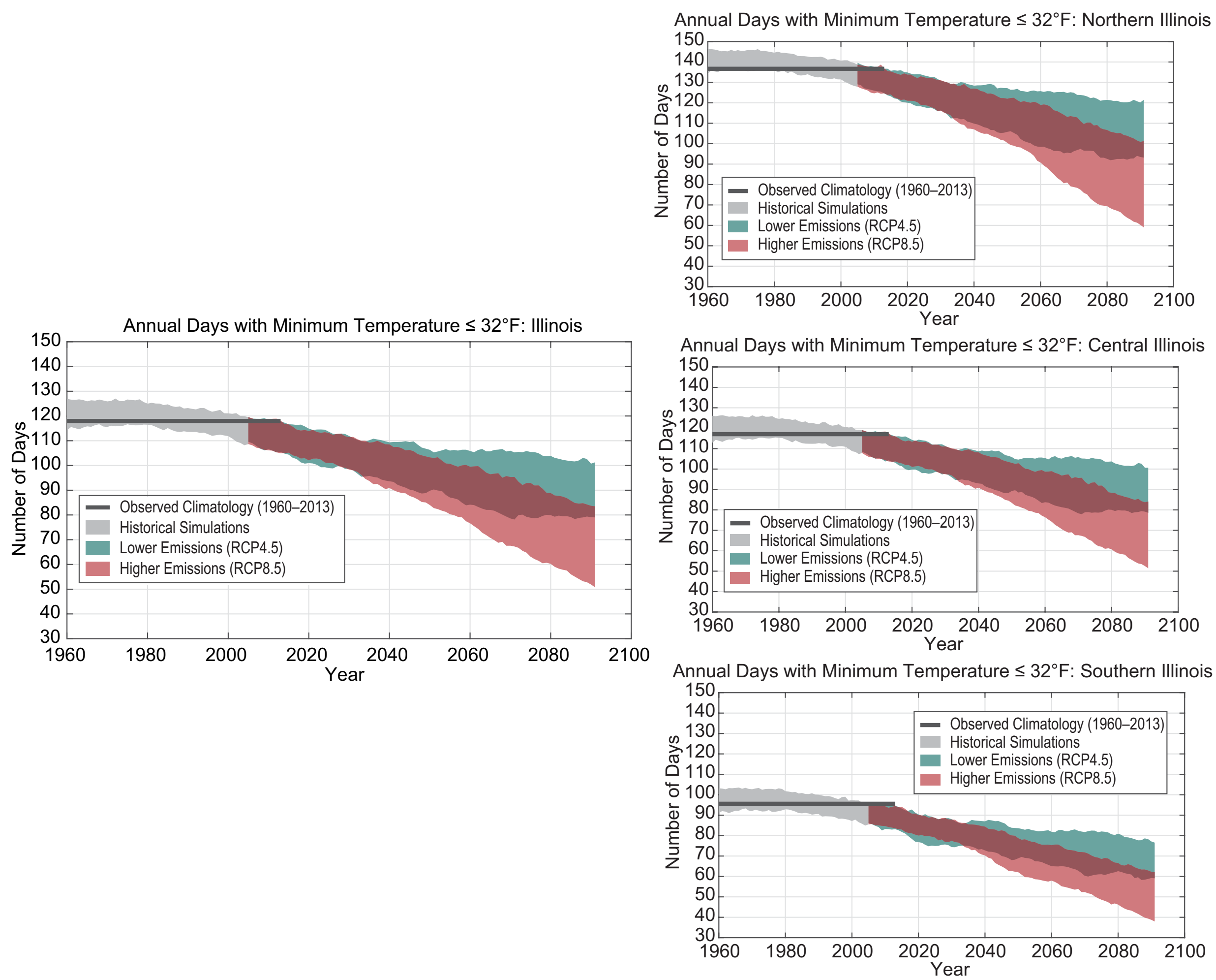

Figure 2.31 These time series (1960–2100) show the simulated historical and projected annual number of days with a daily minimum temperature of 32°F or lower for the state of Illinois (left panel), northern Illinois (upper right panel), central Illinois (middle right panel), and southern Illinois (lower right panel). The observed climatological values averaged for the period 1960–2013 are shown (black line). Historical simulations (gray shading) are shown for 1960–2005. Projected changes for 2006–2100 are shown for a higher scenario (RCP8.5; red shading) and a lower scenario (RCP4.5; teal shading). The shaded ranges indicate 10% to 90% confidence intervals of 20-year running averages from the set of climate models. **Sources:** NCICS and The University of Edinburgh.

Extreme precipitation

The projected changes in the number of days with precipitation of 2 inches or greater for Illinois show an increase everywhere (Figure 2.32). As with extreme temperature, the increase in precipitation varies substantially with time period and emissions scenario. Mid-21st century projections show a 0–60% increase under the lower scenario, and a 30–90% increase under the higher scenario. Late-21st century projections show a 0–60% increase and a 60–150% increase in the lower and higher scenarios, respectively.

The temporal and regional behavior, as well as the range of model projections, are shown in Figure 2.33. By the end of the century, the number of days with precipitation of 2 inches or greater in northern and central Illinois is projected to increase from 0.4 days to 0.3–0.6 days under the lower scenario (RCP4.5) and to 0.4–0.9 days under the higher scenario (RCP8.5; Fig 2.33). In southern Illinois, the projected increases are from 0.7 days to 0.6–1.1 days under the lower scenario (RCP4.5) and to 0.8–1.5 days under the higher scenario (RCP8.5; Fig 2.33).

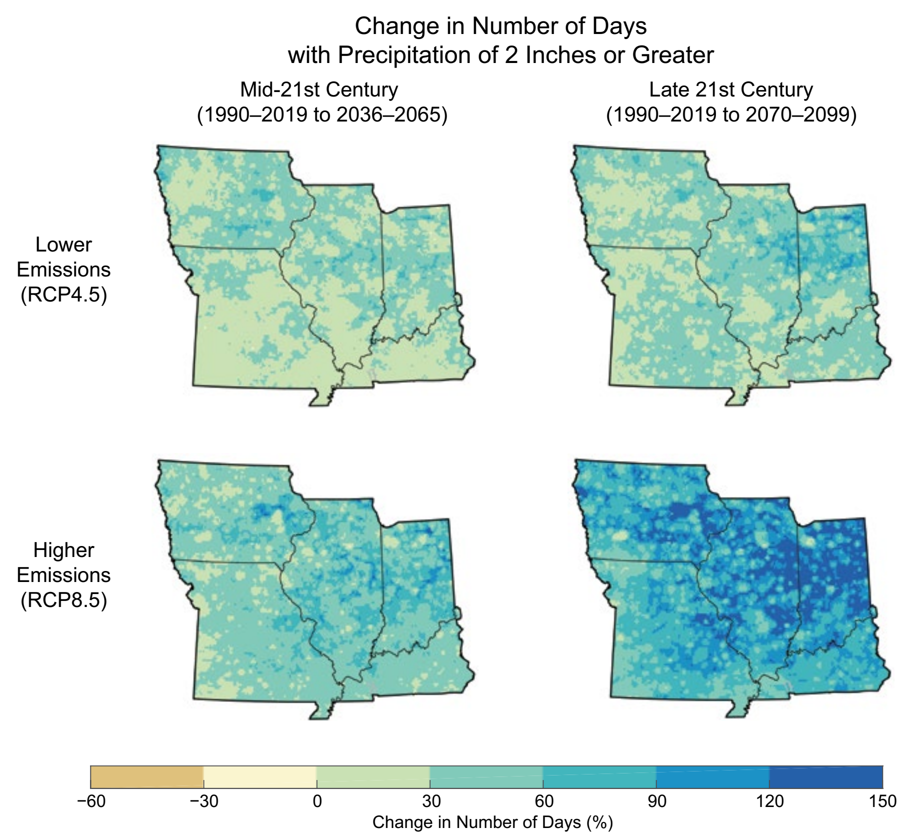

Figure 2.32 The maps show projected changes in the number of days with precipitation of 2 inches or greater for the mid-21st century (left column) and late 21st century (right column) under a lower (RCP4.5) scenario (top row) and a higher (RCP8.5) scenario (bottom row) for the Midwestern United States. All projected values are shown as changes compared with 1990–2019 averages. **Sources:** NCICS and The University of Edinburgh.

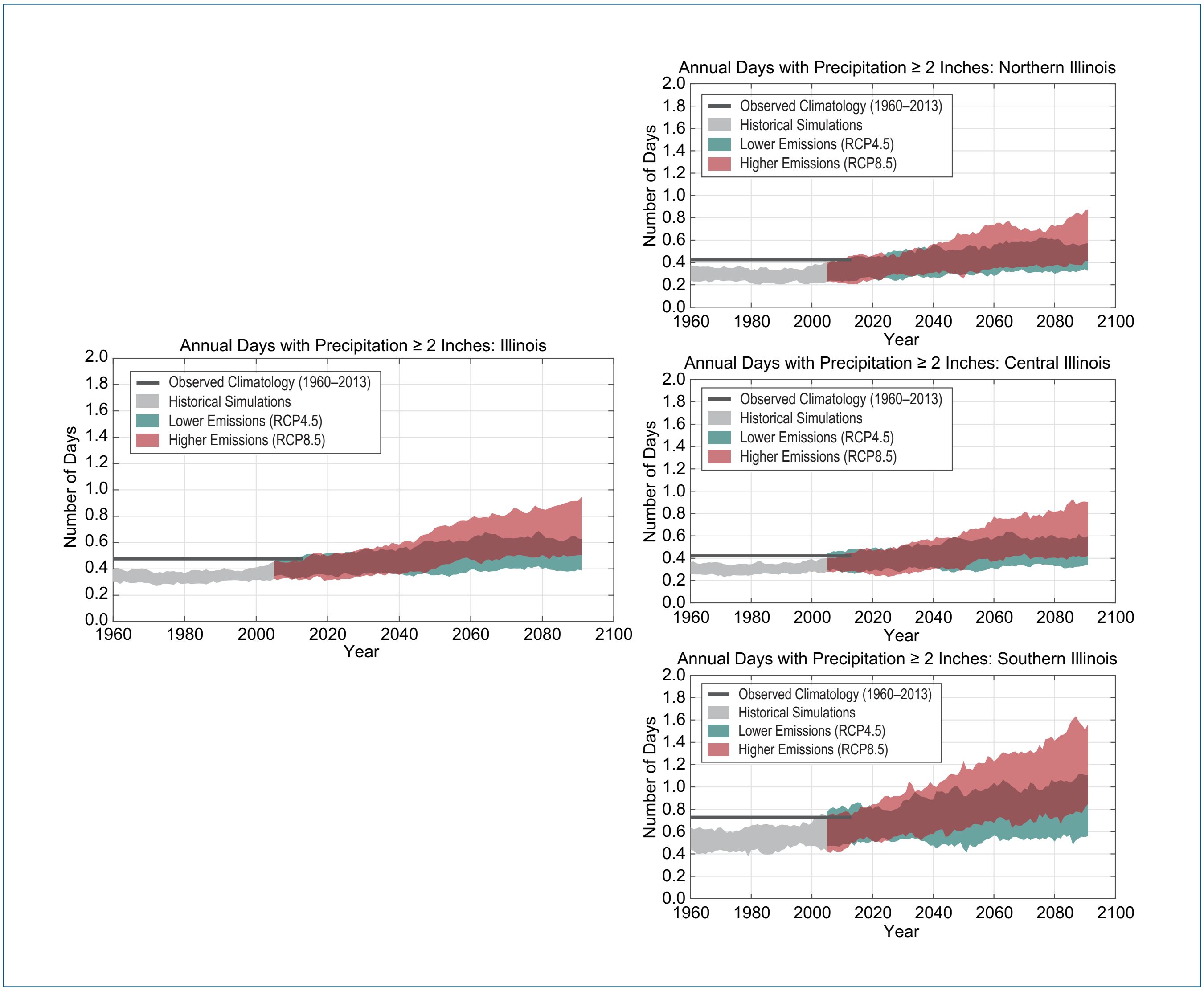

Figure 2.33 These time series (1960–2100) show the simulated historical and projected annual number of days with precipitation of 2 inches or greater for the state of Illinois (left panel), northern Illinois (upper right panel), central Illinois (middle right panel), and southern Illinois (lower right panel). The observed climatological values averaged for the period 1960–2013 are shown (black line). Historical simulations (gray shading) are shown for 1960–2005. Projected changes for 2006–2100 are shown for a higher scenario (RCP8.5; red shading) and a lower scenario (RCP4.5; teal shading). The shaded ranges indicate 10% to 90% confidence intervals of 20-year running averages from the set of climate models. **Sources:** NCICS and The University of Edinburgh.

The projected changes in the average length of the annual maximum number of consecutive dry days for Illinois show increases in the length of dry spells with rather small spatial variations (Figure 2.34). For the mid-21st century, the increase is small, less than 1 day on average for the lower scenario and around 1 day for the higher scenario. For the late 21st century, the increases are around 1 day for the lower scenario and 1–2 days for the higher scenario.

The temporal and regional behavior, as well as the range of model projections, are shown in Figure 2.35. By the end of the century, the average length of the annual maximum number of consecutive dry days in northern Illinois is projected to increase from 12–14 days to 13–16 days under the lower scenario (RCP4.5) and to 13–17 days under the higher scenario (RCP8.5; Figure 2.35). In central Illinois, the projected increases are from 13–15 days to 13–17 days under the lower scenario (RCP4.5) and to 13–18 days under the higher scenario (RCP8.5; Figure 2.35). In southern Illinois, the projected increases are from 14–16 days to 14–18 days under the lower scenario (RCP4.5) and to 14–20 days under the higher scenario (RCP8.5; Figure 2.35).

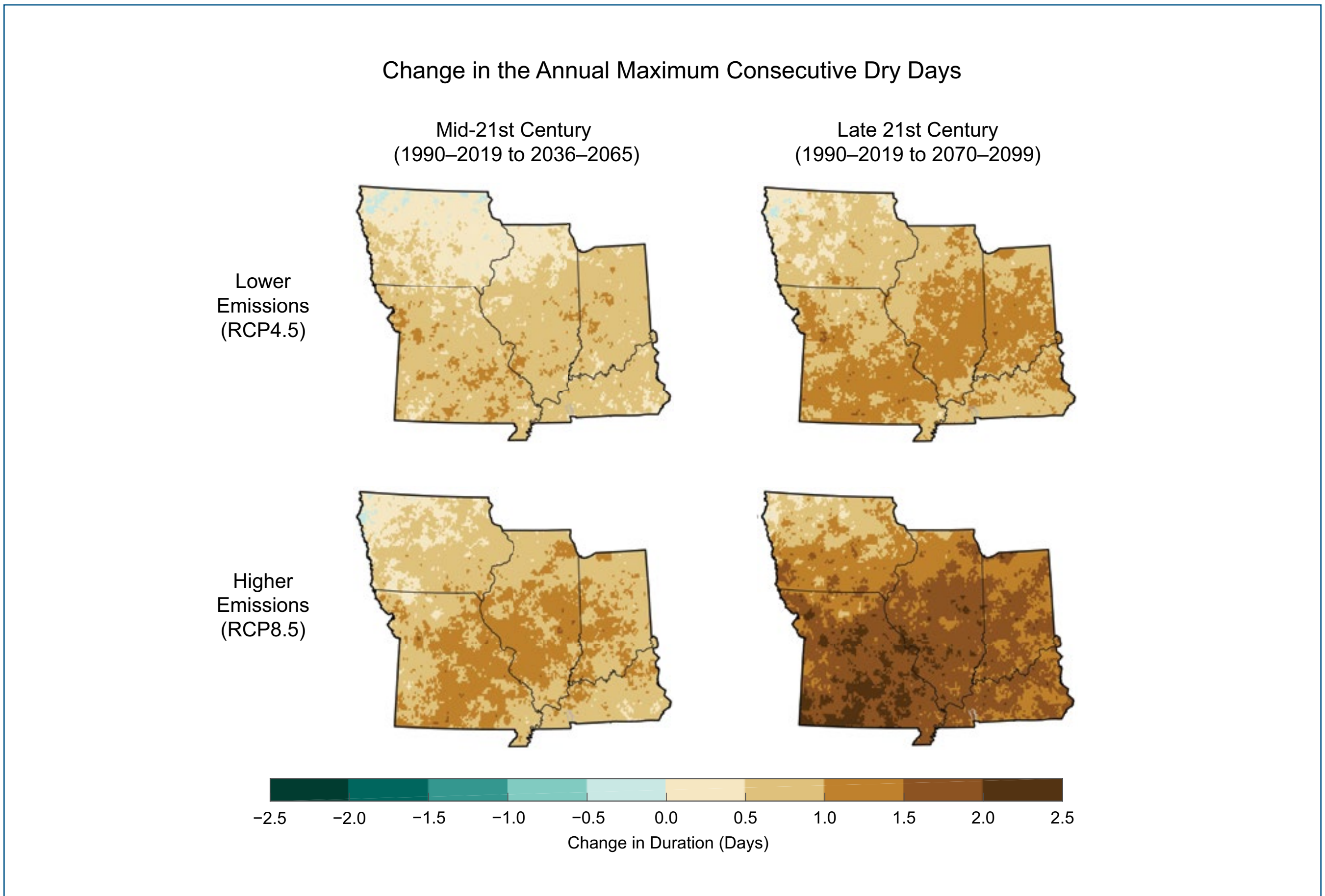

Figure 2.34 The maps show projected changes in the annual maximum number of consecutive dry days for the mid-21st century (left column) and late 21st century (right column) under a lower (RCP4.5) scenario (top row) and a higher (RCP8.5) scenario (bottom row) for the Midwestern United States. All projected values are shown as changes compared with 1990–2019 averages. **Sources:** NCICS and The University of Edinburgh.

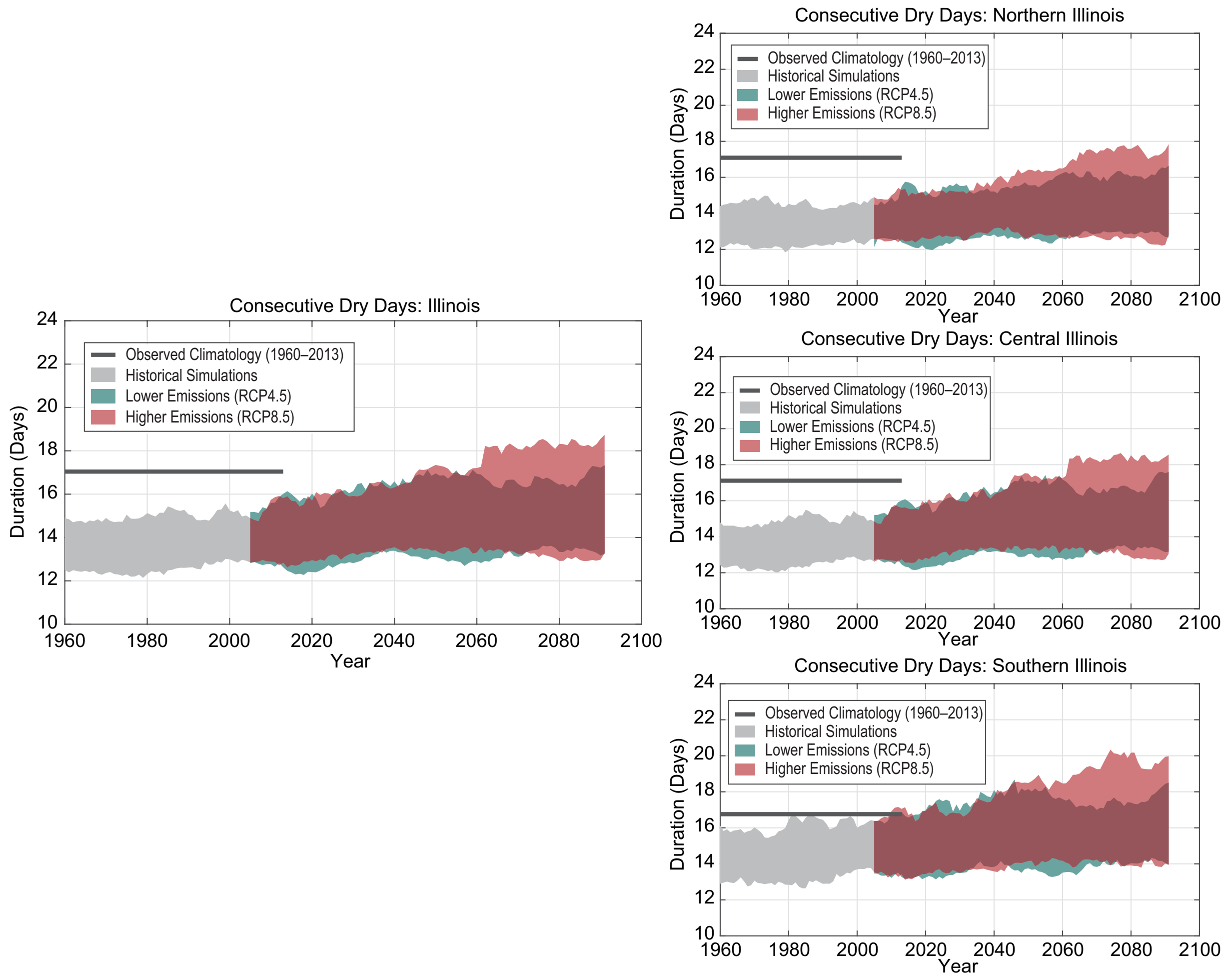

Figure 2.35 These time series (1960–2100) show the simulated historical and projected annual maximum number of consecutive dry days for the state of Illinois (left panel), northern Illinois (upper right panel), central Illinois (middle right panel), and southern Illinois (lower right panel). The observed climatological values averaged for the period 1960–2013 are shown (black line). Historical simulations (gray shading) are shown for 1960–2005. Projected changes for 2006–2100 are shown for a higher scenario (RCP8.5; red shading) and a lower scenario (RCP4.5; teal shading). The shaded ranges indicate 10% to 90% confidence intervals of 20-year running averages from the set of climate models.
Sources: NCICS and The University of Edinburgh.

Projections of variables important to agriculture

Length of the freeze-free season

The projected changes for Illinois show increases in the average length of the freeze-free season with small spatial variations (Figure 2.36). The increases vary substantially with time period and scenario. For the mid-21st century, the increases are about 10–15 days for the lower scenario and around 15–20 days for the higher scenario. For the late 21st century, the increases are around 15–20 days for the lower scenario and 30–45 days for the higher scenario, with somewhat greater increases in northern Illinois.

The temporal and regional behavior, as well as the range of model projections, are shown in Figure 2.37. By the end of the century, the average length of the freeze-free season in northern Illinois is projected to increase from 160 days to 170–200 days under the lower scenario (RCP4.5) and to 190–220 days under the higher scenario (RCP8.5; Figure 2.37). In central Illinois, the projected increases are from 175 days to 180–210 days under the lower scenario (RCP4.5) and to 200–235 days under the higher scenario (RCP8.5; Figure 2.37). In southern Illinois, the projected increases are from 190 days to 200–225 days under the lower scenario (RCP4.5) and to 215–250 days under the higher scenario (RCP8.5; Figure 2.37).

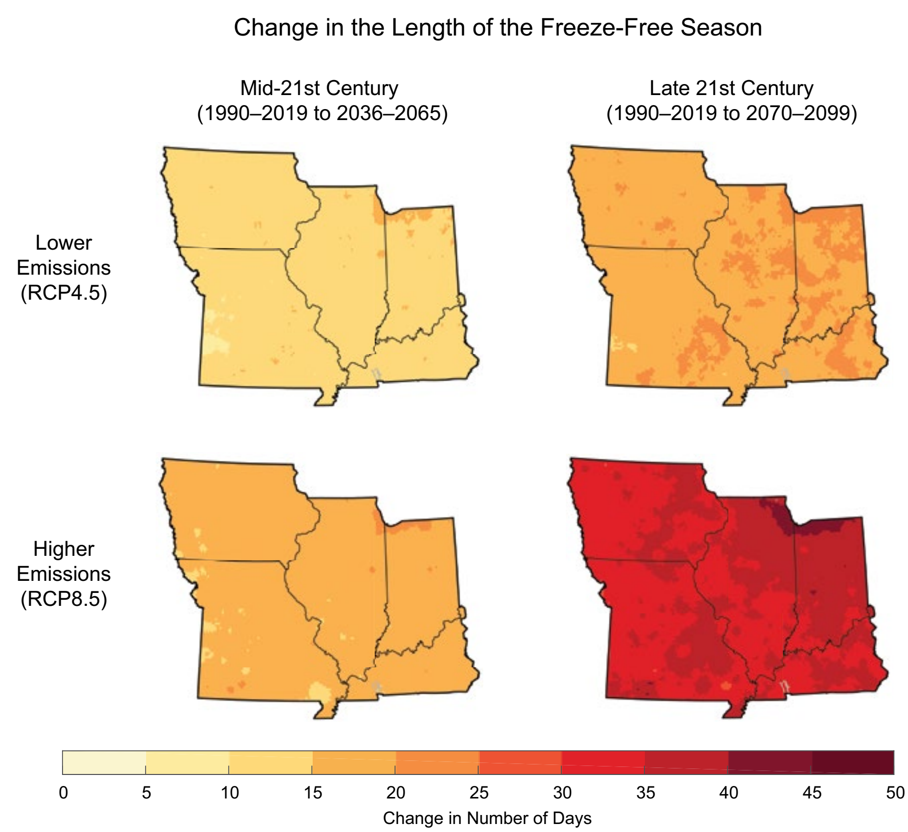

Figure 2.36 The maps show projected changes in the length of the freeze-free season (between the last spring and first fall occurrences of 32°F) for the mid-21st century (left column) and late 21st century (right column) under a lower (RCP4.5) scenario (top row) and a higher (RCP8.5) scenario (bottom row) for the Midwestern United States. All projected values are shown as changes compared with 1990–2019 averages. **Sources:** NCICS and The University of Edinburgh.

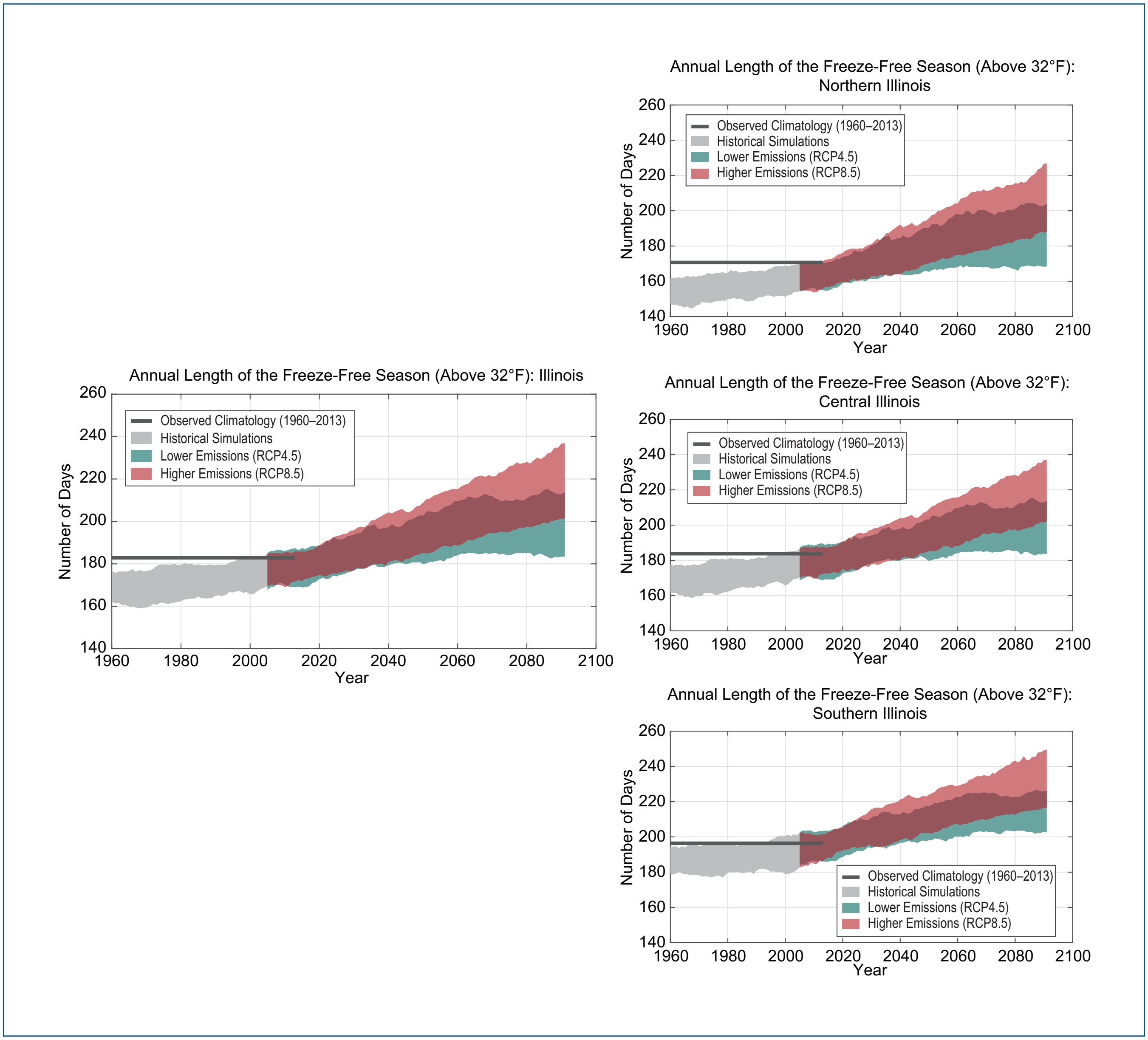

Figure 2.37 These time series (1960–2100) show the simulated historical and projected length of the freeze-free season (between the last spring and first fall occurrences of 32°F) for the state of Illinois (left panel), northern Illinois (upper right panel), central Illinois (middle right panel), and southern Illinois (lower right panel). The observed climatological values averaged for the period 1960–2013 are shown (black line). Historical simulations (gray shading) are shown for 1960–2005. Projected changes for 2006–2100 are shown for a higher scenario (RCP8.5; red shading) and a lower scenario (RCP4.5; teal shading). The shaded ranges indicate 10% to 90% confidence intervals of 20-year running averages from the set of climate models. **Sources:** NCICS and The University of Edinburgh.

Growing Degree Days

Growing degree days (GDD) are a measure of heat accumulation relevant for plant growth and are used to predict crop and pest development rates. GDDs are calculated based on a certain threshold temperature for plant growth, which varies by species. For this analysis, a base temperature of 50°F was used to calculate GDDs for corn and soybeans. The projected changes in the annual number of GDDs for Illinois show increases in GDDs, with larger increases in the south than in the north (Figure 2.38). For the mid-21st century, the increases are about 500–1,000 for the lower scenario and around 750–1,250 for the higher scenario. For the late 21st century, the increases are around 1,000–1,250 for the lower scenario and 1,750–2,250 for the higher scenario.

The temporal and regional behavior, as well as the range of model projections, are shown in Figure 2.39. By the end of the century, the annual number of growing degree days (modified base 50°F) in northern Illinois is projected to increase from 3,200 to 3,700–5,000 under the lower scenario (RCP4.5) and to 4,500–5,700 under the higher scenario (RCP8.5; Figure 2.39). In central Illinois, the projected increases are from 3,900 to 4,400–5,700 under the lower scenario (RCP4.5) and to 5,300–7,000 under the higher scenario (RCP8.5; Figure 2.39). In southern Illinois, the projected increases are from 4,500 to 5,000–6,200 under the lower scenario (RCP4.5) and to 6,000–7,700 under the higher scenario (RCP8.5; Figure 2.39).

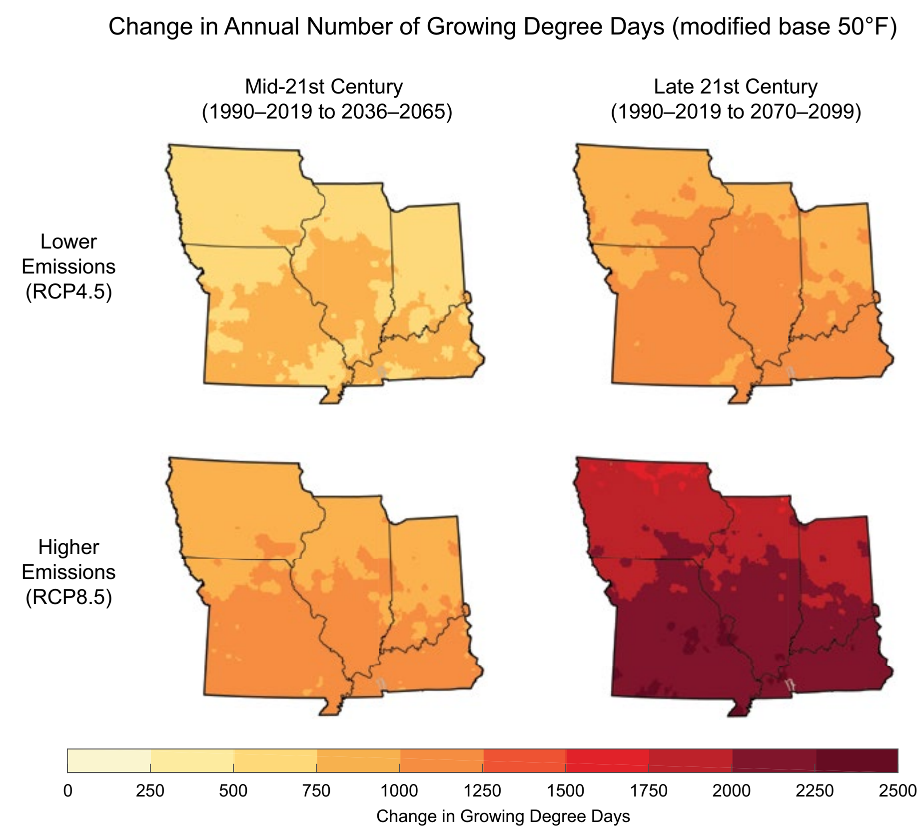

Figure 2.38 The maps show projected changes in the number of growing degree days (modified base 50°F) for the mid-21st century (left column) and late 21st century (right column) under a lower (RCP4.5) scenario (top row) and a higher (RCP8.5) scenario (bottom row) for the Midwestern United States. All projected values are shown as changes compared with 1990–2019 averages. **Sources:** NCICS and The University of Edinburgh.

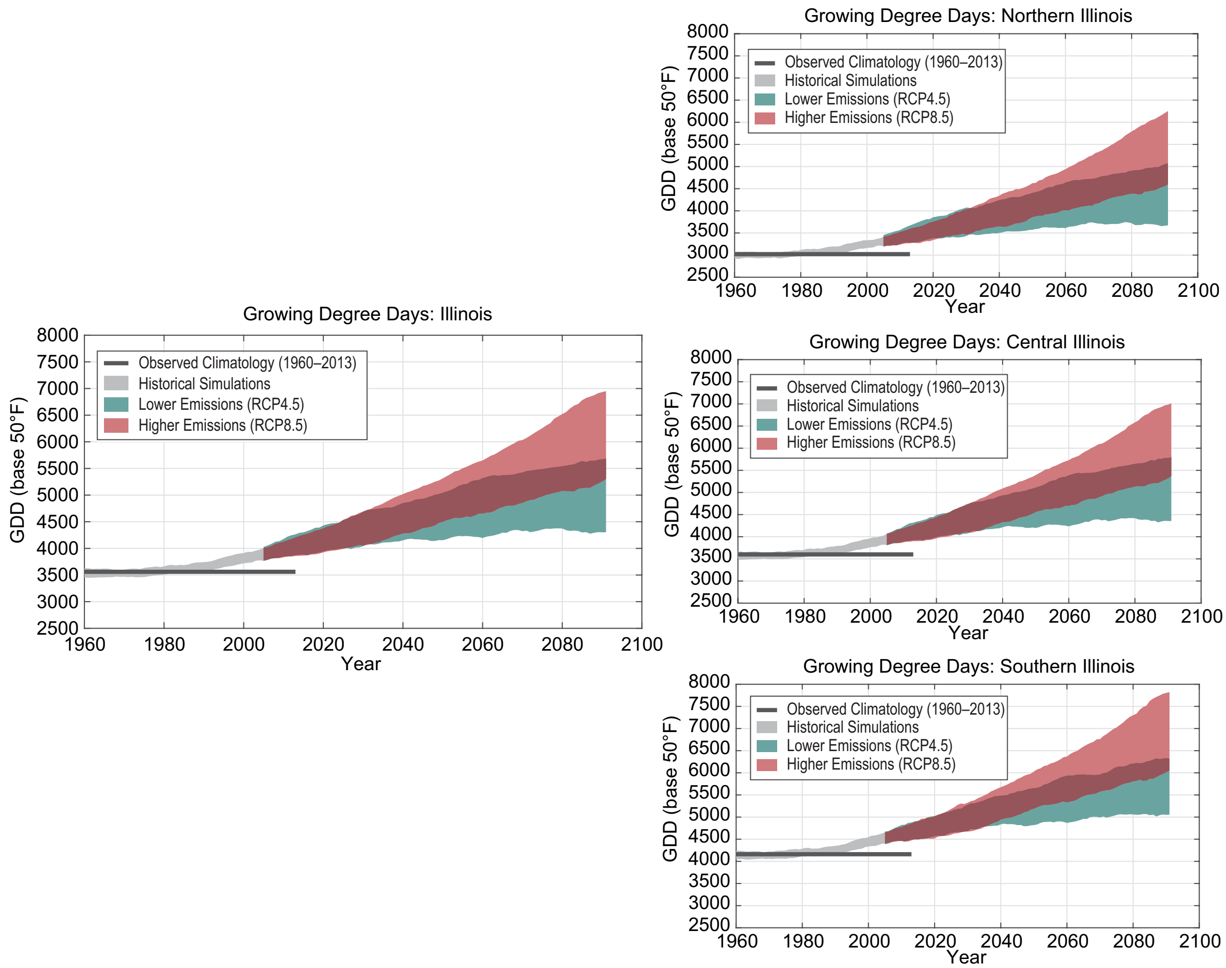

Figure 2.39 These time series (1960–2100) show the simulated historical and projected number of growing degree days (modified base 50°F) for the state of Illinois (left panel), northern Illinois (upper right panel), central Illinois (middle right panel), and southern Illinois (lower right panel). The observed climatological values averaged for the period 1960–2013 are shown (black line). Historical simulations (gray shading) are shown for 1960–2005. Projected changes for 2006–2100 are shown for a higher scenario (RCP8.5; red shading) and a lower scenario (RCP4.5; teal shading). The shaded ranges indicate 10% to 90% confidence intervals of 20-year running averages from the set of climate models.
Sources: NCICS and The University of Edinburgh.

Knowledge and research gaps

While global warming is happening as a result of rising greenhouse gas concentrations, the certainty with which particular impacts will occur varies, specifically, at the local level. Future changes in climate variables directly tied to temperature have the highest level of confidence, including virtually certain global increases in atmospheric water vapor and extreme precipitation. Historical climate changes in Illinois have been similar to global changes in most, but not all, respects. Thus, future climate changes in Illinois are likely to mirror global changes but at a slightly lower level of confidence.

It is very likely that the following changes in climate will occur:

- Increased seasonal and annual mean temperature
- Increased absolute atmospheric humidity
- Increased frequency and intensity of heavy precipitation events
- Increased frequency of very warm nights
- Decreased frequency of cold nights
- Increased intensity of droughts

It is likely that the following changes will occur:

- Increased frequency of hot days

There is uncertainty about future changes in the following climate variables:

- Severe thunderstorm frequency
- Winter storms

Potential research areas should target climate issues with the most uncertainty. Three particular areas of concentration are recommended:

- **High spatial resolution climate simulations**
  The development of very high spatial resolution (4 km or finer grid spacing) climate model simulations over climate timescales (decades) would be beneficial. Such high-resolution simulations can resolve convective clouds and land cover heterogeneity and provide more robust simulations of heatwaves, severe thunderstorms, and extreme precipitation.

- **Refined climate modeling for hot summer days**
  Further research is needed to better understand why there is not an observed trend for increased hot summer days. All climate model simulations project an increase in hot summer days and warm summer nights. While an upward trend in warm summer nights has been observed, there is not an upward trend in hot summer days in Illinois or over most of the Midwest. Thus, there is greater uncertainty about future projections of an increased number of hot summer days.

- **Coupled land-lake-atmosphere modeling**
  There is also a need for coupled land-lake-atmosphere modeling for improved climate projections. The development of integrated models of atmosphere, land, and lakes will improve both the utility of weather forecasts and long-term climate projections and associated impacts on hydrometeorological extremes, agriculture, ecosystem, engineering design, human health, and socioeconomic systems in the Midwest and Great Lakes region (Sharma et al. 2018).

Improvements in the understanding of atmospheric processes important to climate and to the modeling of these processes will continue over the coming decades, but even with improvements there is no reason to expect a major change in the future projections for a given set of future emissions. The actual changes in climate that Illinois will experience will depend significantly on the future emissions of carbon dioxide and other gases and particle emissions—and how they change over time. If efforts to drastically reduce emissions are ramped up, for example, the impacts of climate change could be reduced. Natural variations due to unexpected changes in the solar energy output or due to an unexpected major increase in volcanic activity could also be significant factors affecting future changes in climate.

Contributing Authors

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CHAPTER 3

Climate Change Impacts on Hydrology and Water Resources

Key Messages

1. The majority of gaged streams and rivers in Illinois have experienced increased flooding over recent decades, believed to be driven primarily by changing precipitation patterns and new land development. Flood events that impact key river systems like the Mississippi and Illinois Rivers are likely to continue increasing in frequency in the future.

2. Increased intensities of rainfall events associated with climate change are expected to exacerbate stresses on aging urban drainage systems, many of which are already prone to flooding due to undersized stormwater systems and land development patterns that have altered natural drainage patterns and increased impervious surfaces.

3. Climate change is very likely to increase the incidence of combined sewer outflows (CSOs), which affect water quality of urban streams and rivers and Lake Michigan. Both CSOs and increased overland flooding cause environmental damage and create public health hazards, such as increased exposure to infectious diseases and contaminated drinking water.

4. Increases in precipitation associated with climate change tend to increase nutrient loads in rivers. Crop management and conservation practices (e.g., nitrogen application practices, wetland restoration) can help to mitigate excess nutrient runoff to riverine systems.

5. Projected climate changes are expected to increase both the frequency of drought conditions and the magnitude of shortages in surface water supplies during drought conditions, as surface water supplies are already often limited by low streamflow unless augmented by in-channel or off-channel storages.

6. Increased precipitation, as is projected to occur with climate change, is expected to augment recharge to shallow aquifers, causing higher water tables during spring that exacerbate basement flooding and necessitate more tile drainage in row crop areas. Conversely, increased evaporation and more intense droughts are expected to lower the surface water table during peak pumping conditions in the summer. Over the long-term, persistent net reductions in groundwater recharge can potentially impact the sustainability of groundwater aquifers used for water supply.

Introduction

Water is one of the greatest natural resources in Illinois. In most years, Illinois receives an abundance of precipitation, which normally ranges from 48 inches in the southern part of the state to 36 inches in the north. Surface water abounds in Illinois, with Lake Michigan lying to the northeast, the Mississippi River stretching the length of the western border, the Ohio River running along the southern border, and the Illinois River coursing through the center of the state. Although unseen, important groundwater aquifers also occur throughout Illinois, providing several million Illinois residents with reliable water supplies.

However, a changing climate poses challenges to the water resources of the state. Warmer temperatures increase rates of evaporation and plant transpiration, leading to more moisture in the atmosphere, more precipitation overall, and heavier precipitation events. This phenomenon is best described as an acceleration of the water cycle (Figure 3.1). This acceleration leads to problems like more flooding, increased soil erosion, reduced water quality, and the disruption of activities such as farming and transportation. The changing pattern of increased overall precipitation and heavy precipitation events is happening throughout the Midwest.

Chapter 2 provides strong evidence for the acceleration of the water cycle in Illinois, including observed increases in evapotranspiration, precipitation, and 2-inch-or-greater precipitation events. By mid-century, annual precipitation is projected to increase 0–4 percent in the lower scenario and 3–6 percent in the higher scenario. Winter and spring precipitation is projected to increase through the rest of the century, while summer precipitation could decrease and fall precipitation changes are projected to be small. The number of days with 2 inches of precipitation or more is projected to increase, with larger increases in the higher scenario than the lower scenario and larger increases by late century than mid-century.

Flooding

Historic and projected trends in riverine flooding in Illinois

The detection and attribution of trends in river flows is highly complex due to the numerous factors involved, such as temporal and spatial distributions of precipitation, land use and land cover, and interbasin transfers. For instance, Hirsch and Archfield (2015) explain that flood trends based on short records may not be as reliable as long-term trends, owing to factors that drive hydrologic trends over longer time scales (i.e., decades or centuries), such as long-term storage of moisture in soil and groundwater. In addition, mechanisms that impact river flow are greatly dependent on the size of the watershed. Within a smaller spatial extent, there is an "increased likelihood that a storm will cover the entire catchment and hence lead to soil moisture saturation, with more of the precipitation contributing to the streamflow response" (Sharma et al. 2018).

Flood formation in large rivers like the Mississippi River is particularly complex because these rivers span heterogeneous regions with different climates. For example, it typically takes weeks or months of substantial precipitation, often combined with snowmelt, to generate large flows on the Mississippi River. Figure 3.2 shows the historical annual peak flows in the Mississippi River at St. Louis, Missouri, between 1862 and 2019 (not including a historic peak of 1,000,000 cfs observed in 1844), based on long-term data from USGS. Despite significant fluctuations and the presence of some of the largest peaks earlier in the record, the data in Figure 3.2 show an increase, particularly from the 1930s onward. The long-term increases in maximum flow and flood stage throughout the 20th century are attributable primarily to river engineering, particularly levee construction and in-channel control structures; however, climate change and land-use changes have also contributed significantly (Pinter et al. 2008). Recent hydroclimatic studies project an increase in future floods in the Upper Mississippi River watershed, exceeding the effects of river control structures (Naz et al. 2016; Theiling and Burant 2013; Wu et al. 2012).

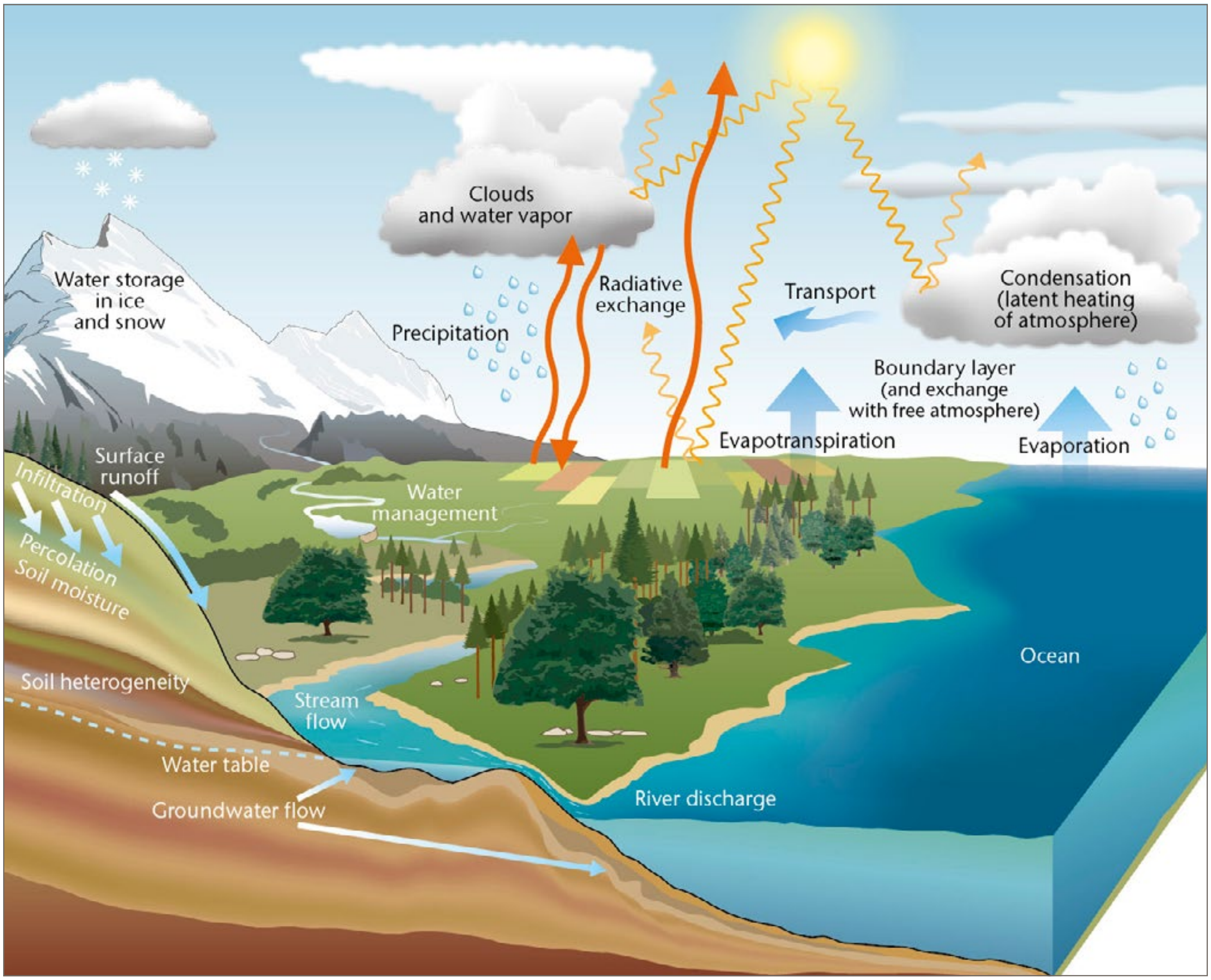


Figure 3.1 A diagram of the water cycle showing the paths water takes in the atmosphere and through the landscape. A warmer climate increases rates of evaporation over water and evapotranspiration over land, producing more precipitation that shows up as increases in soil moisture, stream flows, lake levels, and groundwater. **Source:** UK Met Office (Contains public sector information licensed under the Open Government License v3.0).

Like the Mississippi River, other rivers and streams in Illinois also show increasing trends. Most of their present-day high flows are significantly higher than in the early and mid-1900s. Knapp (2005) determined that changes in both average and high flows coincide with increases in mean annual precipitation, which in turn coincides with increases in heavy precipitation (Angel et al. 2020). These changes in high flows are consistent with findings from several other studies, including Archfield et al. (2016), who found positive trends in the frequency, duration, peak magnitude, and volume of floods across most of Illinois. Observed trends in annual maximum flows in the Illinois River at Valley City (USGS gage no. 05586100), and its two tributaries, the Kankakee River at Momence (no. 05520500), and the Des Plaines River at Riverside (no. 05532500), shown in Figure 3.3, are consistent with similar increases in precipitation (Angel et al. 2020). Despite differences in land management and hydrologic modifications, ranging from the mainly urbanized Des Plaines River watershed to the predominantly agricultural Kankakee River watershed, all three watersheds show a significant increase in annual peak flows, confirming the findings of Hejazi and Markus (2009) that precipitation plays a major role in observed

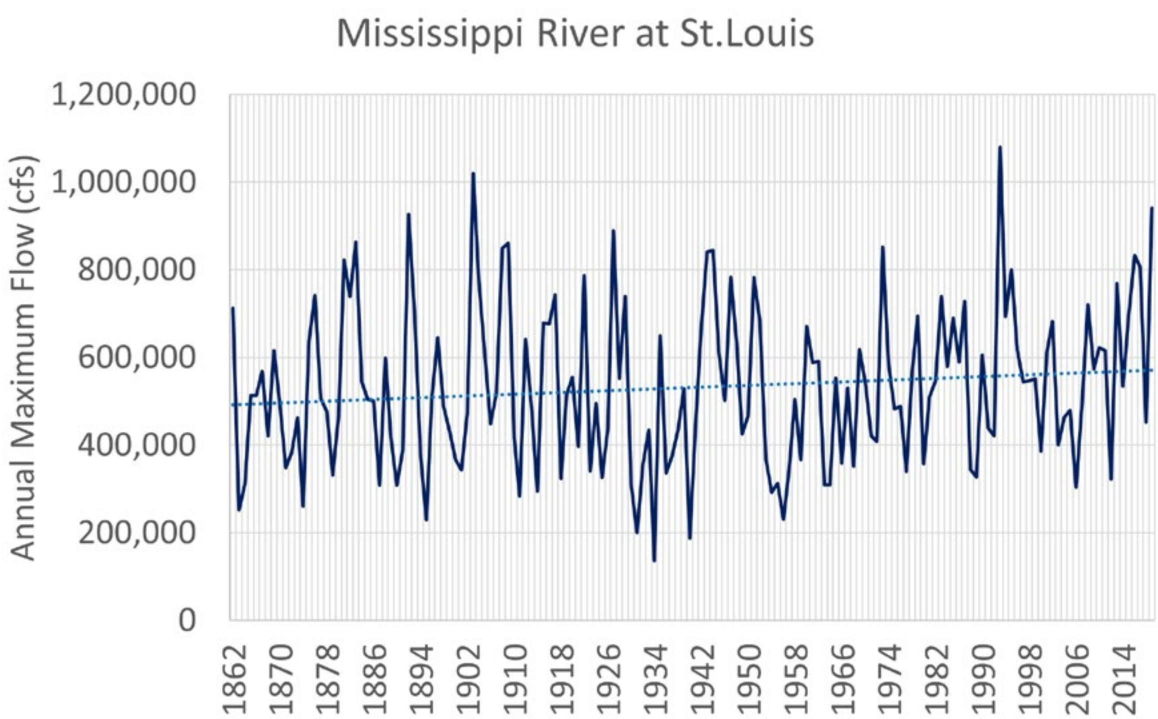


Figure 3.2 Annual maximum flows in the Mississippi River at St. Louis, Missouri. **Source:** USGS 2020.

trends in flood peaks.

As a result of increasing trends in projected heavy precipitation (Angel et al. 2018), it is expected that flooding in the watersheds of Illinois will intensify in the future. This is particularly likely in urban watersheds (Sharma et al. 2018), where increasing trends in flooding match trends in precipitation (Angel et al. 2020, Markus et al. 2018).

Urban flooding

In general, flooding occurs in urban areas when rainfall exceeds surface absorption capacity and drainage systems are overwhelmed. Urban flooding is heavily influenced by local land development, which alters natural drainage patterns and increases impervious surfaces, as well as infrastructure, like aging and undersized stormwater systems (National Academies 2019). Climate change brings an increase in intense rainfall (Easterling et al. 2017), exacerbating flooding in already stressed urban drainage systems.

The increased occurrence of flooding in urban areas has garnered national attention. Figure 3.4 shows an example of flooding in the Chicago region from 2019.

Multiple factors contribute to urban flooding, making it difficult to establish clear cause-and-effect relationships. In addition to local land development patterns and infrastructure capacity, urban flooding may also be influenced by upstream land use and rainfall. Urban areas can experience riverine flooding that is not necessarily driven by local events.

Urban flooding is prevalent and costly across the state's urban areas, as indicated by insurance claims records. Figure 3.5 shows the prevalence of flood insurance claims in urban areas, based on a compilation of private insurance claims, National Flood Insurance Program (NFIP) claims, and federal individual assistance payments between 2007 and 2014. Between 2007 and 2014, 175,775 out of

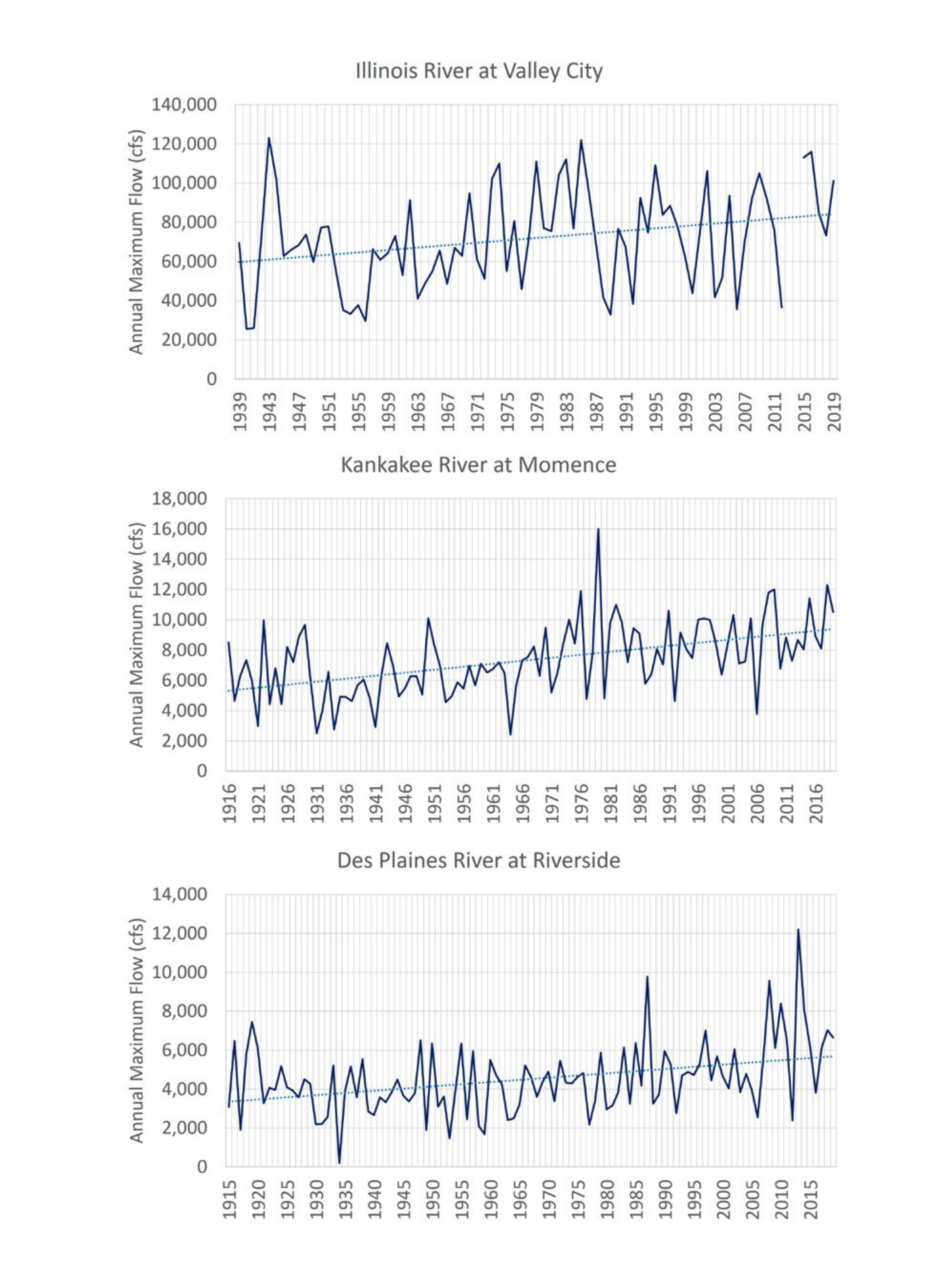


Figure 3.3 Annual maximum flows in the Illinois, Kankakee, and Des Plaines Rivers in Illinois. **Source:** USGS 2020.

Figure 3.4 An example of severe rainfall in the Chicago region during April 2019. **Photo credit:** Karl Gnaedinger

184,716 (95.16%) private insurance claims and 12,950 out of 14,693 (88.13%) NFIP claims were located in urban areas. A total of 94.63% of all claims were located within urban areas (Winters et al. 2015).

Based on the 2010 census, urban areas comprise 7.4% (4,170.45 sq. mi.) of the total land area in the state, and increasing development of these areas may exacerbate potential flood risk. Figure 3.6 shows land-use change between 1992 and 2011 within the current footprint of urban areas in Illinois, based on a comparison of National Land Cover Datasets. Between 1992 and 2011, developed areas increased by 79.8%, while agricultural lands, wetlands, and forested areas decreased. Total depressional water storage areas and potential riverine areas also decreased by 14.42% (Winters et al. 2015).

Many Illinois cities contain older urban areas served by combined sanitary and storm sewers (Winters et al. 2015). Design standards for storm sewer systems have changed over time and vary between communities. Standards proposed in the 1960s and 1970s continue to be reviewed, revised, and debated today (ASFPM 2004). While specifics may vary, in general, storm sewer systems are sized to convey up to a certain amount of calculated runoff based on the likelihood of expected storm events occurring. Most commonly, they are sized to accommodate a 10% annual chance event for conveyance and a 1% annual chance event for storage. Higher runoff peaks and volumes produced by less frequent events are conveyed by streets and swales.

Estimates of the capacity needs for storm sewer systems have increased over time based on statistical analyses of rainfall observations and trends. Between 1961 and 1989, Technical Paper No. 40 (Hershfield 1961) was the primary source for statistical rainfall data. In 1989, the Illinois State Water Survey (ISWS) published Rainfall Distributions and Hydroclimatic Characteristics of Heavy Rainstorms in Illinois (Huff and Angel 1989), known as Bulletin 70, which was subsequently adopted in most of the state for storm

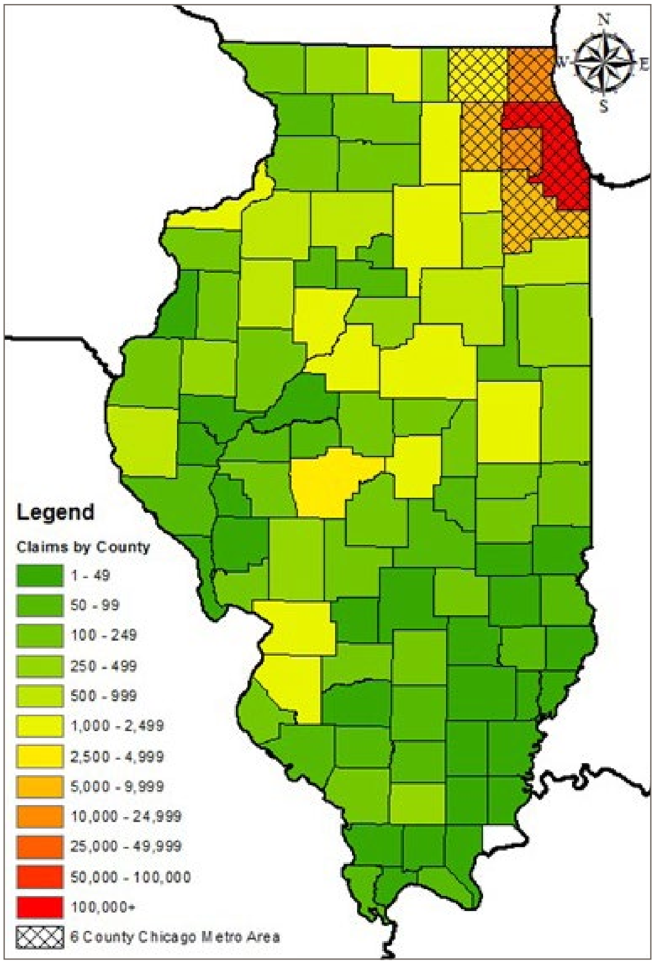


Figure 3.5 Urban flooding claims by county. Between 2007 and 2014, 175,775 out of 184,716 (95.16%) private insurance claims and 12,950 out of 14,693 (88.13%) NFIP claims were located in urban areas. A total of 94.63% of all claims were located within urban areas.
Source: Winters et al. 2015.

sewer design. Updated rainfall statistics were provided by the ISWS in Bulletin 75 in 2020 (Angel et al. 2020), which was adopted by the Illinois Department of Natural Resources, Office of Water Resources. Many communities and counties are in the process of updating their ordinances to require adoption of Bulletin 75. A comparison of the depth of rainfall used for storm sewer design over the years illustrates the need for systems with greater capacities, as the intensity and frequency of heavy rainfall events has increased. Table 3.1 lists the depth of rainfall expected for a storm lasting two hours with a return interval of 10 years (10% annual chance event) and a 24-hour storm event with a 100-year return interval (1% annual chance event).

Table 3.3. Rainfall Depth and Intensity-Duration Estimates for Illinois

Design Storm (inches)	Technical Paper 40, 1961	ISWS Bulletin 70, 1989	ISWS Bulletin 75, 2020
10-year 2-hour	2.37	2.64	2.99
100-year 24-hour	5.75	7.58	8.57

Estimates are for northeastern Illinois (O'Hare Airport) and come from past and present reference documents used for Illinois flood studies and storm sewer design.

Importantly, the rainfall depth used to size and design storm sewers is a key determinant of the capacity of the system. A storm sewer designed to accommodate rainfall depth resulting from a 10-yr, 2-hr storm event, calculated by Technical Paper No. 40, would correspond to a sewer designed to convey only about a 6-yr, 2-hr storm, based on Bulletin 70 calculations. The same storm sewer would reach or exceed full capacity about every 4 years based on the information provided in Bulletin 75.

Although storm sewer systems have evolved over the decades, older systems are undersized and their capacities are increasingly exceeded. More frequent flooding, where runoff is carried in the overflow paths of streets and swales and accumulates in low areas, can be expected due to increased frequency and duration of heavy rainfall (Easterling et al. 2017; Markus et al. 2018). Combined with the impact of increased out-of-bank riverine flooding, more frequent and greater flood damage can be expected in urban areas.

River flood hazard identification

Illinois is bordered by 880 miles of rivers, including 581 miles of the Mississippi River along the western border. In addition, the Wabash River flows along about 230 miles of the southeastern border, and over 130 miles of the Ohio River bend around the southern tip of the state. In total, Illinois contains 87,110 miles of rivers and streams within its borders (IDNR 2020). Sixty-three miles of Lake Michigan's coast also lies along Lake and Cook Counties, and the Illinois

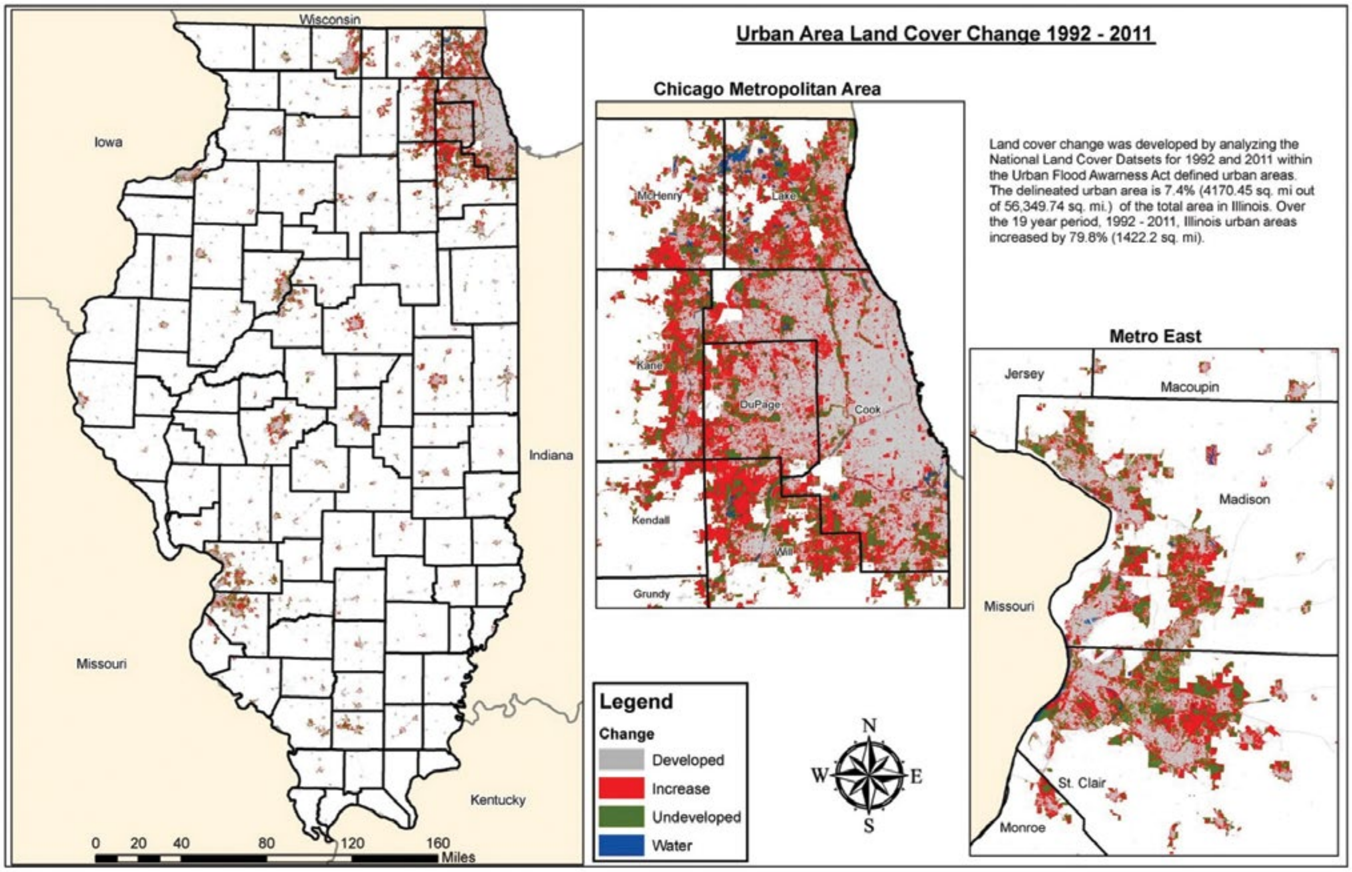


Figure 3.6 Land-cover change within the defined urban areas from 1992 to 2011. Over this 19-year period, developed areas increased by 79.8%. Areas in gray were developed as of 1992, red areas were developed as of 2011, blue areas represent water, and green were still undeveloped as of 2011. **Source:** Winters et al. 2015.

portion of the Lake Michigan watershed is home to half of the total population of Illinois (IEPA 2020).

Illinois has a history of severe flooding events. Every county in the state has had at least one federally declared disaster since 1965 (IEPA 2020). Flooding, flash flooding, and/or lakeshore flooding caused property damage every year between 1996 and 2020 (NOAA 2020). Between 2000 and 2018, Illinois averaged 1.5 floods per week and flooding caused $3 billion in property damage statewide (AGU 2019).

Riverine flooding occurs when the amount of water accumulated in a river exceeds its capacity. Flooding in large basins is among the most predictable of natural hazards. Customarily, the area of inundation or floodplain is identified using calibrated hydraulic models that simulate the depth and extent of riverine flooding for a given discharge. A discharge with an expected frequency (e.g., a 1% annual chance event, a.k.a. 100-year event) is input to the hydraulic model, which calculates the flooded area or floodplain associated with the frequency of the discharge event. Statistical analyses of streamflow records provide discharge values for gaged streams and rivers, of which there are few compared with the number of ungaged watercourses. Where streamflow data are not available, regression equations or hydrology models are used. Coastal flood elevations, which are relevant for the Lake Michigan lakeshore, are calculated as the still water elevation for the 1%-annual chance storm plus the additional flood hazard from wave effects, such as storm-induced erosion, wave setup, overland wave propagation, wave runup, and wave overtopping (Jensen et al. 2012).

Nationwide, flood hazard mapping is primarily performed under the auspices of the Federal Emergency Management Agency (FEMA) in support of the National Flood Insurance Program (NFIP). Flood Insurance Rate Maps (FIRMs) and attendant Flood Insurance Studies (FIS) are produced following specific standards and guidelines (FEMA 2020a). The maps display areas with a 0.2% and 1% annual chance of inundation based on hydrologic and hydraulic models. Flood elevations with 10%, 4%, and 2% annual chance of occurrence are also reported. The flood hazards studied include riverine and coastal flooding.

Although the maps are informative, they have limitations. In Illinois, studies of streams in rural areas terminate where the drainage area of the stream is less than 25 square miles and in urban areas where the drainage area is less than 1 square mile. Storm sewer systems are also not typically considered, and flooding in urban areas arising from overwhelmed systems in the built environment, ponding in low areas, and basement flooding is not systematically identified. Notably, the original flood insurance and regulatory floodplain management purposes for flood hazard mapping established the practice of showing current rather than projected flooding, which does not systematically consider how climate change could impact flood risk.

Decades of insufficient funding left many areas of the state (and the nation) with out-of-date flood hazard data. As of June 2020, fewer than 6% of Illinois streams and rivers shown on regulatory floodplain maps are rated as valid according to FEMA compliance review standards (FEMA 2020b). The remaining miles of floodplains may be based on out-of-date analyses or have never been studied using engineering methods. Five of Illinois' 102 counties have not been funded to update their floodplain maps and are using over 30-year-old paper maps for regulatory and insurance purposes. Coastal flood hazard studies published in 2016 for Lake Michigan will be incorporated in the FIRMs for Lake and Cook Counties (Jensen et al. 2012; Melby et al. 2012). Since 2009, the ISWS has been working with the Illinois Department of Natural Resources, Office of Water Resources, and FEMA to engage in large-scale hydrologic and hydraulic study updates for Illinois. Figure 3.7 shows the engineering studies in progress. The resulting hydraulic models could be leveraged to generate data on potential future flooding based on projections of future extreme rainfall events.

Another nationwide flood risk assessment tool—called Flood Factor—was released by First Street Foundation in 2020.[1] The flood risk model assigns a property-level risk factor for both the present and 30 years in the future (FSF 2020a). The Flood Factor tool suggests that significantly more properties will be exposed to flood risk than FEMA's flood maps and indicates that the number of properties at flood risk will increase over time. In Illinois, the FEMA FIRMs indicate that 205,700 properties are currently at risk of flooding (located in the 1% annual chance floodplain), while the First Street Foundation Flood Model shows 2.2 times that number presently at flood risk (FSF 2020b).

Differences are in part due to the coarse national data sets used in the Flood Factor model. For example, the Flood Factor model is based on the nationwide 30-meter Digital Elevation Model (NRCS 2020), while updated FEMA maps are required to use higher resolution data (1-meter grids) (FEMA 2016). Thus, the flood hazards identified through the FEMA process are more precisely determined, but they are limited to present conditions (for areas where updated modeling has been performed) or are outdated. While updated hydraulic models could be used to investigate the impact of future climate conditions, this has not been done. In the interim, modeling approaches such as the Flood Factor model provide insight into future flood risk, albeit at a coarser resolution, helping to address future climate projections and uncertainty.

1 The Flood Factor risk assessment tool can be found at this link: https://firststreet.org/flood-factor/

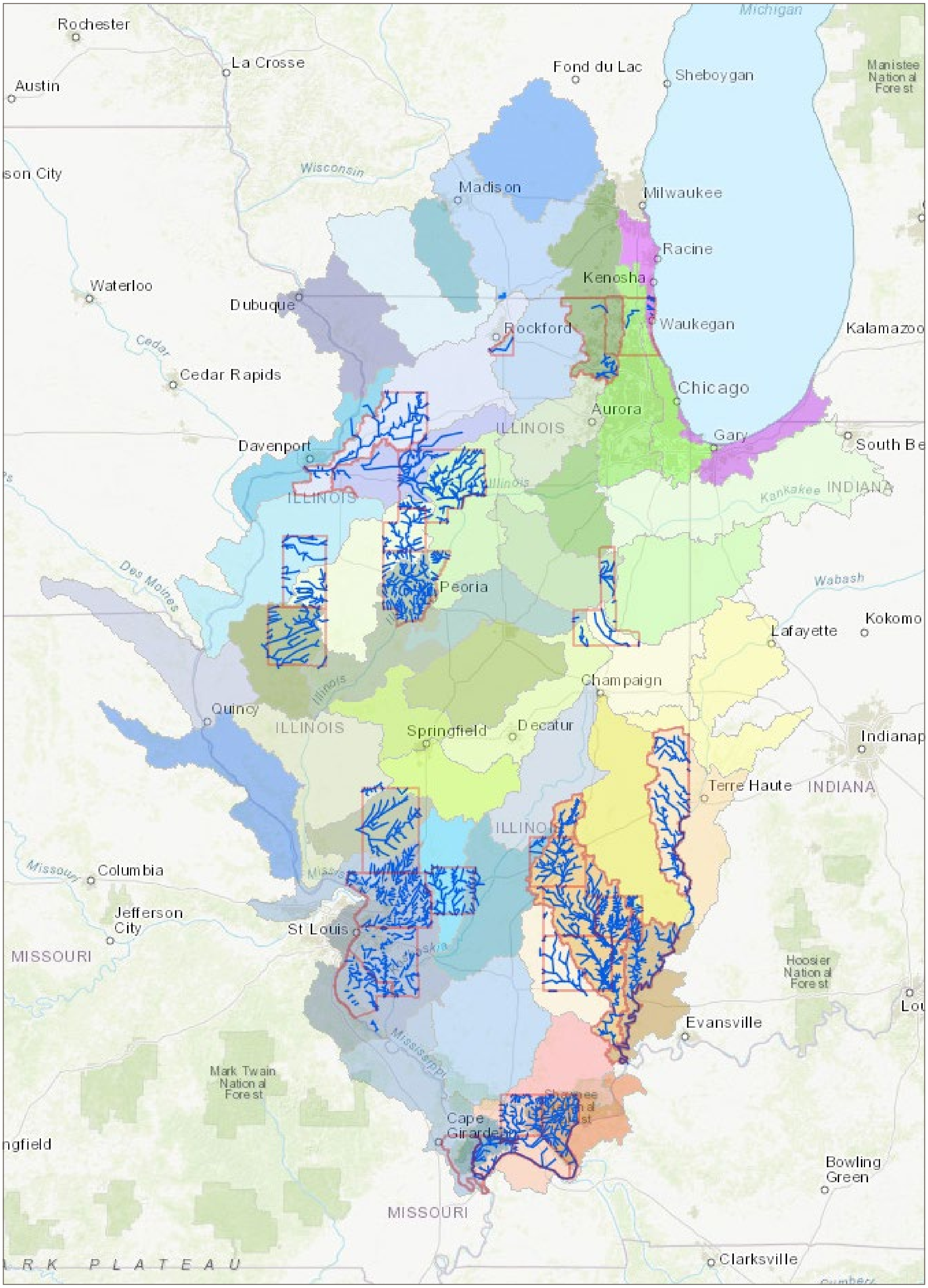
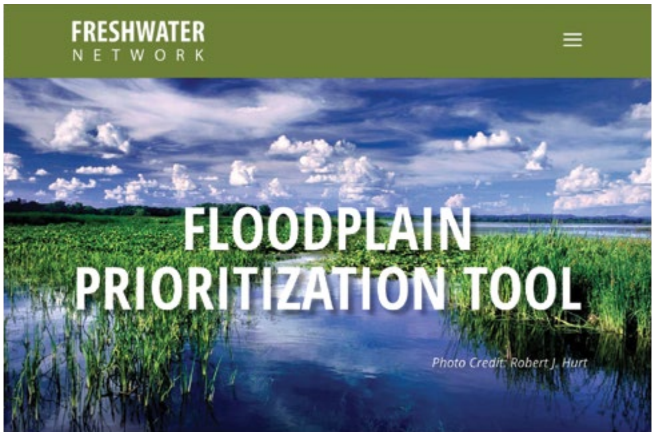


Figure 3.7 Illinois Riverine Flood Studies in Progress, October 2020. These flood studies will help with the development of hydraulic models that can improve projections of future flood events. **Source:** Illinois State Water Survey 2020b.



Floodplain Prioritization Tool

The Floodplain Prioritization Tool was developed by The Nature Conservancy to identify the best opportunities for floodplain conservation and restoration in the Mississippi River Basin, including in Illinois. Healthy floodplains are instrumental for improving water quality, reducing flood impacts, recharging aquifers, improving wildlife habitat, and enhancing outdoor recreation opportunities. The web-based tool can help decision-makers in Illinois—like government agencies, county planners, natural resource managers, and private landowners—optimize investments and minimize the impacts of development on floodplains in the state. The interactive tool allows users to assess tradeoffs related to nutrient removal, wildlife habitat, decreased flooding in adjacent and downstream areas, and other goals, as a way to identify priorities for floodplain conservation and restoration.

To access the Floodplain Prioritization Tool, please visit: https://freshwaternetwork.org/innovative-tools/floodplain-prioritization-tool/

Water quality

Riverine nitrate and phosphorus loads

In response to human health and ecological concerns about elevated nitrate-nitrogen and phosphorus concentrations in surface waters, Illinois and other Midwestern states have developed programs and policies aimed at reducing riverine nutrient loads from both non-point and point sources. The Illinois Nutrient Loss Reduction Strategy—a framework to assess and reduce nutrient loss to Illinois waters and the Gulf of Mexico—adopted the ultimate goal of reducing nitrate and total phosphorus (TP) loads by 45% relative to 1980–96 levels. Interim goals of reducing nitrate loads by 15% and TP loads by 25% by 2025 were also established (IEPA, IDOA, and University of Illinois Extension 2015). Progress toward achieving these goals has been evaluated at the state level by combining nutrient loads in the eight major river systems that drain about 70% of the state land area and extrapolating the load per area to the remaining 30%.

Nitrate and TP loads are highly correlated with river flows (Figure 3.8), which in turn are highly correlated with precipitation. The 2015–19 average nitrate and TP loads for the state were 13% and 37% greater than the 1980–96 baseline loads, respectively, and water flow was 25% greater than the baseline period. However, this pattern is not uniform across the state.

An updated analysis by McIsaac (2019) that will appear in the NLRS 2021 Biennial Report indicates that most of the increased nitrate load occurred in the Illinois portion of the Rock River, where nitrate load increased 135% and water yield increased 60% (unpublished material). Increased precipitation is likely one causal factor, but long groundwater lag times may also play a role. In the baseline period, nitrate loads in this basin were unusually low, despite intensive crop production, which is a major source of nitrate from nitrogen fertilizer, manure, and soil organic matter. Evidence from public water supply wells suggests that nitrate has been accumulating in the extensive groundwater aquifers in the region and

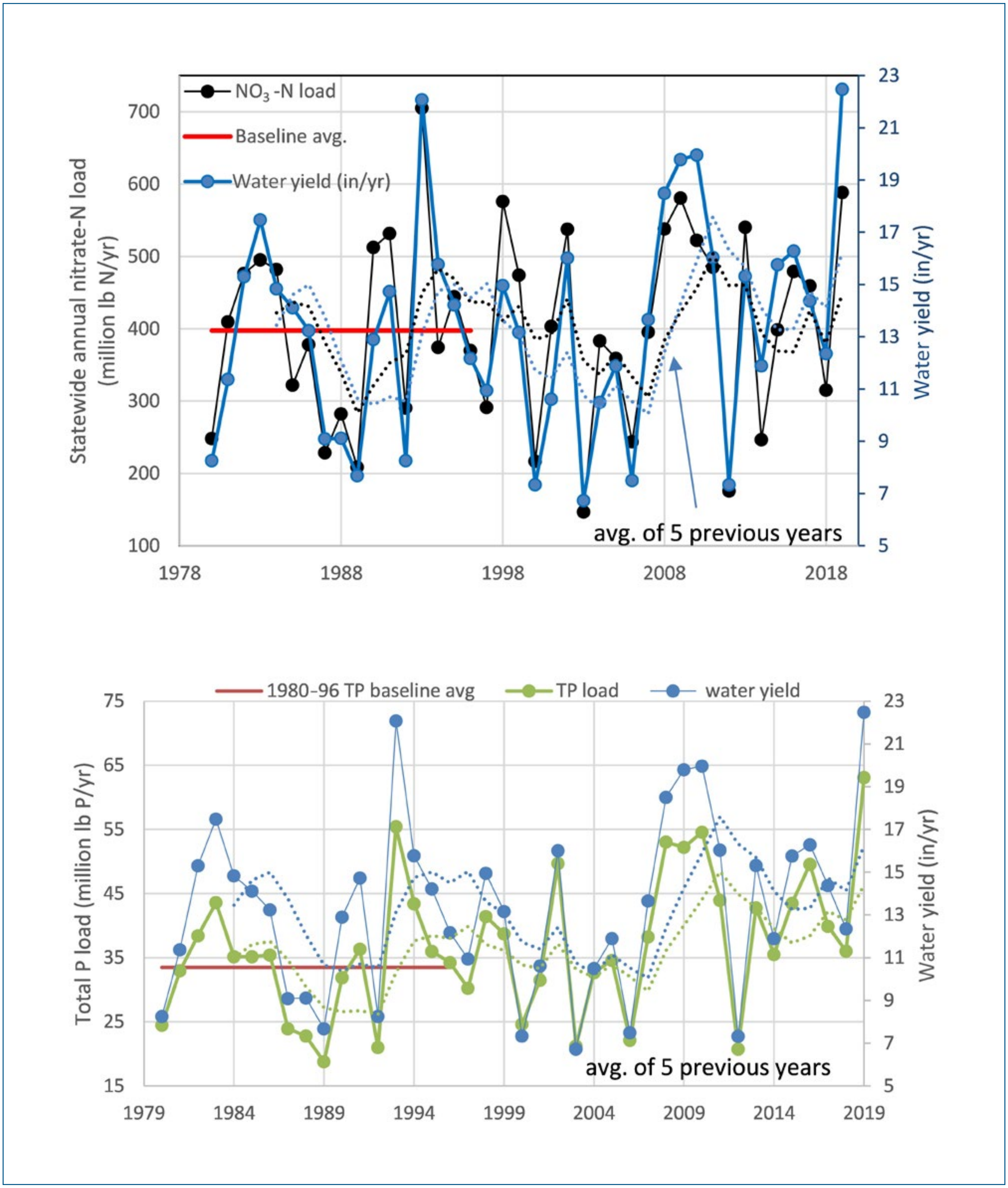


Figure 3.8 Statewide estimated water yields, annual nitrate-nitrogen (NO_3-N) loads (top panel), and annual total phosphorus (TP) loads (lower panel). Water yields are shown in blue and are calculated by dividing the annual discharge by drainage area. Annual NO_3-N loads are in black and TP loads are in green. Dashed lines represent the averages of the five previous years. The red line is the average load for the 1980–96 baseline period. **Source:** updated from McIsaac 2019.

has been increasingly discharging to the Rock River since about the late 1990s (personal communication from W. Kelly, Groundwater Section, Illinois State Water Survey).

In contrast, nitrate loads have declined about 10% in the Vermilion (Wabash Basin), Sangamon, and Kaskaskia Rivers, despite increases of water flow ranging from 9 to 28%. This may be due to increased efficiency of nitrogen fertilizer use. Corn yields have increased substantially, largely due to improved varieties, while nitrogen fertilizer use has increased only modestly. Increased precipitation and drainage tend to promote increased nitrate loss from cropland, but crop management factors can have a counteracting influence.

Increases in TP loads have been generally more uniform across the state, with some exceptions. Reductions in TP load in the Des Plaines River are likely due to a reduction in point source discharge from the Water Reclamation District of Greater Chicago, although the load per unit area remains the highest in the state. There was also a small, 4% reduction in TP loads in the Green River despite a 40% increase in water flow.

The greatest percentage increase in TP loads occurred in the Kaskaskia (86%) and the Little Wabash (77%) rivers, which were associated with increased flows of 28% and 37% respectively. In the Illinois section of the Rock River, TP loads increased 34%, with a 60% increase in water flow. Total phosphorus loads are influenced by factors other than precipitation and river flow. For example, legacy phosphorus released from reservoir sediments may be playing a significant role in the Kaskaskia River, and in the Little Wabash River, land slope and greater propensity for surface runoff may be important factors.

Using a different methodology, Hodson and Terrio (2020) demonstrated that much of the increase in TP loads throughout the state from 1980 to 2017 was in the form of dissolved phosphorus. Dissolved phosphorus can originate from wastewater discharge, as well as surface runoff and subsurface drainage from croplands. In a relevant case study, Jarvie et al. (2017) analyzed factors contributing to increases in soluble reactive phosphorus in rivers draining to western Lake Erie, where a harmful algal bloom in 2014 forced the closure of water supplies for Toledo, Ohio. They found that an estimated 35% of the increased load of dissolved phosphorus was due to increased river flow and 65% was due to greater availability of phosphorus for transport, possibly related to expansion of tile drainage and adoption of conservation tillage practices that contribute to higher concentrations of surface soil phosphorus. These findings suggest that, in this case, the interaction between climate change (increased precipitation and rainfall intensities) and changes in crop management practices appear to have increased soluble phosphorus loads.

While climate change and, most notably, increased precipitation and rainfall intensity tend to increase nutrient loads in rivers, crop management and conservation practices (e.g., wetland restoration) can also serve to mitigate increasing riverine nutrient loads. Additional research is needed to quantify the contributions of different factors and their interactions in different settings in Illinois.

Urban water quality

Urban influences on water quality are strongly linked to hydrology and climate. Changing patterns in precipitation (e.g., the overall increase in precipitation in Illinois and the Midwest) and the increasing tendency for larger precipitation events both have a significant influence on urban water quality as well as quantity. Many Illinois cities already experience frequent localized flooding from intense storms (e.g., CNT 2014; Winters et al. 2015; Wuebbles et al. 2019). Extreme storms are also expected to sharply increase over the next 50 years in this region (Winkler et al. 2012; Pryor et al. 2014; Winters et al. 2015; Kossin et al. 2017), and increased precipitation from these storms is expected to present particular hazards to cities in Illinois that will require convergent strategies to reduce vulnerabilities. Under-resourced communities suffer a disproportionate burden from storm impacts, owing to the confluence of low property values and inadequate infrastructure in low-lying, flood-prone areas (Wilson et al. 2010; CNT 2014).

Cities in the upper Mississippi River system and in the western Great Lakes region, including those in the Chicago region, are being increasingly impacted by flooding. Specific measures of stormwater mitigation performance can be tested against projected future precipitation patterns and corresponding investments in conventional stormwater infrastructure (sometimes referred to as "gray infrastructure") could be made. However, there are considerable concerns about relying on gray infrastructure for urban flooding protection, as infrastructure construction costs are very high and there is limited ability to undertake major expansions of gray infrastructure in highly developed urban areas (Bell et al. 2019; Hopkins et al. 2018). There also needs to be a comprehensive evaluation of the efficacy, economic benefits, and co-benefits associated with the wide range of green infrastructure (e.g., bioswales, raingardens, increased greenspace), including water quality, biodiversity, recreation, and health benefits (Bell et al. 2019; Miller and Dunn 2019).

Figure 3.9 Bioswales are a type of green infrastructure used for stormwater mitigation. **Source:** Kevin Arnold.

Flooding impacts water quality when stormwater overwhelms the capacity of combined sewer overflows (CSOs) and untreated wastewater is released directly into local water bodies. Flooding also increases land surface runoff, mobilizing contaminants from soils—including nutrients, metals, and persistent organic compounds, such as PCBs. Increasing variability in precipitation patterns, especially during the winter and throughout the spring, is exacerbating stormwater runoff and CSO events that affect water quality in urban streams and rivers and Lake Michigan within the Chicago region. Both CSOs and increased overland flooding cause environmental damage and public health hazards, such as increased exposure to infectious diseases and contaminated drinking water (see Chapter 5).

Under current water quality legislation, municipalities are charged by the U.S. Environmental Protection Agency (U.S. EPA) with reducing the number of combined sewer overflow (CSO) events to acceptable levels, either by more effectively maintaining and managing existing stormwater infrastructure or by designing and installing new infrastructure (e.g., increased stormwater storage facilities, green infrastructure, separated sewer and stormwater piping systems) to cope with these problems (Ando et al. 2019; Hopkins et al. 2018). These requirements affect both large and small cities alike. Chicago, for example, has invested heavily in the Tunnel & Reservoir Plan (TARP) Project to reduce stormwater damage in the city and CSOs to Lake Michigan. Smaller municipalities with combined sewers are also profoundly affected by the need to effectively manage existing sewer systems to meet water quality standards. Quantitative assessments of the performance of various available technologies that could be used to cope with projected increases in storm intensity in the future are urgently needed to guide long-term planning toward sustainable infrastructure and management approaches that will remain effective over the long term. Given the extremely high cost of large-scale infrastructure construction, like TARP, it is important to develop strategies that link conventional stormwater infrastructure with distributed green infrastructure to mitigate both local and regional flooding risks.

Groundwater quality

Illinois does not have sufficient groundwater quality monitoring to detect variations in quality related to changes in climate conditions; thus the effects are not well known and are primarily speculative. However, groundwater quality changes are expected, most likely driven by alterations to natural recharge or increased pumping demands on unconfined aquifers.

Whittemore et al. (1989) reported a relationship between the Palmer Drought Index and variations in groundwater quality of public supply wells in Kansas. The predominant effect they observed was that total dissolved solid (TDS) concentrations, primarily sulfate, chloride, calcium, and sodium, slowly increased during droughts due to a lack of diluting recharge. This correlation between drought and groundwater quality was significant only for aquifers with relatively shallow water tables (< 10 meters). Kampbell et al. (2003) also reported increased levels of several dissolved constituents, including nitrate, chloride, sulfate, and orthophosphate, in shallow wells surrounding Lake Texoma (between Texas and Oklahoma) during a short-term drought in 2000. Another potential mechanism that can affect groundwater quality during drought occurs when lowered water tables expose more substrate to atmospheric oxygen, leading to the oxidation of reduced minerals or aqueous species. For example, if a pyritic zone is exposed, the oxidation of pyrite can lead to decreases in pH, increases in sulfate, and increases in arsenic (Appleyard et al. 2006).

Groundwater quality will also be impacted if wetter conditions in the future result in increased recharge of aquifers. Many shallow aquifers are hydrologically connected to streams and rivers and receive recharge from them during floods or high-water episodes. This surface water recharge may introduce contaminants into aquifers that are not typically found in groundwater, including various pharmaceutical and personal care products, pesticides, per- and polyfluoroalkyl substances (PFAS), and pathogenic microorganisms and viruses. If snow and ice events increase due to wetter conditions, a potential impact on both surface water and groundwater quality is increased salinization as a result of increased applications of deicing salts.

Lake Michigan

One of the great resources for Illinois is the state's connection to Lake Michigan, the second largest of the Great Lakes. Lake Michigan moderates temperatures in northeastern Illinois throughout the year by cooling nearby lands in the summer and warming them in winter. Climate change presents a number of challenges to Lake Michigan and its coastlines (USGCRP 2018; Wuebbles et al. 2019), and this section touches on several water-related issues that affect Illinois and its relationship to Lake Michigan (see Wuebbles et al. 2019 for discussion of many other related issues).

In recent years, large rainfalls in the Great Lakes watershed have resulted in extremely high water levels that threaten coastlines and associated properties in the Chicago region. Historically, Lake Michigan's water levels have fluctuated considerably over multi-decadal time scales (e.g., see Wuebbles et al. 2019) and over the long term, depending on the balance between the amount of precipitation, runoff, evaporation, and evapotranspiration in the watershed, and evaporation from the Lake itself. Warmer future temperatures will result in more evaporation (from the Lake) and evapotranspiration (from soils) during the summer and winter, when there is expected to be less future lake ice. Although some studies (e.g., Lofgren and Rouhana 2016; Notaro et al. 2015) have suggested modest changes in future lake levels of a few inches' decrease or increase, there is significant uncertainty in these projections. Because of the potential for higher lake levels to damage coastal infrastructure and increase coastal erosion, there is substantial concern about the potential for projected increases of winter and spring precipitation to increase lake levels. Additional research is needed to fully understand this issue and the potential impacts on Illinois coastlines.

Increases in precipitation are expected to result in higher nutrient loads to rivers, with much of this increase related to agricultural activities rather than urban inputs (Wuebbles et al. 2019). Although the area draining directly to the lake is relatively small and mostly urban in Illinois, local streams and ravines contributing increasingly higher nutrient loads can have an impact on Lake Michigan's water quality that include increased risk of harmful algal blooms. Currently, the majority of the concern with such algal blooms is associated with Lake Erie.

Dissolved phosphorus loading from watersheds is of particular concern because of the potential to cause harmful algal blooms and reduce dissolved oxygen concentrations (Burlakova et al. 2018; Scavia et al. 2014). Since the 1990s, algal blooms and extensive hypoxia zones have re-emerged as problems in Lake Erie (Scavia et al. 2014), linked to phosphorus loadings from the agricultural sector. While such algal blooms have only been a localized problem in Lake Michigan, particularly around Green Bay (Bartlett et al. 2018; Lin et al. 2016), increasing prevalence and size of algal blooms elsewhere in the Great Lakes present a concern for Lake Michigan. Around 50% of phosphorus inputs are derived from point sources and urban sources for all Great Lakes, excluding Lake Superior. Manure is also an important source of phosphorus in Lake Michigan (Robertson and Saad 2011).

From the standpoint of climate change impacts, nutrient delivery from tributaries is the dominant input to the Great Lakes, including Lake Michigan; thus, climate-driven patterns influencing flow regimes are likely to have a large impact on future nutrient delivery (Robertson et al. 2016). Large storms are likely to increase the incidence of sewage bypass in urban areas (i.e., CSOs) and flooding of manure management systems, thereby increasing the input of phosphorus into the Great Lakes.

Water supply

Water demand

Impacts of climate change on public water systems, domestic demand, and cropland irrigation in Illinois were examined with U.S. EPA's Climate Resilience Evaluation and Awareness Tool (CREAT; EPA 2015), which provide projected changes in climate conditions to water resource planners and managers for three climate scenarios: hot/dry, central, and warm/wet. The hot/dry scenario projects hotter and drier conditions; the warm/wet scenario projects less warming but greater precipitation; and the central scenario's projections lie in the middle. Water conservation and water use efficiency improvements that have been observed in recent decades were assumed to be stable in the future scenarios. Under these assumptions, for the three climate scenarios, climate change impacts are expected to increase water demand in 2035 and 2060 in the Middle Illinois, Kankakee River, and Northwest Illinois water supply planning regions (Meyer et al. 2018, 2019a, 2019b). For the Middle Illinois region, both municipal and domestic water demand are expected to be higher for all three scenarios and greater in 2060 than 2035.

Surface water supply

Surface water resources in Illinois include free-flowing streamflow in rivers and streams, stored water in reservoirs or lakes, and water diverted from Lake Michigan. Low-head dams, off-channel reservoirs, or impoundment reservoirs may be used to augment surface water supplies. Historic droughts in the 1930s and 1950s galvanized many municipalities in southern Illinois to build impoundment reservoirs or off-channel reservoirs to address potential water supply shortages associated with long-term droughts. Interestingly, many rivers and streams throughout Illinois have seen increased low and mean flows starting around 1965–1970 (Knapp 2005), as seen in the Kankakee River watershed (Kelly et al. 2019) (Figure 3.10). Low flow and mean flow changes appear to be step changes instead of gradual changes coincident with increased precipitation that has occurred in Illinois.

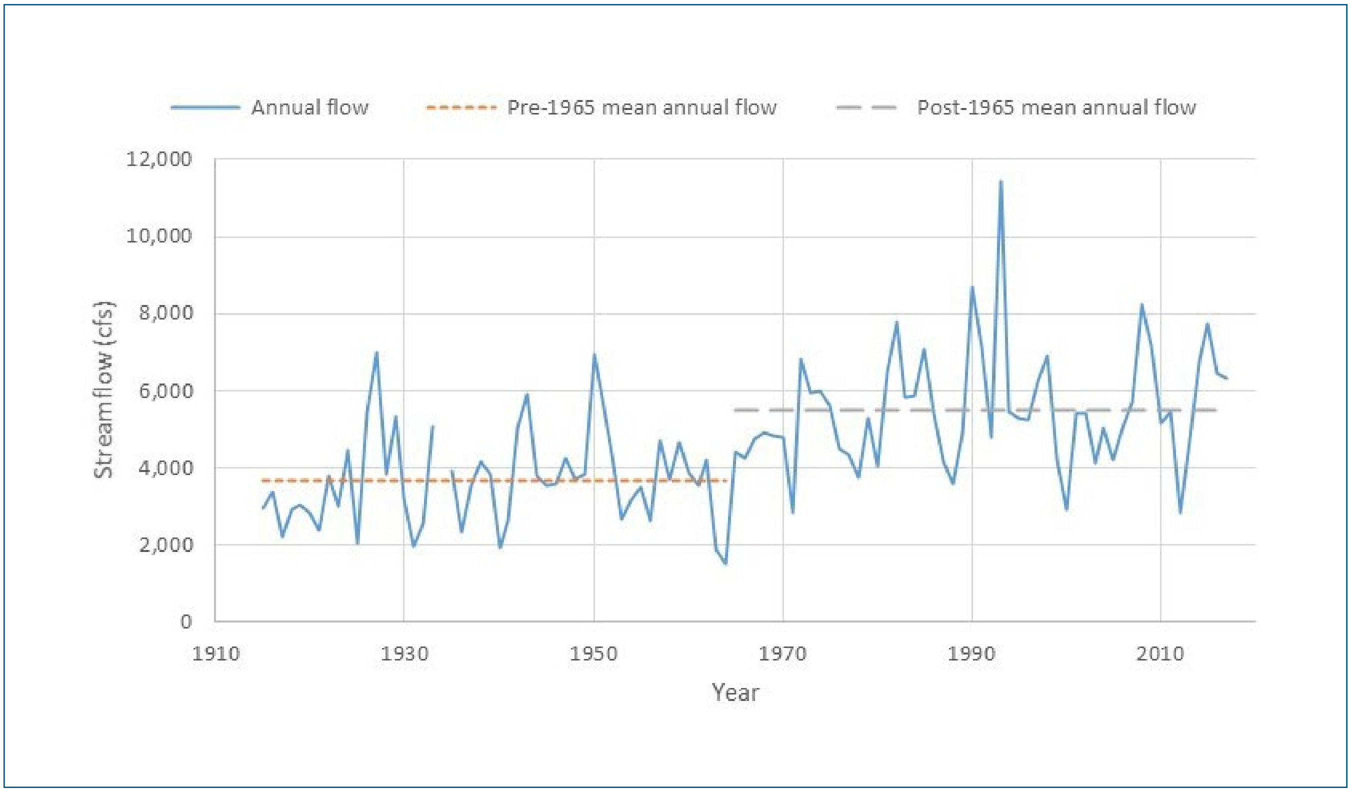


Figure 3.10 Annual streamflow for the Kankakee River near Wilmington, Illinois. **Source:** Kelly et al. 2019.

The impact of future climate on the surface water supply in the Kankakee River watershed has been evaluated by Kelly et al. (2019) for different future climate scenarios, including the two scenarios considered in this report—RCP4.5, the lower scenario, and RCP8.5, the higher emissions scenario. Kelly et al. (2019) also consider an even lower scenario, RCP2.6. Mean annual streamflow and 7-day minimum flow under six different water demand scenarios were compared with streamflow in a baseline period (1986–2006). Mean streamflow is expected to increase by 2100 under all three climate scenarios, indicating the average surface water supply in the watershed will increase as a result of climate change. However, the 7-day minimum flow is expected to decrease under all three scenarios (Figure 3.11). As surface water supply is often limited by low streamflow unless it is augmented by in-channel or off-channel storages, this indicates that climate change may increase risks to surface water supply in drought conditions even though it may increase surface water supply during normal conditions. Coupled with the minimum flow regulations for public waters in Illinois, surface water supplies may be challenged by extended drought and increasing requirements of minimum flow to protect riparian and aquatic species in the future. Increasing temperatures in future climate scenarios also imply increasing electricity demand, which in turn could increase demand for surface water for cooling purposes. Surface water supply to meet cooling water demand by thermoelectric power plants could thus face challenges of diminishing low flow, increasing water temperature, and increasing water demand.

Groundwater supply

The effects of climate change will be less obvious on groundwater resources than on surface water but could still be profound. If precipitation amounts change significantly, this could impact both natural conditions and human behaviors that affect groundwater resources. Projected increases in precipitation would increase recharge to shallow aquifers, which could result in higher baseflows in

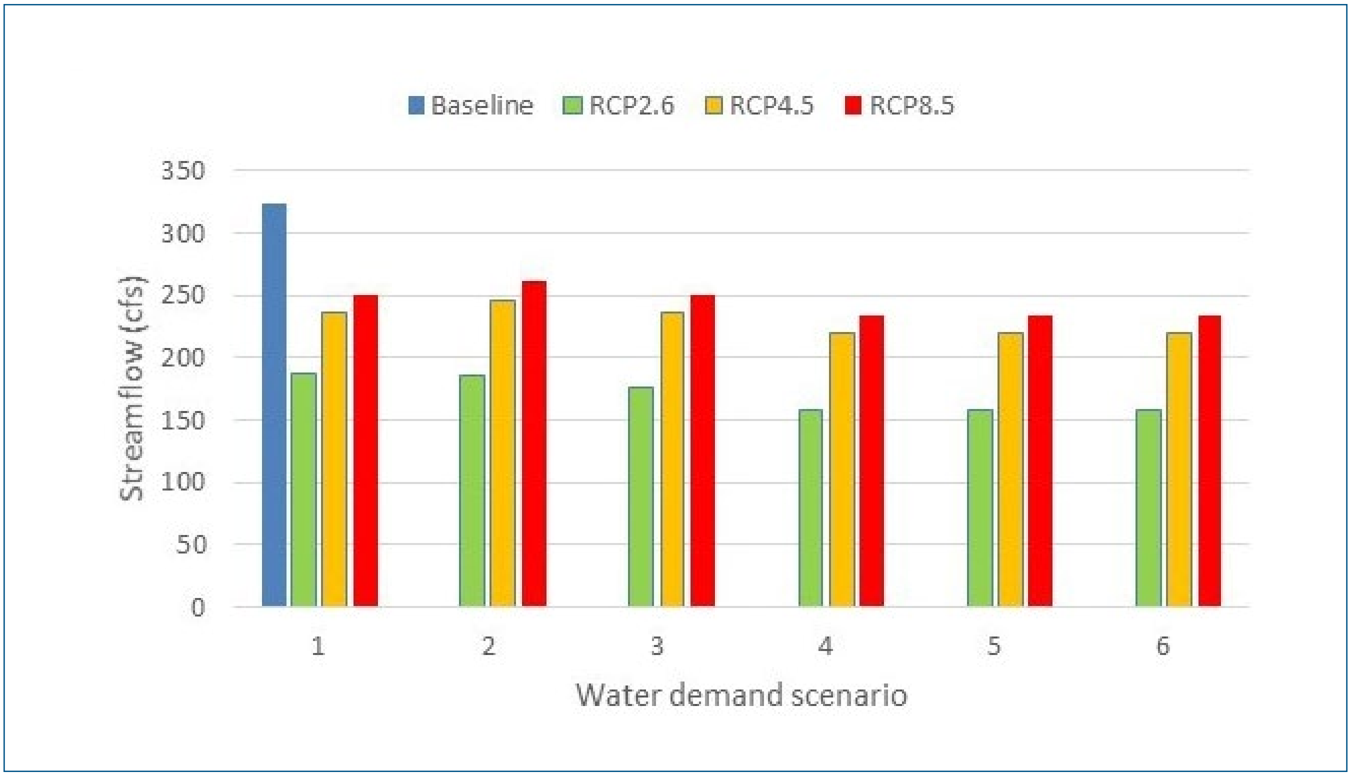


Figure 3.11 Comparison of baseline 7-day minimum streamflow by 2100 for the USGS gage (05527500) at the Kankakee River near Wilmington, Illinois (continuous simulation for 1986–2016) for three climate scenarios and six water demand scenarios. Scenario 1 represents the lowest water demand scenario, while scenario 6 represents the highest water demand scenario. Climate scenarios are RCP2.6, RCP4.5, and RCP8.5. **Source:** Kelly et al. 2019.

streams, higher water tables during spring, increased basement flooding, and more demand for tile drainage in row crop areas. Conversely, more frequent drought could result in lower water tables during peak pumping conditions in the summer, potentially impacting the sustainability of groundwater resources, and increasing costs of extraction, as groundwater will need to be pumped from greater depths. With summer droughts likely becoming more frequent and intense, society may depend more on groundwater resources. Short-term impacts due to increased pumping from aquifers include depressed water levels, shallow wells going dry, and decreased groundwater discharge to surface streams and lakes. A decrease in groundwater discharge will not only contribute less water to surface water bodies, it will contribute to increasing water temperatures, causing additional stress on aquatic biota.

Because Illinois has a humid temperate climate and soils with high moisture-containing capabilities in much of the state, irrigation is unnecessary in most regions. However, recent droughts in Illinois have contributed to an increase in the installation of irrigation wells (Knapp et al. 2017). These irrigation wells are seen as a guarantee for crops in case of dry conditions. Even in wet years, irrigation pumps are generally turned on during parts of the growing season. The volume of irrigation water applied can be quite large, as individual wells can produce more than 1 million gallons per day. During the drought of 2012, approximately 100 billion gallons of water were pumped from irrigation wells in Mason and Tazewell Counties in Illinois during the growing season over an area of about 135,000 acres (Figure 3.12).

A large increase in center pivot irrigation was observed throughout the state following the drought of 2012. In 2012, a GIS analysis indicated that 536,000 acres of Illinois were used for center pivot irrigation. In 2014, a repeated analysis revealed that 625,000 acres were used, a 17% increase in center

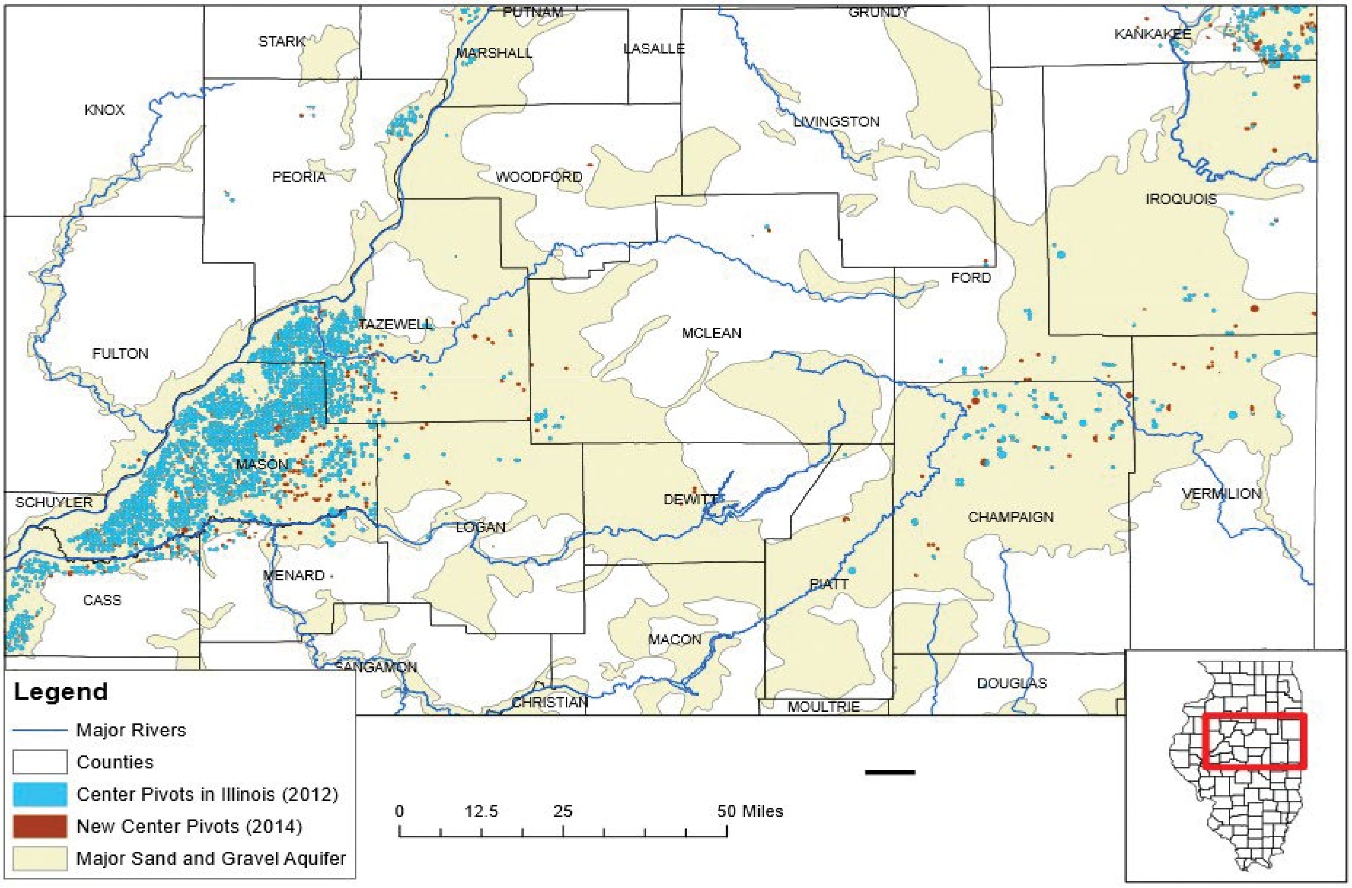


Figure 3.12 Increase in center pivot irrigation in the Mahomet Aquifer of east-central Illinois. There was a 14% increase in irrigated acreage in Illinois in the two years after the drought of 2012, indicating that more numerous droughts in the future are likely to negatively impact aquifers in agricultural regions. **Source:** Bridges et al. 2015.

pivot irrigation (Bridges et al. 2015). The percent increase was consistent across the state: 14% in east-central Illinois (Figure 3.12), 15% in the Green River Lowlands in northwestern Illinois, and 17% in the southern portions of the state.

Irrigation pumping impacts are most pronounced where aquifers are confined, although this impact is largely seasonal. One example is the Mahomet Aquifer in east-central Illinois. During the 2012 drought, the daily irrigation pumping rate in Champaign County was estimated to be around 70 million gallons per day, which was twice the rate of the public and industrial users in the county. Sharp and rapid decreases in water levels were observed, and there were reports of shallow domestic wells in the area going dry (Knapp et al. 2017). Another example is the Sankoty Aquifer in north-central Illinois. Figure 3.13 shows how water levels drop more than 20 feet when irrigation pumps are turned on and rebound when pumps are turned off.

A recent study of the deep Cambrian-Ordovician sandstone aquifers of northeastern Illinois notes that groundwater levels can have large variability (30–100 feet) throughout the year due to different seasonal factors (Abrams and Cullen 2020). While this is hypothesized to be driven in part by climate, other factors also play a role, such as the production schedule of industries and shifting pumping distributions of wells. As water levels continue to decline, wells are increasingly at risk of not being able to meet demands. Changes in precipitation have very little direct impact on this very deep aquifer because it receives little recharge. However, the aquifer is most at risk during peak pumping conditions, and understanding the role that climate plays in fluctuations in demand will be critical.

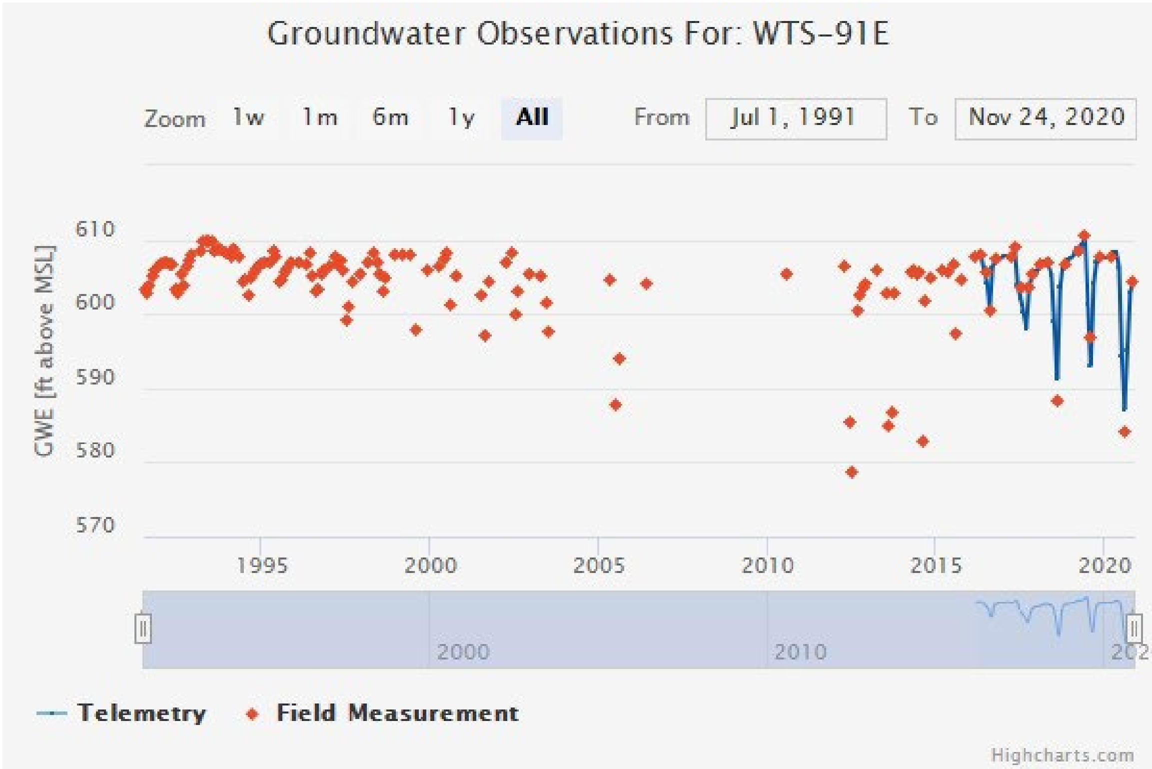


Figure 3.13 Hydrograph showing water levels from the 1990s to 2020 for a well in the irrigation region of the Sankoty Aquifer in Whiteside County, Illinois. Water level declines of greater than 20 feet are observed when irrigation pumps are turned on, then the water returns to pre-pumping levels when irrigation season ends. Increased irrigation wells will lead to increased drawdowns, and non-pumping water levels may trend down over time. **Source:** Illinois State Water Survey 2020a.

Knowledge and research gaps

For planning purposes, the assessment of climate impacts increasingly requires higher resolution projections, including characterization of the full range of precipitation variability to consider how the magnitude, duration, timing, persistence, and extremes of precipitation impact all aspects of agricultural, urban, and ecosystem management. The magnitude and persistence of temperature changes, including temperature extremes in the form of heat and cold waves, are also important to understand. At the same time, the need to develop targeted adaptive resource management strategies is increasing rapidly, in both urban and rural environments. There is an increasing need for strategies that are responsive to both immediate operational needs and longer-term planning and design needs. The development of informed strategies can be facilitated, in part, by reducing uncertainty in our understanding of climate drivers and the changing inter-dependencies in terrestrial environments. Continuing to improve predictive capabilities across the range of built, managed (agricultural), and natural environments will be important to facilitate management and planning needs. The following areas of research need attention in order to sustainably manage Illinois' water resources into the future.

- **Downscaling of climate projections**
  Decision-making at the local level requires higher resolution models than those used to project climate changes at the global or even regional scale. Nested modeling is a popular approach to resolve finer scale variability and, with two to three levels of nesting, it is now often possible to derive statistical attributes at 4-km resolution. While this has significant potential for applications in areas where there is a need, for example, in an urban environment or for agricultural management, these resolutions are still insufficient. In the near future, achieving even higher resolution, such as 1 km, will be feasible. Statistical downscaling approaches can also be used and often perform in a comparable manner to nested modeling for certain studies. There is a need to advance such approaches, perhaps in a blended manner with increasingly higher resolution modeling.

- **Update rainfall frequency studies**
  Due to the changing nature of heavy precipitation in Illinois, the appropriate nonstationary statistical frequency estimation methodology needs to be applied periodically using additional rainfall gauge data as they become available in the future. Updates of rainfall frequency estimates in Illinois are recommended every 15 years (Angel et al. 2020; Winters et al. 2015). Significant research has been undertaken to develop and test new methods for nonstationary precipitation frequency analysis, but those methods still exhibit significant variability in space and time (Angel et al. 2020). In addition, the future projected, downscaled, and de-biased precipitation data (e.g., Markus et al. 2012, 2018; Um et al. 2016, 2017) should also be analyzed using nonstationary methods.

- **Improve urban flooding data and adaptive management strategies**
  Comparative analysis and quantitative assessments of various available tools that could be used to study the effects of projected increases in storm intensity are urgently needed for long-term planning and the development of sustainable infrastructure and management approaches. Additional research is needed to better predict how increases in winter and spring precipitation will affect Lake Michigan's water levels and to determine the potential impacts on urban coastlines. Decades of insufficient funding have left many areas of the state with out-of-date flood hazard data, necessitating more funding for creating new, updated hazard maps. Additional research is also needed to evaluate strategies for linking conventional stormwater infrastructure with distributed green infrastructure to optimally mitigate both local and regional flooding risks, while also maximizing co-benefits to people and nature.

- **Quantify contributions of different factors to riverine nutrient loading**
  While increased precipitation and rainfall intensity tend to increase nutrient loads in rivers, crop management and other factors (e.g., wetland restoration) can also influence riverine nutrient loads. Additional research is needed to quantify the contributions of different factors and their interactions in different settings. Studying the effects of climate change on riverine nutrients is particularly relevant for the Illinois Nutrient Loss Reduction Strategy (NLRS). While it is well established that large nutrient loading episodes are associated with storm/flood events, it is not known to what degree climate change will impact these events or affect the success of agricultural and other management practices in reducing nutrient loads. Research in this area will provide critical feedback to inform NLRS and similar efforts.

- **Advance and integrate emerging sensing systems and prediction**
  New, highly distributed sensing systems have the potential to greatly increase both the spatial coverage and temporal resolution of data on climate change and its effects in Illinois. With the rapid decline in the cost of sensing technologies, miniaturization, and emergence of new measurement platforms such as drones and low earth-orbiting satellites, it is now possible to obtain environmental observations at a higher frequency and much higher spatial density. However, data from these technologies have highly varied coverage and resolution in both space and time, and they have not been closely integrated with existing data sources or synthesized to assess climate change at regional scales. Thus, the emergence of these "big data" sources has brought to the fore the issues of managing, sharing, and integrating big data into a predictive framework both through machine learning/artificial intelligence techniques and with models in a model-data blended framework. These data are also facilitating the emergence of a new generation of models capable of prediction at extremely high resolution. New research is needed to advance predictive capabilities, both for operational decisions and scientific explorations, using such high-resolution data through approaches based in effective model-data integration.

- **Expand research to guide water use planning and management**
  Knowledge gaps regarding how water resources will be affected by climate change create important challenges for planning and management. Research is needed to guide the sustainable management of drinking water from both surface and sub-surface sources, based on the effective assessment of how availability and replenishment capacities will be impacted by climate change. Furthermore, the behavior of agricultural systems under a changing climate remains unpredictable, and research is needed to improve our understanding of climate change-driven changes on crops and crop management systems, including potential changes in irrigation demand. Additional research is also needed to understand how climate change will impact water quality, especially how the loading of nutrients, sediment, and other contaminants from both urban and agricultural areas is most likely to shift. How these various factors, together with associated uncertainties (e.g., technological and economic changes), can be characterized and integrated to guide water use and management best practices is a pressing area of research.

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CHAPTER 4

Climate Change Impacts on Agriculture

Key Messages

1. Agriculture in Illinois is already being impacted by climate change and is likely to face significant hurdles adapting to the changing climate over the coming decades. Future agricultural production in Illinois is strongly dependent on investments made today in agricultural research and development, reducing carbon emissions, and increasing practices to help farmers cope with climate risks.

2. Heat and water stress are likely to reduce corn yields by mid-century in Illinois, although the severity of loss depends on available technology and new management practices. Some yield losses could be overcome if sustained improvements in seed technology and management adaptations, such as planting date and fertilizer adjustments, are able to mitigate the impact of extreme heat and drought. Farmers may also switch to crops that are better suited to the future climate.

3. Increased atmospheric CO_2 is likely to benefit soybean yields in the near-term, but as heat and water stress intensify later in this century, soybean yields are expected to decline. Increased CO_2 is not expected to increase corn yields, even in the near-term.

4. Illinois livestock will face growing threats from climate change related to heat stress, reduced forage quality, and increased disease. Daily temperatures exceeding 86°F trigger heat stress in numerous livestock species, and Illinois will see an increase of 40–55 days per year above this threshold by mid-century and 50–86 days per year by late century.

5. Weeds, pests, and diseases are expected to increase because of warmer winters, increased spring precipitation, and higher temperatures, and will have significant negative effects on crops and livestock in Illinois. Resistance to pest and disease control methods could also compound climate change risks and/or increase management costs.

6. Warming temperatures will shift plant hardiness zones northward, making certain varieties of fruits, vegetables, and nuts unable to thrive in Illinois. Adopting new crop varieties, adjusting management practices, and investing in new machinery may help growers adapt.

Introduction

In Illinois, agriculture forms a central pillar of the economy and a dominant part of the landscape. Illinois' fertile soils, level to gently sloping land, and favorable climate make it uniquely situated to be a major agricultural producer, especially of corn and soybeans. Illinois farmers also raise livestock and numerous specialty crops, including pork, horseradish, and pumpkins. Agricultural commodities generate over $19 billion annually, and billions more are generated each year through agricultural processing, manufacturing, and other agriculture-related industries (IDOA n.d.). The sector employs nearly 1 million people (IDOA n.d.) and supports over 71,000 farms and 116,000 producers (NASS 2019c). Yet, the favorable climate on which Illinois farmers depend is already and will continue to be impacted by climate change. Illinois is expected to face a much different climate than any experienced in the state's history, and agriculture is likely to face significant hurdles adapting to this new climate.

As outlined in Chapter 2, Illinois is now experiencing a climate that is already significantly warmer and wetter than at any time in the last 120 years. Most noticeably, statewide annual precipitation has increased by 4.7 inches since 1895. Precipitation increases have been observed in all four seasons, with much of the observed increases coming from heavy rainfall events that cause flooding and soil erosion. The number of 2-inch rain events has increased by 40% since 1895. Meanwhile, temperatures have risen by 1–2°F across Illinois in the last 120 years. Overall, nighttime temperatures have warmed faster than daytime temperatures, with the strongest warming occurring during winter.

Human-induced climate change will continue in Illinois for the rest of the 21st century. Temperatures are projected to increase between 3–5°F by mid-century and 4–9°F by late century. To put that in perspective, the hottest summer on record in Illinois was 1936, when temperatures were 4.5°F above the 1990–2019 average. By mid-century, that could be considered a typical summer; by late century, it could be considered a cool summer. Meanwhile, precipitation increases are projected to range between 0–6% and 2–10% by mid- and late century, respectively. Importantly, future precipitation changes show strong seasonal differences, with much wetter winter and spring seasons, slightly drier summers, and only small changes in the fall (see Figure 2.14 in Chapter 2). Under the higher scenario, winter precipitation could increase 10–20% and spring precipitation could increase 5–25% by late century, while summer precipitation could decrease by around 5% in the same period. For both temperature and precipitation, the more extreme changes correspond to the higher scenario and the lower ends of the ranges correspond to the lower scenario. Thus, preventing the most extreme impacts to the agricultural sector depends on significantly curbing emissions.

As overall temperatures rise, the risk of extreme heat is expected to rise substantially. Although days at or above 100°F are now very rare in Illinois, they will be increasingly more common by mid- to late century, especially in central and southern Illinois. Chapter 2 shows similar increases in the number of days per year with nighttime temperatures over 70°F. Warmer temperatures also lead to increased evapotranspiration, which can cause significant crop and ecosystem stress during dry conditions. In the reference location of Dekalb, Illinois, evapotranspiration has already increased by 0.17 inches per year since 1990 and it will continue to increase statewide with increasing temperatures. The combination of higher temperatures, less summer precipitation, and longer stretches of dry days between more concentrated rain events is likely to increase the risk of summer droughts. All of these changes could adversely impact agriculture.

Conversely, the risk of colder temperatures is expected to decrease with time. Projections of the freeze-free season and growing degree days (GDD) in Chapter 2 show substantial lengthening of the growing season in Illinois, with both pros and cons for agriculture. Specifically, by mid-century, the freeze-free season could extend by about 10–15 days under a lower scenario and 15–20 days under a higher scenario. In the same period, GDD are projected to increase by 500–1,000 under the lower scenario and

750–1,250 under the higher scenario. Although longer growing seasons with more GDD accumulations may allow for more growth and higher productivity of crops, this could also increase the risk of crop damages from a late spring freeze if crops are planted earlier in the spring. Longer growing seasons may also deplete reservoirs of stored soil moisture, potentially making crops more prone to water stress during critical growth periods.

Although some impacts may be mitigated through management adaptations and technological advances, agricultural production is very sensitive to climate conditions and will inevitably be impacted by increasing temperatures, changes in precipitation patterns, and rising CO_2 concentrations. The extent to which these climate variables are changing has important direct and indirect implications for the agricultural sector, which are described in more detail in this chapter. Owing to the predominance and economic importance of corn and soybeans in Illinois, this chapter emphasizes potential impacts on these two crops. Both direct climate change impacts, such as changes in temperature and precipitation patterns, and indirect impacts, such as how climate change may affect the incidence and management of insects, pests, and diseases, are considered. The chapter also covers potential impacts of climate change on specialty crops and livestock, as well as economic impacts to the sector.

Corn and soybeans

Illinois is consistently a top producer of corn and soybeans in the United States—ranked first in the country for soybean production and second for corn production in 2019 (NASS 2019c). Row crop production of corn and soybeans dominates 55% of the total land area in the state (NASS 2019b), sustains a multibillion-dollar industry that supports the state's economy, and is an especially vital component of rural economies. Given the importance of these crops to Illinois, it is critical to understand how climate change may impact yields and farm management. To better understand these impacts, we consider peer-reviewed literature of field experiments, as well as two models that include long-term trend data, to provide valuable information on the most likely impacts of climate change on corn and soybean production in Illinois.

Effects of warmer temperatures

Both corn and soybean yields are negatively impacted by extreme temperatures. Yields of both crops have been found to decline significantly when optimum growing temperatures are exceeded—temperatures above 84°F for corn and 86°F for soybeans (Schlenker and Roberts 2009). In the future, Illinois is expected to experience an additional 40–86 days per year exceeding the temperature threshold of 86°F. The lower end of the range represents the increase by mid-century under a lower scenario, while the higher end represents the projected increase by late century under the higher scenario. In some cases, different varieties of corn and soybeans, local agroclimatic conditions, and management can mediate yield losses.

In general, temperatures above 95°F for corn and 102°F for soybeans are considered detrimental to reproduction (Angel et al. 2018), although the threshold can also vary by variety and field conditions. In the second half of the century, crop models project that heat stress during the reproductive period will reduce corn yields (Angel et al. 2018). Projections for the annual hottest 5-day maximum temperature in Illinois (Table 4.1) show the extent of the challenge by late century, when sustained heat above these thresholds is expected across the state.

Table 4.1 Projected annual hottest 5-day maximum temperature (°F) across Illinois by late century under the lower and higher scenarios

	Lower Scenario	Higher Scenario
Northern Illinois	96–104	100–110
Central Illinois	98–106	102–112
Southern Illinois	100–107	102–114

Projected temperatures for northern, central, and southern Illinois given in °F.

Extrapolating historical yields of corn and soybeans into the future

Corn and soybean yields in Illinois have increased steadily over the past 40 years (1980–2019), at an average annual rate of nearly 2.3 bushels per acre for corn and more than 0.5 bushels per acre for soybeans. If the yield gains experienced over the past several decades were extrapolated to 2050, average maximum attainable corn yields for the Corn Belt would increase to 236 bushels/acre and up to 250 bushels/acre in some areas, though it is important to note that rain-fed areas often attain yields 20–30% below the maximum due to factors like heat and drought stress (DeLucia et al. 2019). However, it is not possible to simply extrapolate historic yield gains into the future, because it is likely that various climate factors may negatively impact yield gains (DeLucia et al. 2019; Hatfield et al. 2011; Jin et al. 2017). Heat, drought, and other extreme weather events may all influence future yield trends.

It is possible that some challenges presented by climate change may be overcome or mitigated through crop genetic improvements or management practices, but these advances and adaptive measures are hard to predict. Seed technology (breeding and biotechnology) and increased planting density have arguably been the most important contributors to yield increases over the last several decades (e.g., Assefa et al. 2016). In the future, yield and stress tolerance of crops may continue to improve, as seed companies are focused on continuing the yield trajectory by improving yield potential, heat tolerance, pest resistance, and water-use efficiency of crops. However, because future technological advancements are uncertain and not guaranteed, considering a future scenario without all the possible benefits of adaptation is also relevant.

Research on global grain production suggests that the rates of yield gain are already beginning to slow (Grassini et al. 2013; Long and Ort 2010). This is possibly because traits, such as harvest index, which has been increased over recent decades to drive yield gain, may be approaching their theoretical maximum (Hay 1995; Lorenz et al. 2010; Reynolds et al. 2011). Even current rates of yield gain are projected to be inadequate to meet rising demand for key commodity crops in the future (Ray et al. 2013). Genetic improvements can help to continue the trajectory of continued yield increases, but those require immediate and significant investment, while contending with the need to adapt to climate change at the same time. Thus, future yields are uncertain and strongly dependent on choices made now about investment in agricultural science and climate change mitigation.

Corn yields also tend to be negatively impacted by warmer nighttime temperatures, which have already increased by 2°F over the past century and are projected to continue increasing with climate change. As explained in Chapter 2, the number of nights with minimum temperatures of 70°F or higher is expected to increase under both lower and higher scenarios. Under the lower scenario (RCP4.5), Illinois could experience an extra 16–32 warm nights by mid-century and 16–40 warm nights by late century, with temperatures of 70°F and above. Under the higher scenario (RCP8.5), the number of warm nights could increase by 16–40 by mid-century and by 40–72 nights by late century.

Effects of changing precipitation patterns

Under the higher scenario (RCP8.5), climate conditions in Illinois could more closely resemble the drought year of 2012 by the 2050s–2070s (Hoffman et al. 2020). Because the vast majority of Illinois corn and soybean production is rainfed, droughts can greatly impact yields. Drier and hotter summers, which are predicted for Illinois in the future, have the potential to increase water stress on corn and soybean crops, especially during critical growth periods when water stress has the largest negative impacts (Zhou et al. 2020). The most critical growth stage for corn occurs during the silking and grain-filling stages, typically 70–90 days after planting; in Illinois, where corn is often planted in early to mid-May, this usually occurs between mid-July and August (Zhou et al. 2020). For soybeans, the most critical growth occurs during blooming and podding, typically 65–105 days after planting; in Illinois, where soybeans are planted from mid-May to early June, this usually occurs in August or early September (Zhou et al. 2020).

According to an analysis of the impacts of drought and excessive precipitation on corn yields in Illinois between 1981 and 2016, corn yields have historically been impacted more by drought than excessive precipitation (Li et al. 2019). For the study period 1981–2016, extreme drought reduced corn yields in Illinois by as much as 45.7%, whereas extreme precipitation reduced corn yields by around 5.3% (Li et al. 2019). According to crop insurance data, the largest drought losses have occurred in July, the hottest month of the growing season, when corn is in the silking and grain-filling critical growth stage (Li et al. 2019). The most damage is likely when drought occurs concurrently with excessive heat (Li et al. 2019). The largest impact from excessive rainfall occurred in June, the wettest month of the growing season, when most corn has either been planted or has already emerged, although excessive moisture can also cause damage in July during silking and grain-filling growth stages (Li et al. 2019). While excessive moisture does not tend to limit corn yields as much as drought, wet years can lead to condensed growing seasons, wet crops during harvest, and reduced grain quality (Todey 2020).

Historical observations of how annual yields of corn and soybeans have been impacted by significant weather events between 1980 and 2019 are depicted in Figure 4.1. This figure shows significant droughts occurred in 1983, 1991, and 2005, resulting in significant crop losses, especially for corn production. In 1988 and 2012, drought combined with extreme heat led to even greater yield declines. The spring of 2019 was historically wet and resulted in the largest number of Prevented Plant and Replant crop insurance claims on record.

To fully understand the impacts of drought on crops, it is important to consider both soil moisture and atmospheric water demand—dry soil and dry air both restrict photosynthetic activity. On rainfed farms, an indicator of a plant's atmospheric water demand, known as the Vapor Pressure Deficit (VPD), may be the dominant indicator of water stress on crop growth and yield (Zhou et al. 2020). Corn yields, which are more sensitive to VPD than soybeans, are likely to be limited by VPD in the future unless irrigation is greatly expanded and/or genetic improvements can be made to increase water-use efficiencies of corn (DeLucia et al. 2019).

DeLucia et al. (2019) suggest that maintaining current corn yields in rainfed areas may require a more than threefold increase in irrigation without genetic changes to increase crop water-use efficiencies. Northern Illinois sits over the Midwestern Cambrian-Ordovician Aquifer System, which has already been heavily used and substantially depleted for municipal and industrial water use. Thus, increasing demand to draw on this aquifer for irrigation would increase competition for water between agricultural and municipal interests (DeLucia et al. 2019). Because southern Illinois does not sit over a major aquifer, increased irrigation in that region would have to

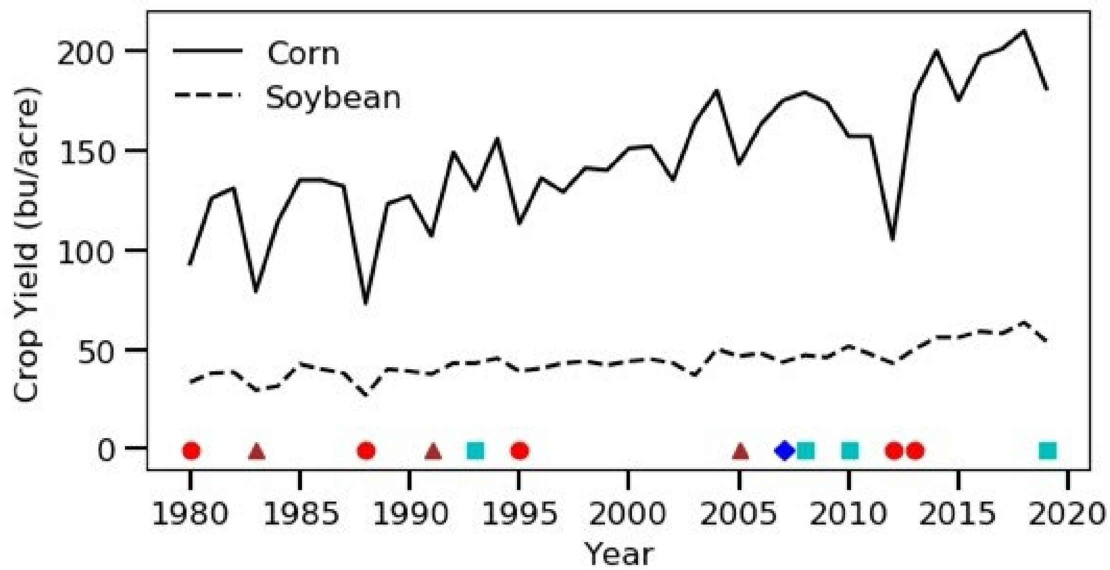

Figure 4.1 Observed corn (solid line) and soybean (dashed line) yields in bushels per acre for Illinois over the period 1980–2019. Colored markers at the bottom of the panel denote years with drought (brown triangle), drought with heatwave (red circle), freeze (blue diamond), and flooding (cyan square). **Source:** USDA NASS 2019a.

depend on surface water and could reduce stream flow (DeLucia et al. 2019).

Effects of Elevated CO_2

One very important consideration for future crop growth is the impact of elevated CO_2 levels on Illinois crops in the coming decades. Using energy from sunlight, plants remove CO_2 from the atmosphere and convert it into sugars that provide the backbone of all plant growth through the process of photosynthesis. Coupled with proteins and/or lipids, these sugars make up the harvestable components of crops. However, a crop's response to elevated CO_2 depends on the form of photosynthesis that the plant uses, which marks it as a C_3 or a C_4 plant. C_3 plants include soybeans, wheat, pumpkins, most fruits and vegetables, and trees, while C_4 plants include corn and sorghum.

Higher concentrations of CO_2 (also called CO_2 fertilization) can benefit crop productivity more for C_3 plants than for C_4 plants. For both C_3 and C_4 plants, elevated concentrations of CO_2 cause the stomatal pores on leaf surfaces to partially close and tends to reduce the amount of water vapor that is released to the atmosphere from leaves (Leakey et al. 2009). This can reduce a crop's demand for water uptake from the soil, conserve soil moisture supplies, and improve crop performance during times of drought stress (Leakey et al. 2009). This is the primary response observed in C_4-type species such as corn. In C_3 plants, like soybeans, elevated CO_2 also tends to increase how much CO_2 is captured from the air and made into sugars by photosynthesis, which can potentially increase growth and yield (Ainsworth and Long 2005; Leakey et al. 2009; Long et al. 2004). However, the effects of elevated CO_2 are modulated by other direct climate factors, including soil moisture and temperature, as well as disease and pest damage.

Climate change impacts on agricultural soil health

Agricultural productivity in Illinois depends in large part on the abundant deep, fertile soils that exist in the state. However, increased precipitation and more intense rain events associated with climate change will increase soil erosion (Angel et al. 2019; Ford 2020) and subsequent loss of soil organic matter (SOM). Higher temperatures are also projected to increase long-term SOM losses (Black et al. 2017). Projected climate impacts on agricultural soils are compounded by intensive tillage practices that are known to reduce SOM.

Soil organic matter plays an important role in the fertility and structure of soils and is critical for maintaining the water-holding capacity of soils and water availability for crops (Hatfield et al. 2013; Hudson 1994). Given these important functions, the loss of SOM will make future soils increasingly less resilient to extreme weather events. As covered in more detail below (see section 4.8), farmers can implement conservation practices to reduce erosion losses (i.e. grassed waterways) and practices like conservation tillage and winter cover crops to improve soil health. Practices that promote soil health also protect and improve water quality, which is similarly expected to be negatively impacted if erosion increases. Wide-scale adoption of cover crops is also one of the most important practices farmers can implement to facilitate carbon sequestration in agricultural soils (Fargione et al. 2018).

The SoyFACE experimental facility in Champaign, Illinois, provides Illinois with a unique knowledge of CO_2 effects on soybean and corn within the state. Free-Air CO_2 Enrichment (FACE) experiments assess the combined impact of elevated CO_2, temperature, and water availability on crops in an open-air field environment. According to this research, elevated CO_2 levels expected to occur at mid-century led to approximately ~15% greater yield in soybeans compared with normal Illinois growing conditions in the first decade of the 21st century (Leakey et al. 2006; Long et al. 2006; Morgan et al. 2005). This is in part because the extra production of sugars at elevated CO_2 by enhanced photosynthesis supports greater nitrogen fixation activity in the nodules on soybean roots (Rogers et al. 2006, 2009). The increase in yield primarily results from an increase in the number of pods per plant, but greater numbers of seeds per pod can also occur.

However, in the future, crops in Illinois will simultaneously experience elevated CO_2 and drier soils, due to higher temperatures and more variable precipitation. Initially, the positive effects of elevated CO_2 will likely outweigh the negative effects of heat and drought. But, as drought and heat intensify, elevated CO_2 will likely exacerbate rather than ameliorate stress for a number of reasons, including greater canopy temperatures and crop water use (Gray and Brady 2016; Jin et al. 2017; Ruiz-Vera et al. 2013; Thomey et al. 2019). Figure 4.2 depicts how elevated CO_2 is likely to affect soybeans under wet and dry conditions at mid-century.

In contrast with soybeans, field trials using FACE found that elevated CO_2 did not stimulate yield in corn growing in Central Illinois (Leakey et al. 2004, 2006). However, as drought becomes more severe in the future, the benefits of stomatal closure and reduced rates of water use due to elevated CO_2 may help to ameliorate yield loss from future droughts (Ottman et al. 2001). In sum, elevated CO_2 has the potential to benefit both corn and soybeans through drought protection. However, benefits from elevated

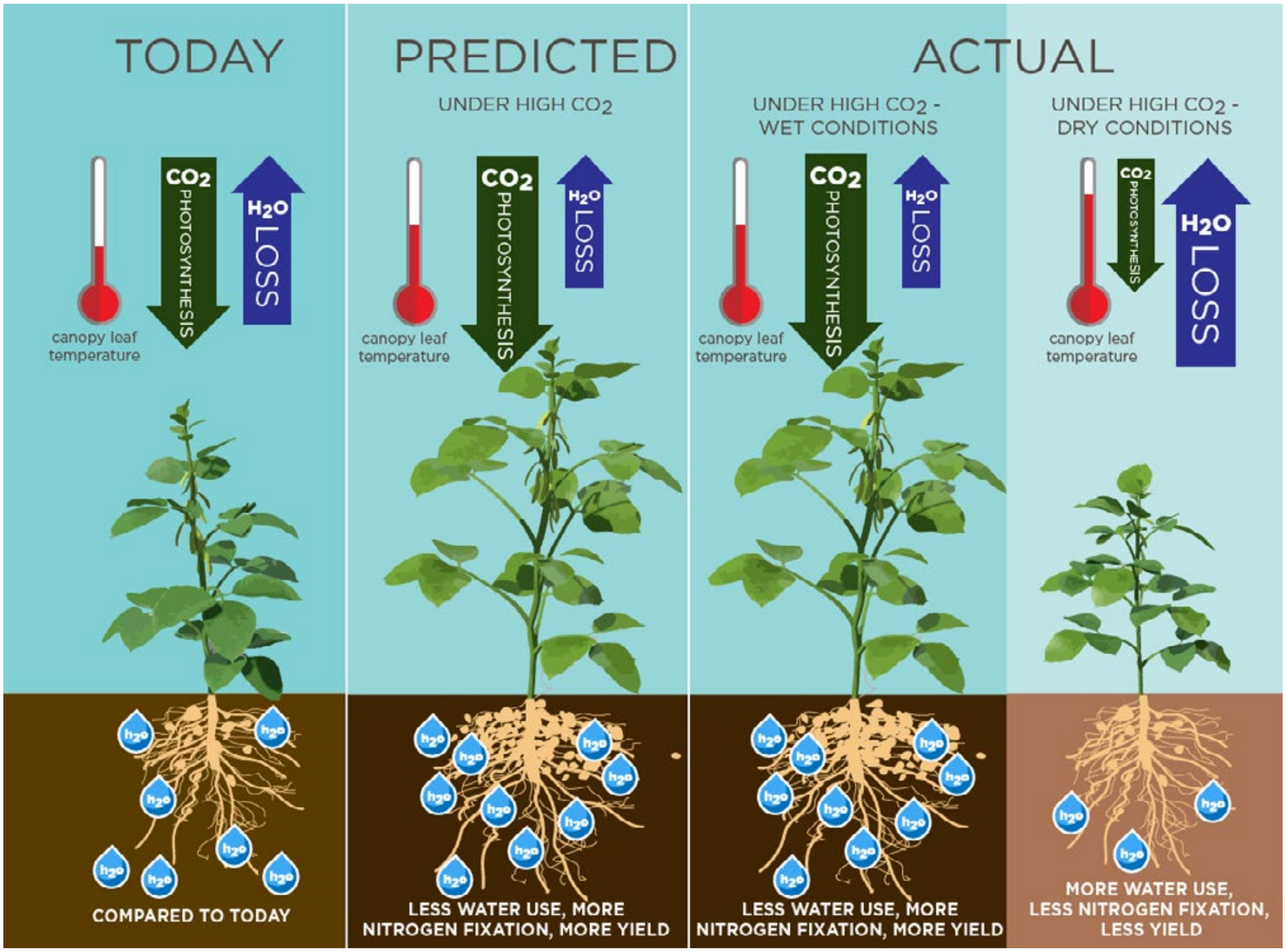

Figure 4.2 Soybean response to CO_2 and moisture conditions under climate change. As CO_2 levels rise compared with current levels, soybean yields will increase or decrease depending on moisture conditions. Under wet conditions, soybean yields are projected to increase by mid-century as a result of elevated CO_2. However, drier conditions will exacerbate stress, decreasing nitrogen fixation and resulting in lower yields. **Source:** Graphic by Julie McMahon.

CO_2 to soybean yields will be lost as drought stress becomes stronger and more frequent later in the 21st century (Jin et al. 2017).

The basic responses of plants to elevated CO_2 described above can also have subsequent indirect effects on crop quality, tolerance to pests and diseases, and agroecosystem function in a complex range of ways, depending on other aspects of the crop growing environment (e.g., temperature, drought, soil type) and crop management (e.g., fertilizer application, planting density). For example, although elevated CO_2 generally increases yield of C_3-type crops when sufficient water is available, it has been shown to negatively impact nutritional quality (Long et al. 2006). Reductions in seed quality take the form of lower contents of zinc, iron, and protein in crops such as wheat (Loladze 2014, Myers et al. 2014). In leguminous crops such as soybean, protein concentration is unaffected, but zinc and iron concentrations are reduced (Myers et al. 2014). Also, when adequate water is available, reductions in crop water use caused by future elevated CO_2 will reduce ecosystem evapotranspiration and are expected to increase run-off and streamflow (Husain et al. 2013; Jha et al. 2006; Leakey et al. 2009). The potential impacts of rising CO_2 on pest biology are difficult to project because examples of positive and negative outcomes have been observed in interactions of crops with different pests and diseases (Zavala et al.

2008; Zavala et al. 2017; Ziska and McConnell 2016), as discussed in greater detail below.

Projected impacts on corn and soybean yields from models

To complement the information outlined above, we also used two different modeling methods to help estimate the impacts of climate change, due to temperature, precipitation, and CO_2 levels, on corn and soybean yields in Illinois—a statistical model (Miao et al. 2016) and a simulation model, ISAM (Lin et al. 2021; Song et al. 2013). Although fundamentally distinct, the two methods represent the two most widely used approaches to predict the yield impacts of future climate change. The major difference between the two methods is that the statistical model does not consider management adaptation or future CO_2 concentrations, while ISAM includes CO_2 fertilization and specific management adaptations (e.g., earlier planting date, increased fertilizer use). Neither modeling approach considers uncertain future improvements in seed technology. The details of both approaches are described in the Supplemental Materials that accompany this chapter.

The results of the two approaches show stark differences, based on whether management adaptations are considered or not (see Supplemental Table S4.1). Without adaptive management and in the absence of any CO_2 fertilization effect, corn and soybean yields are projected to decrease 13–18% and 15–21%, respectively, in mid-century and 20–41% and 23–47%, respectively, by late century due to climate change. Under this scenario, extreme heat exposure has the largest impact on both corn and soybeans. If management adaptation and CO_2 fertilization are included, the ISAM model results indicate that it may be possible to offset negative yield impacts predicted by the statistical model in all but the higher climate change scenario (RCP 8.5) for corn in late century. ISAM model results suggest that yield gains of 8–13% in corn and 17–23% in soybeans could occur by mid-century, depending on the scenario. By late century, corn yields are projected to increase by 7% under the lower scenario and decrease by 7% under the higher scenario, while soybean yields are projected to increase by 17% under both scenarios. The beneficial impact of adaptation on yield is smaller under the higher scenario that results in more extreme climate change. Consistent with the SoyFACE experiments conducted at the University of Illinois, the CO_2 fertilization effect is projected to have a much larger impact on soybean yield than corn.

In the ISAM projections, which include management adaptation, the actions with the largest impact on corn yield are earlier planting date and increased use of nitrogen (N) inputs; the management adaptations considered are not projected to contribute meaningfully to soybean yield (see details in Supplemental Figure S4.2). With regard to increased N use, it is important to note that the ISAM model does not consider other environmental tradeoffs. Increasing the use of N fertilizer can be expected to worsen water quality even more than it is impaired today. This creates even stronger incentives to improve N use efficiency in corn and to implement strategies that minimize N runoff.

In general, technological progress and management changes are difficult to predict and, thus, not entirely captured by either model. It can be assumed that adaptation and technological progress will occur and may be able to at least partially offset anticipated yield decreases, especially advances in seed technology. Given the number of unknowns, it is difficult to predict exactly how corn and soybean yields will fare in the future under a warming climate. As such, these projections must be understood as estimates of *possible* future scenarios. Additional research is needed to help improve the accuracy of projections of how corn and soybean yields will be impacted by climate change in Illinois.

Days suitable for fieldwork

Beyond directly impacting crop performance, climate change could also affect aspects of farm management and the timing of planting and harvest. Days Suitable for Fieldwork (DSFW) is a measure of the number of days in a given week that fieldwork can be performed. The biggest determinant of this is soil trafficability—the physical ability to operate farm machinery in fields. If soils are overly wet, it can prevent farmers from working in fields to perform tillage, fertilization, chemical applications for weed and pest control, planting, or harvesting. For instance, soils that are too wet in the spring can cause delays in pre-planting fieldwork, when spring tillage and pre-plant fertilization are typically performed, which would lead to a delay in planting. Late planting can reduce yield potential, depending on the maturity rating of the cultivar planted and the number of Growing Degree Days (GDD) the particular cultivar requires. A shortened season can be particularly problematic for corn, which requires more GDD to reach maturity than soybeans (Todey 2020).

Historically, the spring period leading up to and including planting is the most critical time of the year for fieldwork. The wetter late-winter and spring conditions predicted with future climate changes can reasonably be expected to reduce DSFW during this critical period. When corn planting is delayed late enough (dependent on latitude and cultivar) farmers must decide whether to switch to a shorter season cultivar requiring fewer GDDs (often with lower expected yield), switch to soybeans, or possibly make an insurance claim. Evidence suggests that Corn Belt farmers have mostly not chosen longer season hybrids even as the growing season has lengthened (Abendroth et al. 2021). Prevented Plant claims can be made for insured crops if extreme weather conditions preclude planting during the established planting window. In 2019, for example, an extremely wet spring resulted in historically unprecedented Prevented Plant claims (Todey 2020).

To project how the number of DSFW may be impacted by a changing climate, we used a statistical model based on historical data (Gramig and Yun 2019). This model provides an estimate of how DSFW may change across the entire growing season, as well as the planting and harvest periods. The projected values are plotted in Supplemental Figure S4.3 for the lower (RCP 4.5) and higher (RCP 8.5) scenarios at mid- and late century, alongside the observed data from 1981–2017. A variety of future trends were considered because the assumed trend can have a significant influence on future predictions. The details are discussed in the Supplemental Materials that accompany this chapter.

The overall results project a slight downward trend in mean projected DSFW when comparing the mid-century (2045–2054) to the late century (2085–2094) decades, but the range of estimates are similar to the observed historical data across scenarios during each part of the year and across past and future decades. The planting period is of particular interest because there has been a downward historical trend in mean DSFW per week during the most active planting weeks when comparing 1981-1998 with 1999–2017 (see Supplemental Table S4.4). The mid-century projected period suggests a slight increase in DSFW during the historic planting period compared with 1981–2017 but does not clearly indicate a further reduction. It is important to note that a wider range of possible DSFW values in late century compared with mid-century reflects the greater uncertainty in climate predictions further into the future. Findings suggest that there may be a further increase in DSFW during the harvest period, as was observed over the most recent 36 years.

Management adaptations and adjustment of the timing of field operations will likely be necessary under future climate change. The recent downward trend in days suitable per week (Supplemental Table S4.4) in the planting period is important. Wetter early growing season conditions in the future may result in fewer average DSFW per week, but if the growing season gets longer there will likely be more total days available to perform fieldwork before the historical planting period begins. That said, if earlier planting is necessary to avoid extreme summer heat and protect future yields—consistent with the simulated management adaptations (Supplemental Figure S4.2) in this study—this is likely to constrain the ability to shift spring fieldwork earlier than it has been performed historically.

Weeds, pests, and diseases

As described above, changes in the future climate will have direct impacts on crops. Elevated CO_2, higher temperatures, and changing precipitation patterns will also affect weeds, pests, and diseases, with important indirect effects on crops.

Weeds

Weeds cause the largest direct economic losses in agronomic crops among all pests (Pimentel et al. 2000), and many researchers believe changes in climate will affect multiple aspects of crop and weed interactions (Ziska and McConnell 2016).

As explained above, higher concentrations of atmospheric CO_2 will favor net photosynthetic productivity of C_3 plants. Davis and Ainsworth (2012) reported that C_3 and C_4 weed species were equally likely to dominate the weed community in soybeans under ambient CO_2, but that there was a 90% likelihood that C_3 species would dominate the weed community under elevated CO_2. While many problematic weeds of contemporary cropping systems are C_4 plants, such as waterhemp (*Amaranthus tuberculatus*) and Palmer amaranth (*A. palmeri*), others are C_3 species, such as common lamb's quarters (*Chenopodium album*) and common cocklebur (*Xanthium strumarium*). Ziska (2001) demonstrated that aboveground biomass and leaf area significantly increased for common cocklebur (C_3) and significantly decreased for sorghum (C_4) when they were grown in competitive mixtures under elevated CO_2.

Figure 4.3 Mature waterhemp (*Amaranthus tuberculatus*), a problematic weed for Illinois farmers. **Source:** Aaron G. Hager

An increase in temperature is likely to impact not only which weed species are present, but also the competitive ability and emergence patterns of these weeds. Tubiello et al. (2007) predicted that elevated temperature would favor C_4 over C_3 weed species. However, the C_3 weed jimsonweed (*Datura stramonium*) produces more aboveground biomass under elevated temperatures, which may make it more competitive with agronomic crops (Cavero et al. 1999). Dekker (2004) reported that green foxtail (*Setaria viridis*) emerged later in the season under warmer conditions, causing less crop–weed interference with corn. Higher temperatures during winter months could increase survival of winter annual weed species that frequently establish in untilled fields following crop harvest.

Changes in precipitation patterns combined with increasing CO_2 and elevated temperatures are likely to affect the geographical distribution of certain weed species, and dry soil conditions can increase the competitiveness of some weeds with crops.

Crop plant diseases

Climate change is also likely to affect the incidence of pathogens (i.e., disease-causing organisms) and disease in corn and soybeans, which are already impacted by many different diseases. Although warmer, wetter conditions generally increase the incidence and severity of plant diseases, weather effects on plant pathogens are complicated; thus, changes in the climate will impact distinct pathogens and the development of diseases differently.

Average temperature increases will broaden the range in which some pathogens can survive or "overwinter." For example, southern rust, which impacts corn, is caused by a fungus that is an obligate parasite, meaning that it needs a living host to grow and reproduce. There are no living hosts in Illinois during the winter, so this pathogen must travel north from more tropical regions each year and appears in the Midwest only later in the growing season. Warmer weather could allow the southern rust fungus to overwinter further north and appear in Illinois earlier in the season, increasing the potential to cause yield loss.

Conversely, this shift in average annual temperature may also affect the disease incidence of pathogens that are more problematic in cooler environments. White mold, caused by *Sclerotinia sclerotiorum*, ranked as one of the top 10 yield-limiting diseases for soybeans from 2010 to 2014 (Allen et al. 2017). White mold disease incidence and severity may be limited by climate change, as the pathogen growth and development is limited with warmer temperatures (Roth et al. 2020).

Pests

Insect pests attack virtually every crop grown in the world, and as crops come to dominate the landscape, as corn and soybeans do in Illinois, insects adapt to use this enormous food supply to become major pests. This has been a major theme for corn in Illinois, while insect pests of soybean have remained at remarkably low levels despite decades of widespread soybean production. At the same time, other insects and microbial pathogens, such as fungi, that use insect pests as a food supply increase as insect pests increase and help in controlling outbreaks. Climate change will affect pests, as well as their biological control agents.

Insect development and overwintering survival are largely driven by temperature. Increases in temperature with climate change are expected to result in northward range expansions for many, and perhaps most, insect species, including major pests. Models indicate that the effect of this on Illinois agriculture will depend on Illinois's position in relation to these ranges. For example, the migratory corn earworm (*Helicoverpa zea*) is likely to become more of a pest in Illinois as projected warmer temperatures allow it to successfully overwinter further north (Diffenbaugh et al. 2008). Similarly, a stink bug complex that includes several species that are not currently found in Illinois (e.g., redbanded stink bug, *Piezodorus guildinii*) could become more of a problem as the range shifts. The Western corn rootworm (*Diabrotica virgifera virgifera*), one of the most destructive corn pests in North America, is expected to expand northward (Aragon and Lobo 2012); while Illinois will remain a favorable habitat, the potential impacts on local densities are not clear. In addition to range expansions, an increase in average temperatures may result in more generations per year for many insects and, ultimately, higher population densities.

Precipitation amounts affect all agricultural pests, and changes in precipitation patterns will inevitably bring changes in pest abundance. The magnitude and direction of these changes will depend on the biological characteristics of individual species. For example, excessive soil moisture early in the growing season could simultaneously reduce the abundance of certain pest populations, such as corn rootworm (Riedell and Sutter 1995), while increasing that of others, such as slugs (Douglas and Tooker 2012). Drought conditions can favor outbreaks of certain pests, like spider mites (English-Loeb 1990), and increase the sensitivity of plants to insect feeding. In general, the impacts of changes in precipitation on pests are less certain than those related to temperature.

Elevated levels of atmospheric CO_2 and other greenhouse gasses may also affect insect pest management by affecting the biology of both host plants and insect pests. There is some concern that elevated levels of CO_2 will compromise plant defenses, facilitating increased insect damage. For example, elevated CO_2 levels have been found to reduce plant defenses and increase insect herbivory in soybeans (Zavala et al. 2008). In addition, elevated CO_2 and ozone (O_3) levels increased oviposition of a rotation-resistant variant of the western corn rootworm in soybean (Schroeder et al. 2006).

Managing weeds, pests, and diseases in a changing climate

Undoubtedly some weeds, pests, and diseases will become more challenging to manage in Illinois as the climate continues to change. New genetic sources of resistance combined with herbicide, insecticide, and fungicide applied within the context of a well-balanced integrated pest management (IPM) approach are likely to help growers manage many of these challenges. However, dealing with these challenges is likely to necessitate additional applications of pesticides, herbicides, and fungicides, which could increase expenses as well as the potential for water contamination and other off-target issues (e.g., dicamba drift).

It is also likely that the predominant management options will be affected by climate change. For instance, higher soil temperatures could decrease the duration of weed control with certain soil-residual herbicides, making weed control more difficult. Precipitation variability can also diminish the consistency of in-season weed control with soil-residual and foliar-applied herbicides. Most surface-applied residual herbicides that are not mechanically incorporated require precipitation within about seven days after application to optimize activity. Cuticle thickness and leaf pubescence can increase under moisture-stress conditions, which can limit the absorption of foliar-applied herbicides (Patterson 1995).

Climate change may also decrease the effectiveness of both genetic and chemical controls for weeds, pests, and diseases, especially due to the development of resistance to these methods of control. A wide range of weed species have already developed resistance to more than half of the existing herbicide classes (Heap 2020), so as climate change increases the competitiveness of certain weeds, herbicides will not be entirely capable of neutralizing the impact. Crop breeding and genetic engineering will remain the predominant methods for managing diseases in crops, but this approach requires constant updating as pathogens evolve, which may happen faster as temperatures increase. For example, warmer weather means faster growth and genetic turnover for fungal pathogens, which is expected to accelerate the development of pathogen resistance to genetic methods of control. Likewise, it is expected to increase pathogen resistance to fungicides. Weed, insect, and disease resistance to chemical and genetic methods of control is expected to continue to develop, making management more difficult in the future.

Livestock

Livestock production is an economically significant component of Illinois agriculture. Ruminants (beef and dairy cattle, sheep, and goats), swine, and poultry (broilers, layers, and turkeys) contribute $14.1 billion to the state's economy (Decision Innovation Solutions 2015), and as of 2019, Illinois was the fourth largest producer of hogs and pigs (NASS 2019c). Beef production is less dominant, but still significant, contributing over $830 million in gross income to the state in 2019 (NASS 2019c).

Estimating climate change impacts on livestock is complex because of the various species of animals and diverse management practices used across the state (e.g., confinement housing versus pastured animals). In general, however, livestock will likely be negatively impacted by multiple climate-related factors such as heat stress, reduced-quality forage, and disease.

With a warming climate, heat stress will be an increasing concern in Illinois since higher temperatures affect numerous biological functions of livestock that can ultimately reduce overall productivity. Livestock are especially susceptible to heat stress due to their rapid metabolic rate and growth and species-specific characteristics, such as rumen fermentation, sweating impairment, and skin insulation. For example, pigs are very sensitive to heat, largely due to a low sweating capacity (Nardone et al. 2010).

Heat stress reduces productivity in livestock by compromising growth, reproduction, and overall health (Nardone et al. 2010). Depending on its intensity and duration, heat stress may cause metabolic disruptions, oxidative stress, and immune suppression, causing infections and even death (Nardone et al. 2010). Most livestock species perform best at temperatures between 50 and 86°F. When temperatures exceed 86°F, many species (cattle, sheep, goats, pigs, and chickens) will reduce their feed intake 3–5% for each 1.8°F increase (NRC 1981). By mid-century, Illinois could experience 40–80 days above 86°F per year, depending on the climate scenario; the number of consecutive days above 86°F is also expected to increase. The number of days per year projected above 86°F are displayed in Figure 4.4. Higher humidity will also exacerbate heat stress in livestock.

Changes in precipitation have direct effects on the timing and duration of pasture growing seasons and on plant growth, which affects the quantity and quality of forage produced. Elevated CO_2 and higher temperatures could decrease the nutritional quality of livestock forages in Illinois, by reducing soil nitrogen availability, which in turn reduces crude protein levels (Craine et al. 2017). Climatic changes may promote growth of mycotoxin-producing fungi during grain and forage harvest, drying, and storage (Frank 1991) that may have negative effects on specific tissues and organs, such as the liver, kidney, oral and gastric mucosa, brain, or reproductive tract. Some mycotoxins may interfere with disease resistance and make animals more susceptible to infection (Bernabucci et al. 2011).

There is evidence that the severity and distribution of livestock pests and diseases are also climate sensitive (Henry et al. 2012). Climate change may affect the vector, the host environment, the pest or disease itself, and the epidemiology (Thornton et al. 2009) in ways that alter factors such as distributions of diseases and disease vectors, rates of pathogen or parasitic development, and transmission rates between hosts. Climate change may favor some pests and diseases, while disadvantaging others, leading to changes in distribution and population density.

For example, ticks have been expanding their geographic ranges and increasing in population in recent decades largely due to climate change and changes in land use (Diuk-Wasser et al. 2012; Estrada-Pena et al. 2012; Gatewood et al. 2009; Leger et al. 2013; Medlock et al. 2013; Ogden et al. 2013). Ticks are vectors for pathogens that can transmit serious as well as fatal infections (Dantas-Torres et al. 2012). The lone star tick (*Ambylomma americanum*) was historically restricted to southern states, with some populations extending as far north as southern New Jersey. Recently, however, due to changes in climate and seasonal activity, its range has increased further into northeastern and Midwest states, including Illinois. Diseases transmitted by ticks to livestock are a major constraint to animal production and, globally, the economic impact of ticks is particularly high for livestock (Jongejan and Uilenberg 2004; Uilenberg 1995). In general, tickborne diseases are health and management problems for cattle and small ruminants.

Some adaptive measures may be undertaken to reduce the impacts of climate change on livestock, although they may result in increased production costs. For example, cooling systems can be used to control the climate conditions for some livestock such as pork and poultry. Producers will likely need to increase ventilation in response to higher temperatures, increasing costs (Bowling et al. 2020). Other adaptive measures include changes to forage and pasture management and genetic improvements to improve the heat tolerance of animals (Nardone et al. 2010).

Specialty crops

Illinois' favorable climate and fertile soil make it well-suited for growing more than corn and soybeans. Illinois producers also grow a number of specialty crops, including pumpkins, sweet corn, potatoes, snap peas, green peas, Christmas trees, apples, horseradish, and peaches. According to the 2017 Census of

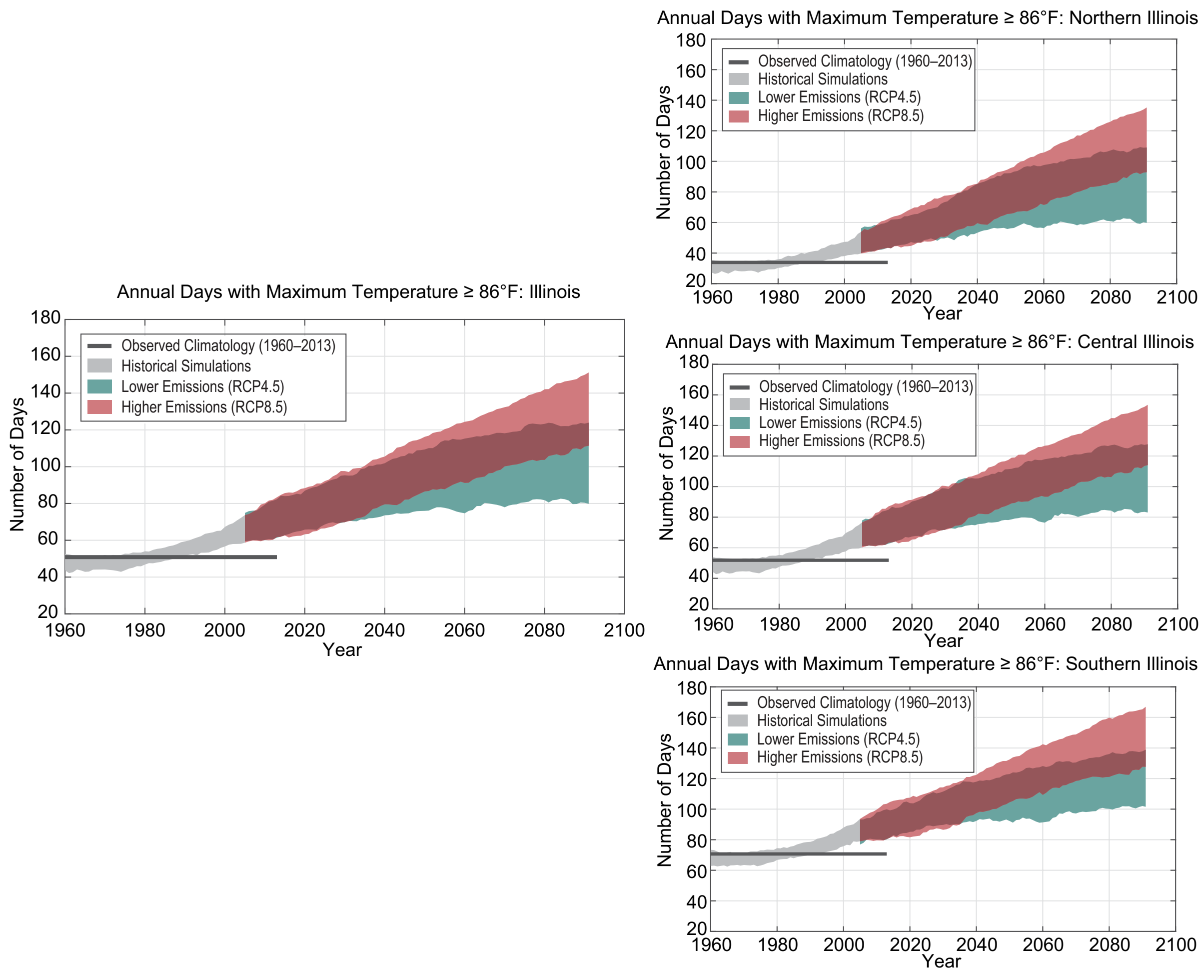

Figure 4.4 These time series (1960–2100) show the simulated historical and projected annual number of days with maximum temperature ≥86° F for the state of Illinois (left panel), northern Illinois (upper right panel), central Illinois (middle right panel), and southern Illinois (lower right panel). The observed climatological values averaged for the period 1960–2013 are shown (black line). Historical simulations (gray shading) are shown for 1960–2005. Projected changes for 2006–2100 are shown for a higher scenario (RCP8.5; red shading) and a lower scenario (RCP4.5; teal shading). The shaded ranges indicate the 10% to 90% confidence intervals of 20-year running averages from the set of climate models. **Sources:** NCICS and The University of Edinburgh.

Agriculture, over 3,200 farms grow specialty crops across 90,160 acres, and specialty crop production in the state is valued at over $873 million (NASS 2017a). Illinois is the number one producer of pumpkins in the United States (NASS 2019c), producing over 90% of the country's processing pumpkins, which are used for canning and cooking (Stiers 2017). Illinois is also the top producer of horseradish, containing over half of the total acreage dedicated to this crop in the country (NASS 2017b).

Specialty horticulture crops are especially sensitive to changes in seasonal temperature and rainfall patterns. Above normal or unseasonable rain can result in planting delays, which in turn often results in harvest delays and an increased risk of crop loss. Rising temperatures can affect plant functions like dormancy periods, flower induction, pollination and fertilization, flower and fruit abortion, disease and insect populations, and overall crop quality, all potentially leading to negative yield impacts or reduced marketable crops. Because the local, national, and global system required to feed Illinois citizens is complex and intertwined, a potential two- or three-week shift in a growing season can upset supply chains, labor schedules, and other behind-the-scenes agricultural practices.

Historical records show that USDA Plant Hardiness Zones have started to shift northward over the last few decades (Krakauer 2018). Increasingly warmer temperatures during the winter will continue to shift Plant Hardiness Zones, expanding the suitable range for certain crops further north. This includes crops like peach, pluot, and nectarine, which are currently confined to commercial production in the southern portion of the state. It may also become possible to grow fruit that does not grow well in the current climate of Illinois, such as certain bramble-type crops like boysenberry and loganberry or less common crops like jujube.

Although increasing temperatures and altered growing seasons may make it possible to grow new crops, the heat will also hurt specialty crops traditionally grown in Illinois, like pumpkins, apples, and tomatoes. All three crops respond negatively to increasing temperature.

- Flower expression in certain pumpkin species is temperature dependent; specifically, high temperatures delay flower formation and favor male over female flowers. Since the female flower produces the fruit, more female flowers are desirable. Pumpkins are also sensitive to moisture, and a future climate with wetter conditions during critical growth stages may increase the risk of disease, such as bacterial spot (Angel et al. 2018).
- Tomatoes tend to abort flowers under high night and day temperatures, resulting in lost yield and revenue.
- Growers already utilize sunburn protection products for sensitive apple cultivars like Honeycrisp, which increases the cost of production. As temperatures increase, it is reasonable to expect that growers will need to protect additional cultivars or plant different apple varieties.

Many woody perennials, including fruit-producing plants, have evolved to avoid breaking dormancy too early by first needing to accumulate a certain number of chilling hours (generally between 35°F and 50°F) (Bowling et al. 2020). If too few chilling hours are accumulated during a given season, some cultivars will be unable to produce flowers or fruit or will be much less productive. Most specialty crops grown in Illinois need 700–1,300 chilling hours to break dormancy, and Illinois averages between 1,650 to 1,450 chilling hours per year from north to south. Southern Illinois is predicted to see a downward trend in chilling hours by the end of the century, from a current range of 1,450–1,575 hours to 1,050–1,450 hours, meaning some cultivars of nut and fruit species currently grown there may no longer be suitable in that region.

Chilling hours can also accumulate early in the season, causing buds to break dormancy during a late winter or early spring warm spell. If chilling requirements have already been met and plants bloom during earlier warm spells, they will be more susceptible to frost damage (Bowling et al. 2020). The observed annual trend towards earlier last spring freeze dates (Figure 4.5) could be particularly problematic if shorter, warmer winters in the future are followed by a freeze event, which can devastate a crop. Historical crop insurance loss data for the Midwest region indicate an increasing trend in freeze-caused losses in January, February, and November (Reyes and Elias 2019). In general, temperature fluctuation during the chilling period can cause problems for specialty crops. Too much temperature fluctuation during the chilling period can lead to erratic blooms, yield loss, and reduced fruit quality (Bowling et al. 2020).

To deal with pests, many specialty crops are likely to require increased applications of pesticides and fungicides as temperatures and humidity

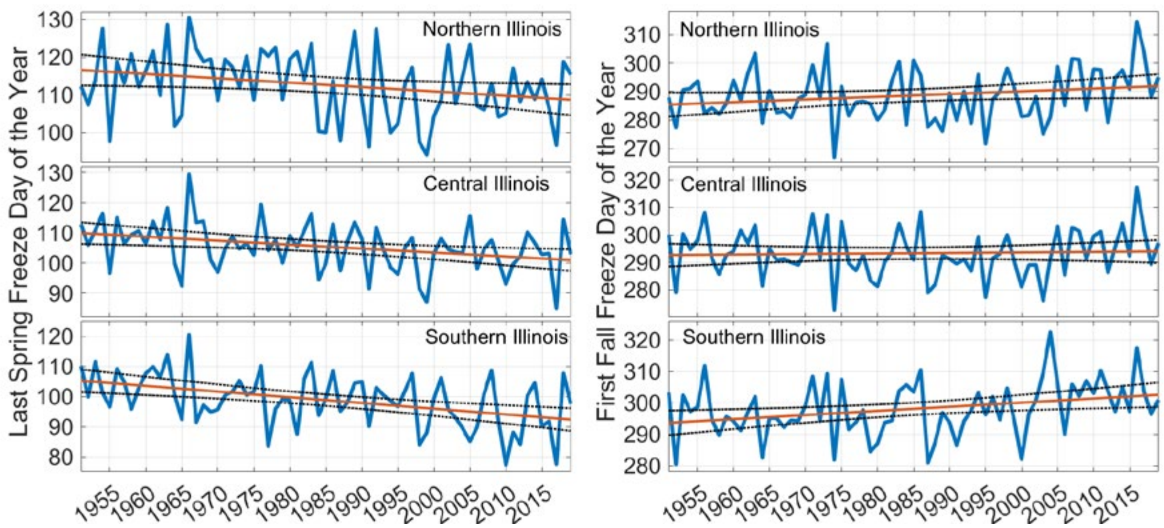

Figure 4.5 Last spring freeze and first fall freeze dates for northern, central, and southern Illinois since 1950, based on a 32°F freeze threshold. The historical trend line (red), with 95% confidence intervals (dotted lines), shows that the last spring freeze date is occurring earlier, and the first fall freeze date is occurring later in the season across all three regions of the state.

rise (Bowling et al. 2020). Most fungicides and insecticides are already applied 10 to 20 times per season, because many have at most a two-week window of efficacy, depending on precipitation. With increased precipitation, pesticide residues will also tend to be washed off plant surfaces and from the soil more quickly, requiring alternate methods of control or additional pesticide applications (as allowed by the label), which can increase the risk of pesticide resistance.

Unlike agronomic crops, specialty crops rely more heavily on human labor for planting, maintenance, and harvest. In Illinois, 41% of specialty crop farms report using hired labor (NASS 2017a). This is especially true for Amish and Mennonite growers, who rely on human and animal labor. Tractors used for horticultural crops also tend to be smaller and less likely to have temperature-controlled cabs. Certain implements, like transplanters, require a human crew, but have no protection from the elements. Without moving to systems with full environmental controls, which greatly increases the cost of production, tunnel production (poly-houses) may become impossible to operate during summer months due to the impact of extreme temperatures on labor crews and crops. If the temperature increase under climate change is extreme enough to impact the hours when laborers can work, this will necessitate an important management adaptation or cause a move toward more mechanization to replace labor needs.

Similarly, increased temperatures may impact agritourism, which is important to the economic viability of horticultural production. If climate change causes hotter or otherwise less desirable outdoor conditions, reduced fruit and vegetable quality, or an inability to plant the most desired varieties, this could have an important impact on visitation to farms that market directly to consumers and generate income from related agritourism activities such as u-pick, farm markets, food stands, tours, corn mazes, and special event rentals (e.g., weddings, parties, festivals).

Climate change may pose particular risks for fruit tree farms because investments in trees cannot be quickly adjusted to accommodate the shifting climate. Fruit trees take several years to establish and produce fruits, and farmers expect to produce fruit from new trees for a decade or more.

Climate change is likely to result in a shift of production from open field to protected culture, where growers have more control of environmental conditions. Climate change may also lead to a shift in the specialty crops and/or cultivars grown in Illinois to those already better suited for the near future, or it may create greater demand for heat-tolerant cultivars. However, in comparison with the significant amount of academic and industry effort dedicated to developing new traits and genetic adaptations for corn and soybeans, investment in the development of new cultivars for specialty crops is relatively low.

Agricultural economy and policy

According to one report, Illinois is likely to face economic costs as a result of yield losses due to climate change (Gordon et al. 2015). In the earlier part of the century (2020–2039) Illinois could experience either gains or losses, ranging from economic gains of $1.1 billion to losses of $2.6 billion per year, with losses more likely than gains (Gordon et al. 2015). By the end of the century, Illinois is likely to lose anywhere from $1.5 to $13 billion per year from crop losses (Gordon et al. 2015). To put these numbers in perspective, between 2000 and 2018, Illinois farmers averaged $15.4 billion in gross cash income from farming with $2.2 billion (14%) each from crops and animal and related products and $900 million (6%) from federal payments (USDA-ERS 2019).

The costs of adapting to climate change on Illinois farms will depend on the nature of the adaptations undertaken. Large capital investments will be required, for instance, if farmers choose to install irrigation. As new seed technology becomes available, farmers will certainly plant these new seeds if the cost is justified by the returns, as has been the case for seed technology improvements made over the last several decades. It seems very likely that the timing of field operations will be influenced by when it is wettest, hottest, and driest during the year. Under hotter and drier summer conditions, farmers will likely try to plant earlier to avoid damaging extreme heat and potentially drier soil conditions, but if wetter predicted winter and early spring conditions also occur, this may limit the ability to adjust planting dates earlier to avoid summer heat. The extent to which farmers are able to adapt to climate change and the cost of those adaptations will affect overall economic impacts on the agricultural sector.

Farm Bill policy implications

There are three areas of farm policy spending that are most critical for Illinois: crop insurance, commodity, and conservation programs. In the context of the federal Farm Bill, crop insurance is generally the largest program, much of it for the premium subsidy to farmers. Historically (prior to the 2014 Farm Bill), commodity title program spending was the second largest, followed by conservation programs. The two largest commodity payment programs are the Agricultural Revenue Coverage (ARC) and Price Loss Coverage (PLC) programs that compensate farmers when revenue (revenue = price × yield) or prices, respectively, drop below prespecified levels. These programs only cover the 22 top commodity crops and exclude fruits and vegetables. ARC and PLC provide income support when “shallow losses” are experienced but do not protect farmers from the large yield or price impacts that crop insurance does.

Figure 4.6 shows annual government payments by program in Illinois (excluding crop insurance subsidies and indemnities). It is worth noting that federal farm payments spiked to their highest levels in recent memory during 2019–2020, as the Trump administration compensated farmers for market impacts of the political trade war waged with China and supported farmers during the COVID-19 pandemic.

Crop insurance is the largest program in terms of spending and numbers of acres. It is an insurance program operated as a public–private partnership from which a farmer elects the type and level of

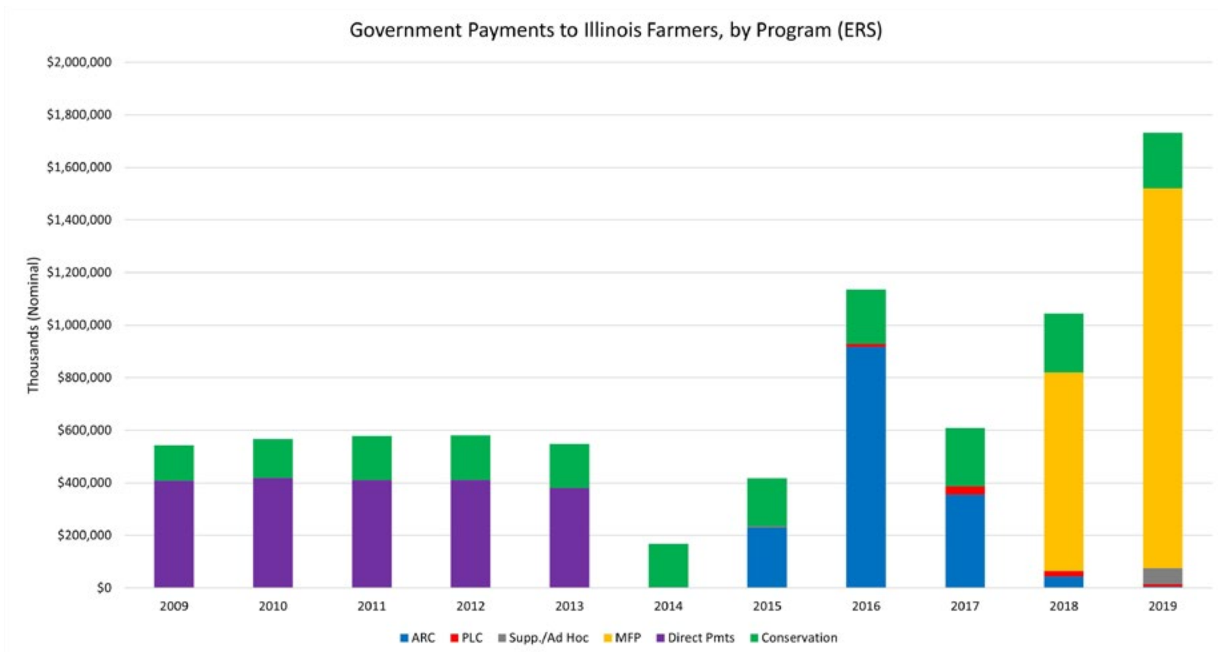

Figure 4.6 Annual government payments by program in Illinois (excluding crop insurance subsidies and indemnities). ARC denotes Agricultural Revenue Coverage; PLC denotes Price Loss Coverage programs; Supplemental and Ad Hoc payments are for disasters such as the 2019 floods; MFP denotes Market Facilitation Program payments to compensate for Trump trade policy–induced market losses; and conservation includes all conservation program payments. No crop insurance subsidies are included in these data. **Source:** USDA-ERS 2019.

coverage for the crops planted on the farm. The premium cost is subsidized by a predetermined amount depending on the coverage level and type of policy purchased and covered by the federal government through the Federal Crop Insurance Corporation (FCIC). Among commodity farmers nationally, and in Illinois, the most popular insurance policy is revenue coverage. Many farmers purchase up to 85% coverage. Revenue coverage is calculated by the farmer's actual production history (APH), which is a 10-year average of the yields for the crop on the field or farm.

It is well established that subsidized crop insurance has the effect of incentivizing production on more risky acres that would not be cropped in the absence of subsidies (Miao, Hennessy, and Feng 2016). This is evidenced by the fact that crop insurance payouts in more risky areas exceed premiums paid (Coble and Barnett 2013; Glauber 2004). An ongoing topic of debate is whether having crop insurance deters adaptation to climate change. Crop insurance compensates farmers in years with extreme weather events, such as the 2012 drought that resulted in severe, widespread yield losses, and the extremely wet spring of 2019 that resulted in a record number of Prevented Plant claims (Schwartz 2019; Todey 2020) due to flooding of already planted crops or the inability to plant before the subsidized crop insurance planting deadline. These kinds of extreme events are forecast to occur with higher frequency and intensity under a changing climate (see Chapter 2). The U.S. Government Accountability Office (GAO) previously found that the annual crop insurance contracts are not well suited to encouraging farmers to reduce long-term exposure to climate change risks and that, without encouraging practices that reduce long-term risk, the government unintentionally encourages vulnerability to climate change that may exacerbate federal exposure to losses in the future (GAO 2014).

There is considerable room to improve the design of crop insurance to encourage wider use of practices that increase the resilience of yield to extreme events and to avoid production on land where crops would not be grown if subsidized insurance were not available. In particular, changes to conservation compliance or requirements for more general best practice provisions could be instituted in order for farmers to be eligible for federal crop insurance subsidies and to avoid the disincentive to adapt to climate change that crop insurance currently creates.

Among conservation program spending, the largest programs are the Conservation Reserve Program (CRP), Conservation Stewardship Program (CSP), and Environmental Quality Incentives Program (EQIP). The Conservation Reserve Program takes land out of production to supply environmental benefits and control crop supply to a certain extent; farmers are paid a land rental payment and the cost to convert enrolled cropland to conservation land use. CSP and EQIP are both working lands agricultural programs that provide cost-share assistance to farmers to implement for the first time or expand, respectively, conservation practices used on land where crops or livestock are being actively produced. There is a downward trend (see Figure 4.7) in total acres enrolled in conservation programs, despite an increasing trend in total conservation program outlays per year over the last decade.

Conservation practices like those subsidized by CSP and EQIP have been discussed for over a decade as providing climate change mitigation benefits, by incentivizing the use of practices that can increase the ability of agricultural soils to remove carbon from the atmosphere. There is also increasing interest in the adaptation benefits that conservation tillage, cover crops, and controlled drainage may confer in terms of yield protection during increased drought conditions expected under future climate change. The same practices may also reduce soil erosion from increased rainfall in the winter and fall, when bare soil is susceptible to runoff.

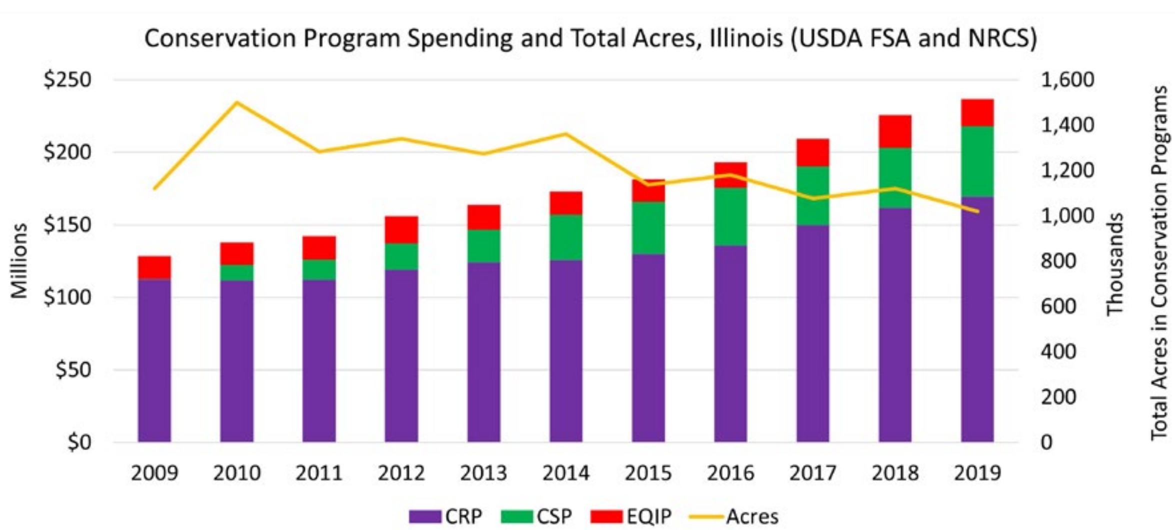

Figure 4.7 Illinois Conservation Program Acres and Spending, 2009–2019, for Conservation Reserve Program (CRP), Conservation Stewardship Program (CSP), and Environmental Quality Incentives Program (EQIP). The yellow line shows the total number of acres enrolled in Illinois.

Unfortunately, the data required to empirically analyze the causal effect of these practices on crop yield and resilience to extreme weather events are not publicly available. There is an effort underway following passage of the 2018 Farm Bill to combine the data necessary to conduct this analysis with data from the USDA's Risk Management Agency (APH data), Farm Service Agency (cropping and farm program participation data), and Natural Resources Conservation Service (working lands conservation practices funded by federal programs). Such an analysis may be able to provide a more conclusive understanding of the influence that different conservation practices have on crop yield when extreme heat, drought, or wet conditions are experienced in a given location and year.

Strategies for sustainable farming in a changing climate

Farmers have long been adapting to variability in weather patterns, for example by investing in larger planters to reduce planting windows and using drought-resistant crop varieties. Continued management adaptations will likely be necessary to limit exposure to risk from climate change. For instance, climate conditions may be more favorable for double cropping winter wheat with soybeans across a larger area and further north than has been historically possible. Among the potential adaptations that farmers can implement, there is growing interest in using more environmentally sustainable practices. To the extent that some of these sustainability-enhancing practices, such as use of winter cover crops, can also improve yield resilience to future climate change and reduce production risk, there may be increased opportunity to leverage synergies between conservation and risk management in the future. As interest grows in more sustainable agricultural systems and regenerative agriculture, there may be additional income streams to financially support the expanded use of voluntary conservation practices.

Incorporating voluntary conservation practices into existing farm operations can help to increase resiliency to climate change (IPCC 2007). For example, including practices that enhance soil organic matter (SOM) can serve to increase agricultural resiliency during drought situations. Minimizing soil disturbance and retaining agricultural crop residues (e.g., conservation tillage) provides additional plant material on the soil surface that minimizes soil loss and maintains soil organic carbon and the health of important soil fauna (Delgado et al. 2011). Incorporating agricultural practices that build SOM into farming operations will be key as warmer temperatures and higher precipitation increase rates of SOM decomposition and erosional soil losses from fields.

Winter cover crops and grassed waterways are well documented to reduce soil erosion (e.g., Dabney et al. 2001; Fiener and Auerswald 2003) and may provide added protection against topsoil loss and gully formation during intense rainfall events, which are predicted to increase during winter and spring when agricultural fields might otherwise be fallow. Planting fast-growing cover crop mixtures after fall harvest that can accumulate significant biomass (>30% soil cover) before freezing could be especially effective at reducing erosion between commodity crop production seasons (Kaye and Quemada 2017). Including plant types that produce deep taproots (e.g., forage radish) can reduce soil compaction and increase potential resilience of corn crops to drought by providing roots with access to deeper water sources (Chen and Weil 2011). Multi-species cover crop plantings should increase soil water management options by reducing erosion and compaction during periods of soil saturation or droughts.

Higher soil temperatures increase the rate of mineralization in the fall; thus, higher nutrient leaching can occur when soils with elevated inorganic N are mineralized and subsequently become recharged with water in the winter and spring (Finney et al. 2016). Cover crops could reduce impacts of extreme rain events on leaching losses of fall-applied fertilizers (Kaye and Quemada 2017), providing important benefits for water quality. More intense rainfall events that overlap with the transition from cover crops to cash crops may result in a smaller window to kill off cover crops during the spring prior to planting that could lead to delayed planting or poor seedbed preparation that limits cash crop establishment. This risk is lower for farm operations that use no-till practices and could be reduced further with no-till planting of cash crops into a living cover crop that is subsequently killed (Kaye and Quemada 2017).

Nutrient losses from intensively managed lands in the Midwest are predicted to increase with changing climatic conditions, exacerbating negative effects on aquatic species, local drinking water quality, and ultimately hypoxia in the Gulf of Mexico (Fennel and Testa 2019; Hatfield and Prueger 2004; Rabalais et al. 2010). However, many of the same conservation practices that would support sustainable farm production in the future also provide ecosystem services that protect the environment. Practices that increase soil health, and subsequent nutrient and water storage capacity for plant uptake (e.g., cover crops), may also increase filtration capacity of soils to reduce nutrient loss to water resources (Hatfield et al. 2013). Edge-of-field soil conservation practices that reduce erosion in fields (e.g., grassed waterways, vegetated buffers, prairie strips, constructed wetlands) also capture nutrients in surface water runoff that would otherwise flow into adjacent waterways. There is a clear need for both edge-of-field practices that intercept and treat excess nutrients from subsurface tile drainage systems and practices that increase perennial cover to reduce erosion, increase soil hydrologic function, and contribute to carbon sequestration (e.g., Basche and Edelson 2017; Lemke et al. 2011). Precision agriculture may also be used to incorporate real-time spatial data that optimizes crop inputs, such as fertilizers and other chemicals, to reduce excess nutrient losses and runoff from agricultural fields.

It will be important to adopt a comprehensive approach that includes multiple strategies and a diverse set of practices that can be integrated into farm operations to improve sustainability outcomes for agriculture and the environment in the face of a changing climate. Additional technical assistance and resources will increase the ability of farmers to incorporate operational changes that may sustain agricultural resilience in the future. Increased investment in extension services and agricultural advisors would be beneficial to support farmers as they adopt best practices and new adaptation strategies.

Edge of Field Roadmap

Research shows that in-field soil health and nutrient management practices alone are not enough to protect freshwater resources, especially with projected climate changes. The Nature Conservancy, Soil and Water Conservation Society, and Meridian Institute developed an edge of field (EoF) roadmap—a blueprint for scaling up edge of field practices that improve water quality and the resiliency of farmlands. The roadmap introduces nine recommendations to advance EoF practices at multiple scales, highlighting the need for multi-sector collaboration to build the case for EoF practices, increased technical assistance, and capacity for implementation, and to cultivate a culture of conservation and innovation that includes EoF practices as part of a whole-systems approach to conservation in agriculture.

To learn more about edge of field practices and download the *Leading at the Edge* report, visit: https://www.nature.org/EdgeofField.

Figure 4.8 At this farm in central Illinois, the conservation practices of a constructed wetland and cover crops (in background) are "stacked" together to reduce the impacts of soil erosion and nutrient loss from agricultural drainage tiles to provide soil health, water quality, and wildlife habitat benefits.

Knowledge and research gaps

Significant research has been done to understand the potential impacts of climate change on the agricultural sector in the Midwest. The results of that research can be used to take proactive steps to make Illinois' agricultural sector more resilient in the face of climate change. Nonetheless, further information would be useful to refine our understanding of how climate change will impact Illinois' agricultural sector, especially because the number of factors involved can complicate efforts to project exactly how climate change will alter production. Although certain variables have straightforward impacts, like temperatures over certain thresholds negatively impacting yields, other dynamics are less easy to project. For example, some research suggests that unabated climate change could shift the optimal geographies for growing rainfed corn and soybeans northward, from Iowa and Illinois to Minnesota and the Dakotas, although productivity in those regions will also depend on soil productivity (Hoffman et al. 2020). Adverse climate conditions in other regions of the country could also create new dynamics to consider in Illinois, like increases in the regional population (Angel et al. 2018) and/or competing demands for land and natural resources. Such changes could have major implications for farming in Illinois.


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More knowledge and research in the following areas will be beneficial to further our understanding of the potential impacts on the agricultural sector and rural communities in Illinois:

- **Crop technology**
  It is impossible to know today how breeding and plant genetic advancements will progress as the climate continues to change, but technological advancements are likely to be a major determinant of crop yield protection and future gains in the face of climate change. Recent research suggests that, if past technological gains continue during the 21st century, this could mitigate future yield losses from climate change (Burchfield et al. 2020); however, more research on this topic is needed, and such advances will require significant new investment.

  In particular, more research and investment could be focused on developing specific traits to take advantage of and make crops more resilient to changing climate conditions. For example, biotechnology and breeding should account for and take advantage of the effects of elevated CO_2 on water use in C_3 plants (Ainsworth et al. 2008; 2012; Condon et al. 2004; Slattery and Ort 2019). In addition, genotypes vary in sensitivity to CO_2, which could be exploited to identify key genes and adapt crops for improved performance in future growing conditions (Bishop et al. 2015; Leakey and Lau 2012).

- **Complex plant responses to increasing CO_2 emissions**
  One of the greatest uncertainties about climate change relates to interactions between elevated CO_2 and other abiotic and biotic factors. More experiments with combined stresses and different management practices are needed. Given the demand for both food and fuel production, additional studies on C_4 crops are also needed. Future experiments should also consider multiple levels of elevated CO_2 to inform projections of agricultural performance in the latter half of the century, as FACE experiments

have not yet included experimental treatments of elevated CO_2 greater than 600 ppm.

- **Research in understudied areas**
  Two areas of agriculture with the least information today and, thus, the greatest future uncertainty, are how pests and diseases and specialty crops will be impacted by climate change. The scientific understanding of climate change impacts on pests, insects, pathogens, and weeds is limited, as is knowledge about the interactions of these organisms within complex agricultural landscapes (Gowda et al. 2018). There is also a critical lack of information about the impacts of increased variability and extreme weather events on horticultural crops, which is needed to project how or where climate change impacts may be the greatest. This information is needed to respond to and proactively mitigate these future impacts.

- **Climate mitigation potential of farming practices**
  Agriculture has the ability to mitigate a portion of future climate change through carbon sequestration in soil and perennial vegetation, through improved nutrient-use efficiency of fertilizers, and through reduced methane emissions from ruminant livestock and manure. However, more research is needed to quantify such mitigation measures (Gowda et al. 2018) and to develop effective policies and regulations to ensure widespread adoption of best practices.

- **Social science research on vulnerability and adaptation in rural communities**
  Gowda et al. (2018) identify the importance of social science research to improve our understanding of the vulnerability of rural communities, strategies to enhance adaptive capacity and resilience, and barriers to adoption of new strategies. The agricultural sector in Illinois forms an important component of rural communities and economies, and ultimately, the importance of understanding the impacts of climate change on agriculture will provide valuable information that can help farmers and rural communities take proactive steps to become more resilient.

With so many factors to consider, it is important to approach research on this issue holistically. A systems approach to research could facilitate a better understanding of the vulnerabilities of Illinois' agricultural system to climate change and help to quantify the costs of business as usual relative to the adoption of adaptation and mitigation strategies (Gowda et al. 2018). In general, additional knowledge and research on the impacts of climate change on farming in Illinois will be critical to assist communities in developing the most effective strategies to mitigate and adapt to climate change.

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Supplemental Materials

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CHAPTER 5

Climate Change Impacts on Public Health

Key Messages

1. The projected increases in temperature and precipitation will have many negative effects on health in Illinois.
2. The risk of severe heat-related illnesses, such as heat exhaustion and heat stroke, will increase as extreme heat events become more frequent and more severe under the changing climate.
3. The increase in likelihood of heavy precipitation events will cause more flooding in Illinois. This will result in an increased risk of waterborne infectious diseases, mold exposure, injuries, and the emotional distress that accompany the flooding of homes and businesses.
4. Rising temperatures and increasing precipitation are already creating conditions that permit mosquitoes and ticks to survive in previously unsuitable locations. In addition, the biting season will become longer. These changes are expected to increase the risk of vector-borne diseases, such as Lyme disease and West Nile virus.
5. Levels of mold, pollen, and ozone pollution, which are triggers of asthma and allergy, are expected to increase and the pollen season will lengthen, resulting in more severe respiratory allergies and more frequent asthma attacks.
6. The health impacts of climate change will vary by community: those with already high rates of chronic disease, poor housing, and barriers to accessing health care, healthy community design, and clean air are expected to experience more severe health impacts from climate change than the population of Illinois overall.
7. Economic assessments indicate substantial costs due to increases in climate-sensitive health conditions. Those assessments also convey the potential benefits of taking action to limit the extent and impacts of the changing climate.

Introduction

Climate change is expected to make a variety of types of illnesses more common in Illinois (CDC NCEH 2020; Crimmins et al. 2016; Smith et al. 2014; Watts et al. 2019). Higher temperatures and more frequent heat waves will result in more heat-related illness. More rainfall will also result in health problems, like respiratory illness related to bacteria and mold exposure. As emissions rise, climate changes will result in a number of environmental changes with adverse health impacts, ranging from vector-borne diseases to mental health challenges, as summarized in Figure 5.1.

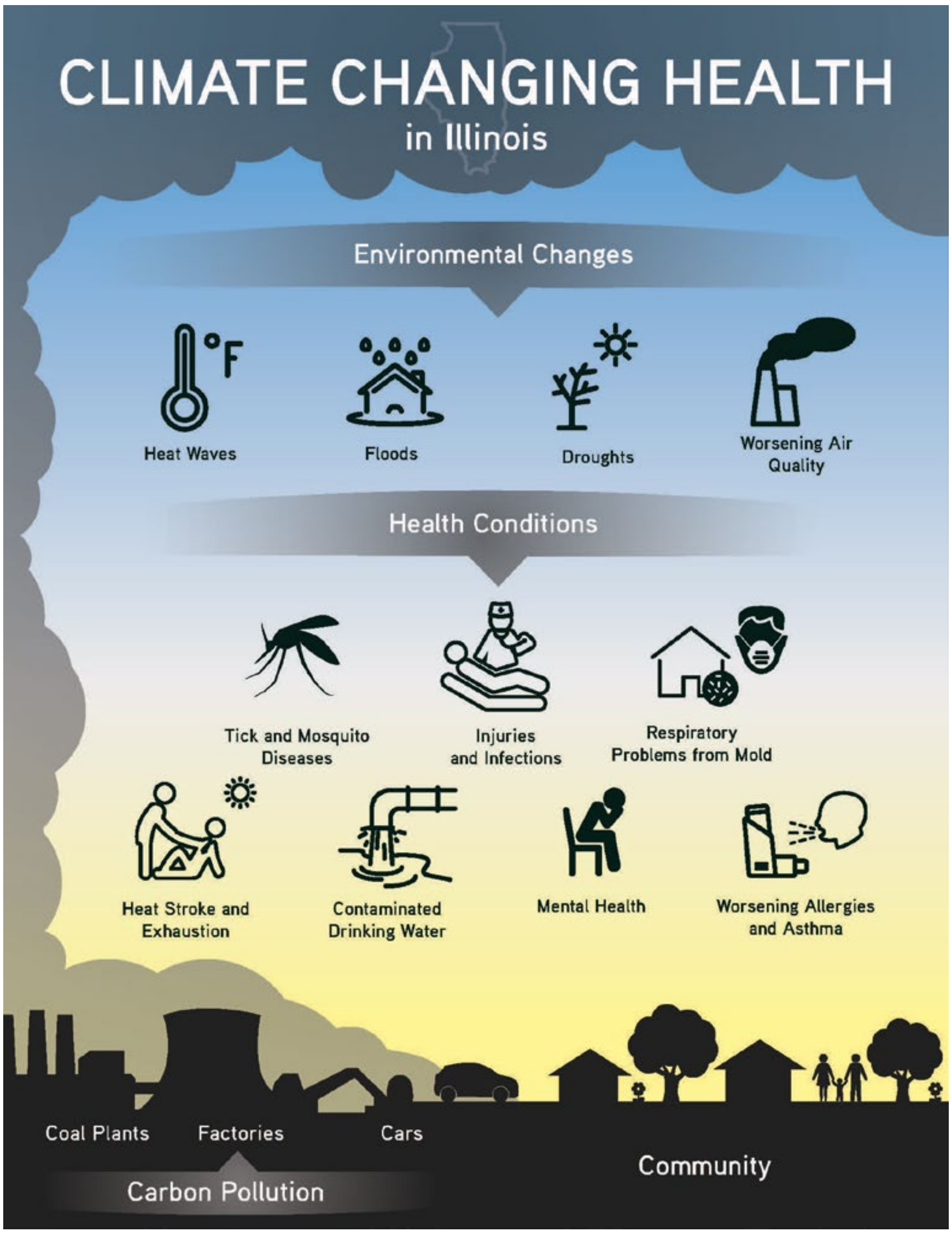

Figure 5.1 Pathways through which carbon pollution changes the climate and climate change harms health in Illinois. More frequent and severe extreme heat, precipitation, and worsening air quality are the climate change impacts of most concern for health in Illinois.

The health impacts of climate change are pathway dependent and location specific, meaning that impacts will depend on where you live. For example, those who live near rivers and streams will be at a higher risk of flood-related impacts than those who do not. The severity of these impacts is influenced by pre-existing health status, social conditions, resources, and local adaptive capacity to climate change (Crimmins et al. 2016; Rudolph et al. 2018; Shonkoff et al. 2011). In the following pages, we describe the ways that continued changes in the climate are expected to change the frequency with which various health problems will occur in Illinois.

Community vulnerability to disasters

Climate change is a threat multiplier that aggravates existing stressors and health disparities. For example, the 1995 Chicago heat wave is an example of how vulnerable populations are at higher risk of experiencing climate impacts. During that event, the highest fatality rates were among the elderly in low-income communities of color (Klinenberg 2002). During heat waves, the demand for electricity increases because people use more air conditioning, which helps prevent heat-related illness (Kenword and Raja 2014). However, hotter weather and sustained heat waves increase the likelihood of electricity shortages, resulting in brownouts or blackouts and exacerbating the risk of heat-related illnesses. Critical infrastructure (e.g., health care, water, wastewater, electrical supply) is also more likely to be in poor shape in low-income communities before disasters occur, increasing the likelihood of power outages. Critical infrastructure may also be challenged by increases in flooding. Individuals who are dependent on home medical equipment (or even refrigeration to keep insulin and other medicines cool) may also lose their life-saving medical supports during power outages.


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To evaluate the disastrous consequences of Hurricane Katrina in 2005, the U.S. Centers for Disease Control and Prevention (CDC) studied why some flooded areas in and around New Orleans recovered at very different rates. CDC researchers found that social factors and community factors were the key determinants, and they developed the Social Vulnerability Index (SVI) based on that information. The SVI has since been used to identify regions of the United States that are expected to fare poorly following natural disasters (Flanagan et al. 2011; Flanagan et al. 2018; Lehnert et al. 2020; Wolkin et al. 2015). The four key components of the SVI are socioeconomics, household composition, demographics, and housing/transportation (Flanagan et al. 2018). In Illinois, a number of counties are considered to have a high level of vulnerability, including Alexander, Jefferson, Lawrence, Saline, and Vermilion Counties, while many other counties face moderate to high levels of vulnerability. The public can access the vulnerability of their community—based on social factors—to disasters through an interactive map maintained by the CDC.[1] The Federal Emergency Management Agency (FEMA) recently created the National Risk Index, which is an online mapping application that identifies communities most at risk for 18 natural hazards and incorporates the SVI. It visualizes natural hazard risk metrics and includes data about expected annual losses, social vulnerabilities, and community resilience.[2]

Heat and health

Rising temperatures are leading to more severe and frequent heat waves. Heat impacts in the Midwest will be particularly strong. Illinois has experienced severe heat waves with devastating health outcomes, including one in 1995 that resulted in more than 700 deaths in the Chicago area (Whitman et al. 1997). If greenhouse gas emissions are not substantially reduced, heat waves like the 1995 Chicago heat wave are expected to increase in frequency and could occur as often as once every year by the 2050s (Hayhoe et al. 2010).

High outdoor temperatures—particularly in combination with high humidity and high nighttime temperatures—can lead to a spectrum of heat-related illnesses. These range from relatively mild heat rash and heat cramps to more concerning heat syncope (fainting), heat exhaustion, and life-threatening heat stroke (Figure 5.2) (CDC 2019c). As temperatures rise, the risk for these illnesses is rising as well (Crimmins et al. 2016). Extreme heat also increases the risk of heart attacks and other life-threatening cardiac events (Crimmins et al. 2016). Conversely, while increases in temperature in Illinois are expected to increase the risk of heat-related illness and death, they are expected to decrease the number of deaths due to extreme cold.

The health risks associated with heat waves are driven in part by elevated nighttime temperatures (Crimmins et al. 2016), indicating that an opportunity to cool down at night is important for preventing heat-related morbidity and mortality (Ragettli et al. 2017). Chapter 2 of this report notes that the overnight minimum temperatures and the number of days with warm nights are increasing throughout Illinois. The average overnight minimum temperature in Illinois has increased by as much as 3.5°F over the last century, with the largest change in northeast Illinois, south of Chicago (see Chapter 2). By 2040, there could be up to 40 more days with warm nights in Illinois, particularly in southern Illinois, compared with the average number of days with warm nights from 1990–2019.

People with chronic medical conditions and mental illness, those who live alone, people without access to air conditioning or who cannot afford to use it, and the elderly are at greatest risk of dying in heat waves (Crimmins et al. 2016; Jagai et al. 2017). In addition, people who do physically demanding work outdoors, such as farmworkers, landscapers, and construction workers, are also at risk for developing heat exhaustion and heat stroke (Crimmins et al. 2016).

1 CDC's interactive SVI map can be found at this link: https://www.atsdr.cdc.gov/placeandhealth/svi/index.html

2 FEMA's National Risk Index map can be found at this link: https://hazards.geoplatform.gov/portal/apps/MapSeries/index.html?appid=ddf915a24fb24dc8863eed96bc3345f8

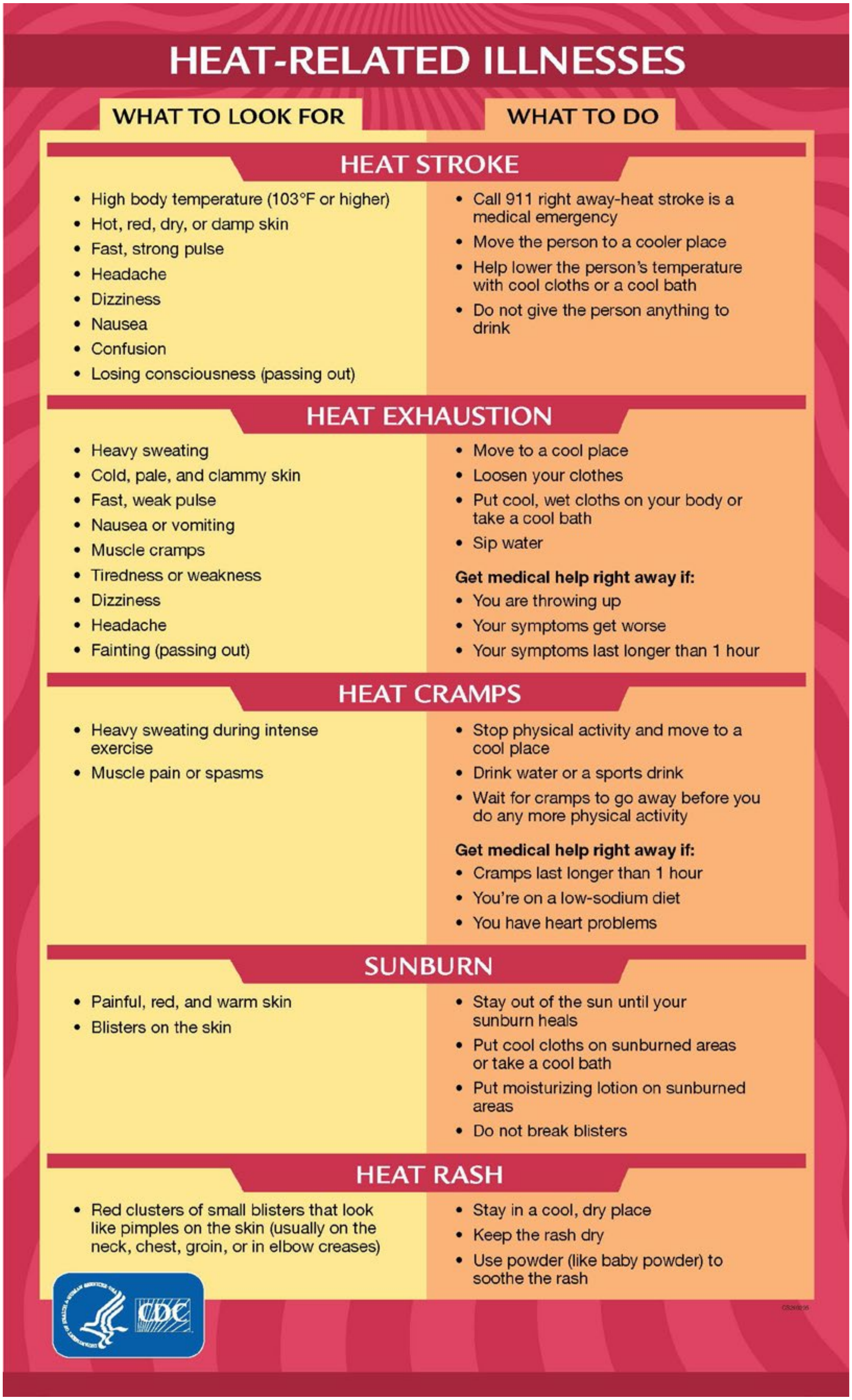

Figure 5.2 Warning signs and symptoms of heat-related illness. **Source:** CDC 2019c.

People of color and low-income earners are more likely to have asthma, self-report fair or poor health, and live in communities with fewer green and blue spaces (CDC 2018b; CDC 2018e; Clark et al. 2017; Marshall and Gonzalez-Meler 2016). These characteristics place them at a higher risk of extreme heat. Even in the absence of recognized heat waves (extreme and prolonged heat), hot weather results in hundreds of hospitalizations across Illinois each year (Jagai et al. 2017).

Urban heat island effect

Urban areas with relatively little green space and significant asphalt, concrete, and large brick structures tend to get hotter than adjacent suburban and rural areas (Mohajerani et al. 2017). They also tend to stay warmer at night, making it difficult for people to cool down (Figure 5.3). This phenomenon is known as the urban heat island effect, and it is not limited to major cities like Chicago (EPA 2020a). The urban heat island effect can vary even within the same city, since land cover varies considerably. Some neighborhoods in a city may have extensive tree cover and shade, while others lack greenspace altogether. Suburban areas with vacant lots, extensive asphalt, and little vegetation also contain microclimates that are hotter than surrounding areas with more green space. As the climate of Illinois continues to warm, higher temperatures combined with the urban heat island effect could result in record temperatures in some urban and suburban areas, further increasing the risk of heat-related illness in those communities.

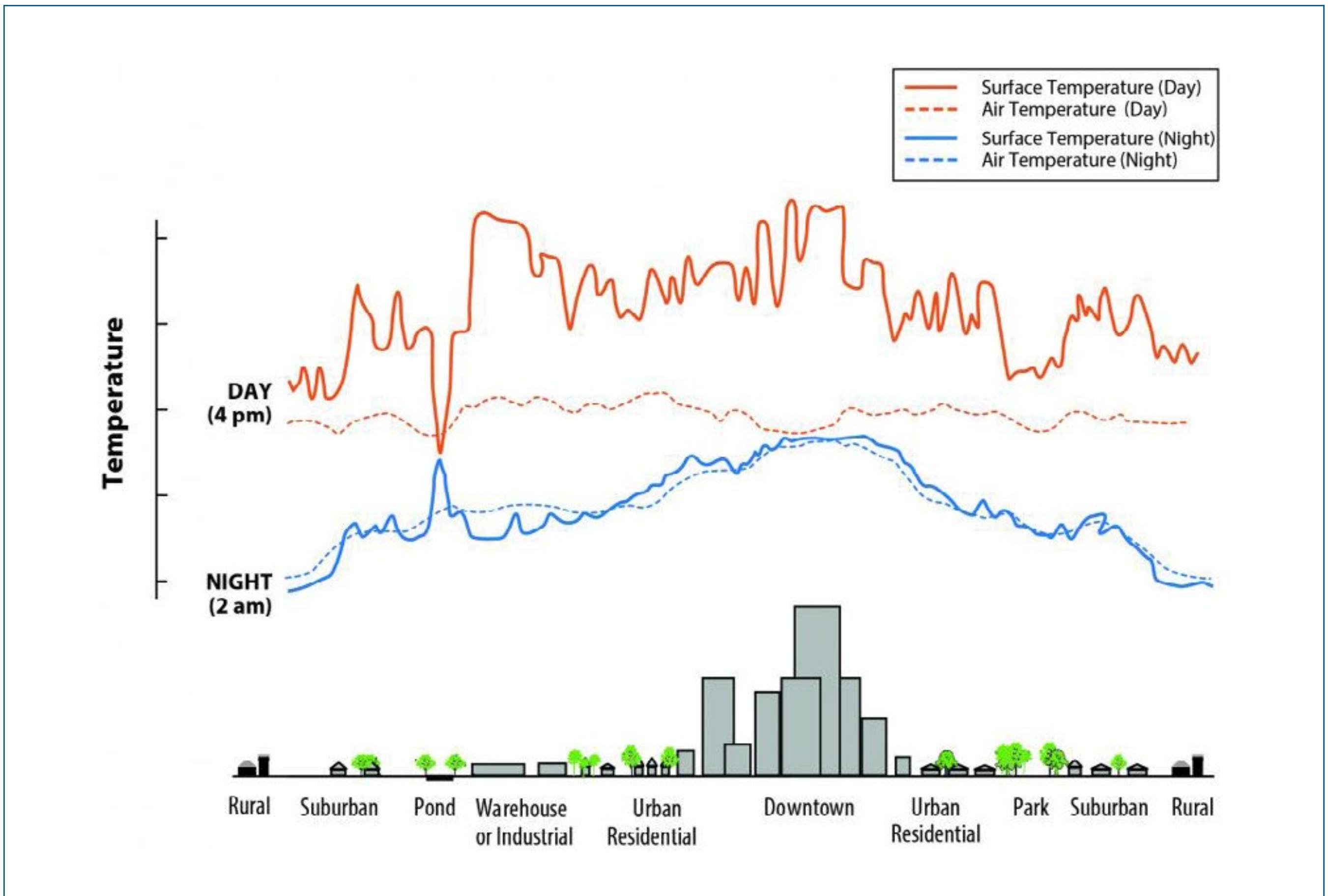

Figure 5.3 Diagram of the Urban Heat Island Effect. Asphalt, concrete, buildings, and car pollution typically make cities hotter than suburban and rural areas, while parks, open land, and bodies of water can help to cool down cities.
Source: EPA 2020a.

Rural heat health

The risk of heat-related illness is not limited to urban areas (Jagai et al. 2017; Vaithyanathan et al. 2020). On a per capita basis, people in parts of rural Illinois are actually at greater risk of being hospitalized with heat-related illness than people in urban areas. Based on the number of heat hospitalizations in each county from 1987–2014 and the population of each county, Figure 5.4 shows that the risk of being hospitalized for a heat-related illness in Illinois is higher in rural counties than in urban counties. The color of the county indicates how urban or rural it is: red is the most urban and purple is the most rural. The size of the dot in each county represents the hospitalization rate: the larger the dot, the higher the rate of hospitalizations for heat-related illness (Jagai et al. 2017). This observed higher rate of heat hospitalization in rural counties may be due to a number of differences between urban and rural areas. For example, exposure to ambient heat in rural areas is higher because there is more outdoor work in agriculture than in urban areas. The elderly also make up a bigger percent of rural communities than urban communities (Parker 2018; USDA ERS 2018). Rural communities are more spread out, making it harder to check in on neighbors. Distances from homes to the nearest hospital are greater in rural areas. Finally, formal cooling centers and methods for transporting the elderly to those centers during heat waves are better established in urban areas.

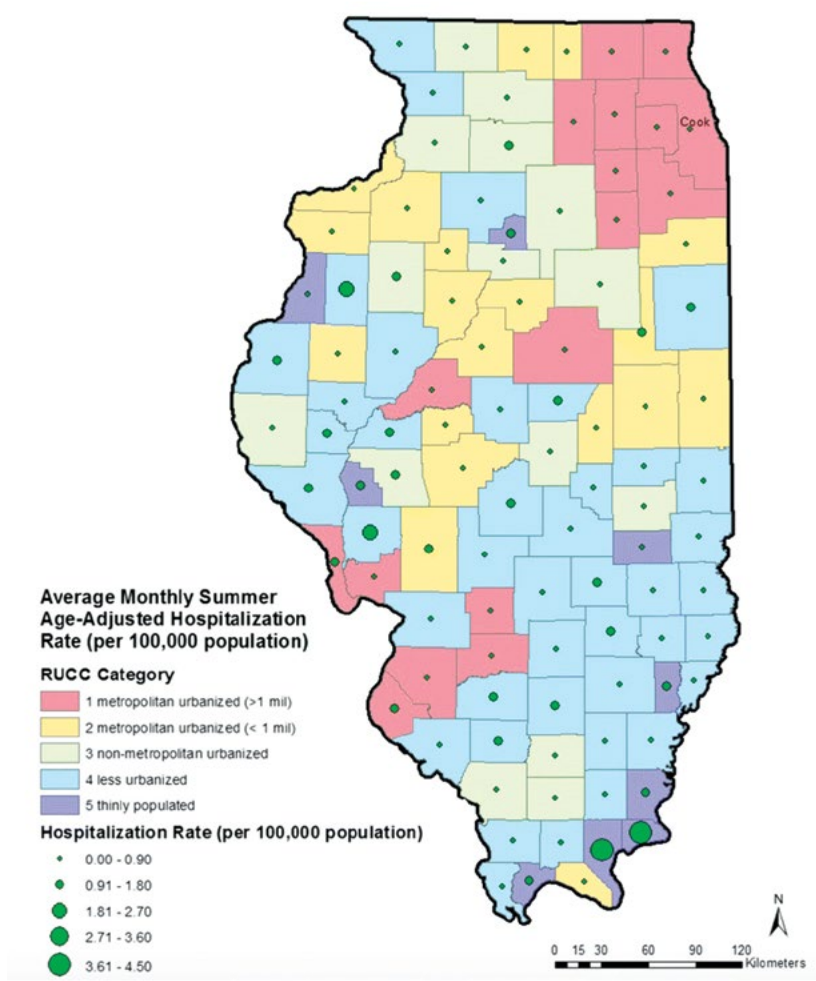

Figure 5.4 Map of heat hospitalization rates by county in Illinois. RUCC stands for the rural-urban continuum code; for a given area, it is a measure of the population density, degree of urbanization, and adjacency to a metro area. **Source:** Jagai et al. 2017.

Flooding and health

As noted in Chapter 2, the annual amount of rainfall in Illinois is expected to continue increasing, with much of that increase occurring in the spring. Over the past 30 years, very heavy rain events have become more frequent in Illinois, and this trend is expected to continue (see Chapter 2). In addition to the damage done to homes and businesses, flooding often causes a wide range of health problems.

Water quality

Heavy rain events and accompanying runoff are expected to negatively impact water quality and increase incidents of waterborne disease and illness. At Chicago's Lake Michigan beaches, levels of fecal indicator bacteria are known to increase after rainfall (Dorevitch et al. 2017; Shrestha et al. 2020). Many Illinois communities have combined sewer systems, in which stormwater and wastewater flow through the same pipes. A well-documented limitation of combined sewer systems is "combined sewer overflow" or "CSO" events that occur during heavy rainfall.

In CSO events, stormwater from city streets, together with domestic sewage, exceeds the capacity of wastewater treatment plants, resulting in a mix of raw sewage and stormwater flowing into local rivers or lakes without treatment. Research done elsewhere in the United States has shown that, in communities that discharge CSO flow into surface waters, rates of diarrheal illness in children increase in surrounding communities following rainfall; the researchers found that rates of such illness do not increase in other nearby areas that do not receive CSO flow (Jagai et al. 2015). Numerous outbreaks of waterborne diarrheal disease—in some cases, life-threatening—have resulted from the contamination of drinking water as a result of heavy rainfall (Clark et al. 2003; Dura et al. 2010; Fong et al. 2007; Salvadori et al. 2009). As noted in Figure 5.5, several of those outbreaks have occurred in Illinois. In Ontario,

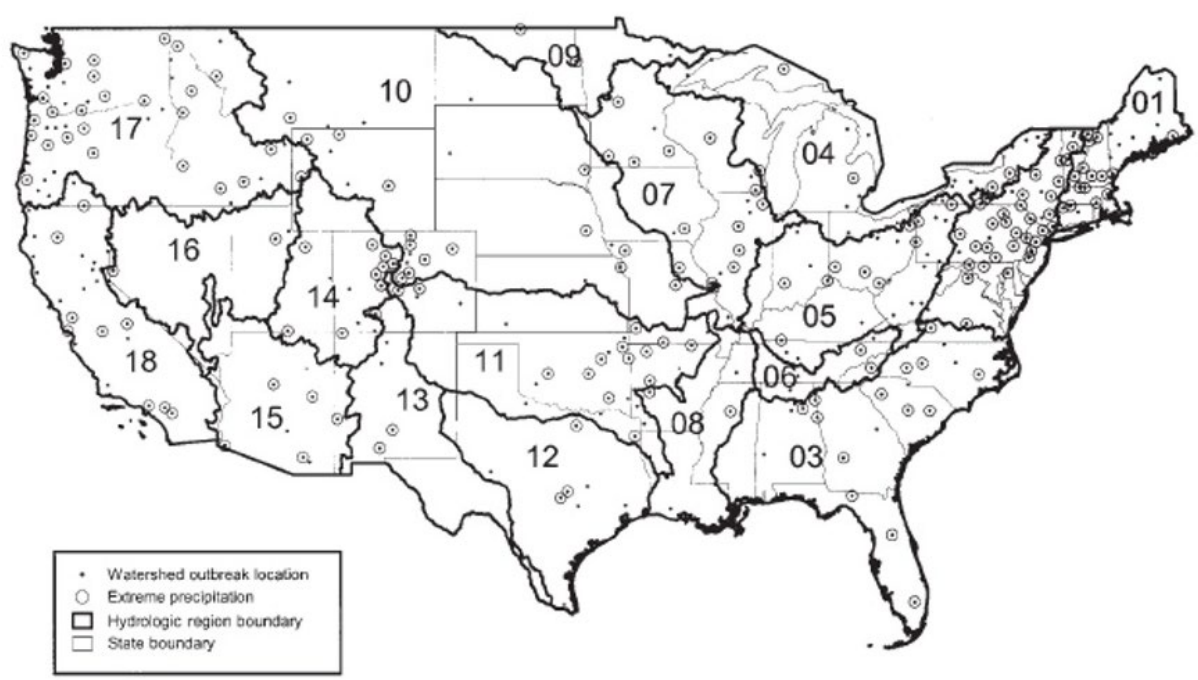

Figure 5.5 Waterborne disease outbreaks and associated extreme levels of precipitation in the United States, 1948–1994. During this period, almost 70% of waterborne disease outbreaks in the United States happened after an extreme precipitation event. **Source:** Curriero et al. 2001.

Canada, a particularly dangerous strain of *E. coli* bacteria caused life-threating infections in hundreds of residents, particularly children. The cause was the flow of animal manure to drinking water wells, which occurred after heavy rains (Auld et al. 2004; Bruce Grey Owen Sound Health Unit 2000; Clark et al. 2003). Many rural Illinois communities are dependent on private or public wells, which puts them at risk for similar events.

The largest waterborne disease outbreak in U.S. history occurred in Milwaukee, Wisconsin in 1993 (MacKenzie et al. 1995). In that outbreak, a combination of factors—precipitation, animal waste entering Lake Michigan, and drinking water treatment failures—resulted in over 400,000 cases of acute gastrointestinal illness. At Chicago's Lake Michigan beaches, levels of fecal indicator bacteria are known to increase after rainfall, even in the absence of wastewater discharges into the lake (Dura et al. 2010; Fong et al. 2007). This suggests that bacteria found in adjacent parks, in parking lots, and on beach sand also flow into beach water after rainfall. Several analyses of the timing of gastrointestinal illness outbreaks in the United States, Canada, and Europe have shown that waterborne disease outbreaks are more likely to occur following heavy rainfall than during dry weather (Curriero et al. 2001; Guzman Herrador et al. 2016; Thomas et al. 2006). In the absence of upgrades to stormwater, wastewater, and drinking water infrastructure and management, increases in heavy precipitation in Illinois are expected to cause more outbreaks of gastrointestinal infections, particularly in children.

Another threat to drinking water quality comes from chemical, rather than microbial hazards. Residents of many areas of Illinois rely on groundwater wells for their drinking water. In a southwestern Illinois region where karst geological features are common, many contaminants of emerging concern and bacteria have been found in groundwater wells (Dodgen et al. 2017; Panno et al. 2019; Zhang et al. 2016). The authors concluded that the majority of wells contained human waste or agricultural fertilizer that had been diluted by precipitation (Dodgen et al. 2017). Increases in precipitation in such areas may represent a threat to the quality and safety of groundwater and, therefore, drinking water in rural areas.

Flood risks to health care facilities

Flooding can threaten the ability of health care facilities to function. It can also make it unsafe for people with medical emergencies to travel to hospitals and other health care facilities. Hospitals, nursing homes, and hemodialysis centers have had to close their doors and/or transfer patients from flooded to non-flooded facilities under dangerous conditions in floods (Adalja et al. 2014; Dosa et al. 2007; Kelman et al. 2015; Murakami et al. 2015; Teperman 2013). Forthcoming research shows that dozens of Illinois health care facilities are located in floodplains (Grossman et al. 2021), indicating that important health care facilities may not be accessible or even operational during floods, which are becoming more frequent and severe in Illinois.

Flooding and carbon monoxide poisoning

Carbon monoxide is a colorless and odorless poisonous gas produced when wood, gasoline, charcoal, or other fuels are burned. If combustion occurs indoors or in poorly ventilated spaces, carbon monoxide levels can become dangerously high, leading to carbon monoxide poisoning. Based on information from many prior floods in the United States, the most common causes of carbon monoxide poisoning are the indoor use of gasoline-powered equipment such as power washers (to clean up after floods) and generators (to temporarily provide power) (CDC 2008; Daley et al. 2001; Iqbal et al. 2012). In the absence of improved storm water management and carbon monoxide poisoning prevention efforts, the occurrence of such cases of carbon monoxide poisoning in Illinois (and throughout the Midwest) is expected to increase in frequency as a result of more frequent and severe flooding.

Injuries

Flooding often results in physical injuries, many of them severe (Du et al. 2010; Yale et al. 2003). Motor vehicle incidents—primarily a result of driving through flooded areas—are responsible for many of the most severe flood-associated injuries. Electrical injuries (due to contact with downed power lines) and foot injuries (due to stepping on submerged nails and other objects) are also linked to flooding.

Respiratory health

Increased precipitation and higher temperatures can result in air quality problems, which can exacerbate existing respiratory health conditions, trigger new ones, and affect healthy lungs.

Floods

Flooding of homes and workplaces promotes the growth of fungi (mold) and bacteria on wet or water-damaged materials. Flooded homes have been shown to have much higher levels of airborne bacteria and fungi than non-flooded homes (Emerson et al. 2015; Rando et al. 2014). High levels of airborne fungi and bacteria, and chemicals that they produce, can trigger upper respiratory tract symptoms (such as runny nose, sinus congestions, and post-nasal drip) and lower respiratory symptoms (such as cough, wheezing, and asthma attacks). Occupational exposures to moldy, water-damaged materials in flooded buildings can also increase the risk of developing respiratory symptoms. Levels of these indoor air pollutants can be particularly high during restoration activities after flooding, as was observed following Hurricane Katrina. In a study of 791 workers in New Orleans, those who worked in flood restoration activities were more likely to have sinus and respiratory symptoms than those who did not perform restoration activities (Rando et al. 2012).

Allergies

Climate change is expected to increase exposure to seasonal allergens (e.g., ragweed, other types of pollen), which can trigger respiratory symptoms for those who are allergic. Since warmer winters, earlier springs, and longer falls will extend the agricultural growing season (see Chapter 2), these changes in climate will also extend the growing season for pollen-producing plants. A working group of the American Academy of Allergy, Asthma, and Immunology summarized several ways that climate change is already impacting risks for asthma and allergies (Poole et al. 2019). The authors noted that data from the United States, Canada, and Europe show that the pollen season is getting longer, starting earlier and ending later than in the past. As summarized in Figure 5.6, the length of the ragweed pollen season has increased significantly in Great Lakes and Great Plains states. In addition, heavy rainfall and thunderstorm events can break up certain pollens into smaller particles that quickly disperse, and laboratory studies demonstrate that the amount of ragweed pollen produced per plant increases with higher concentrations of carbon dioxide (Cecchi et al. 2018; D'Amato et al. 2015; D'Amato et al. 2016; Hughes et al. 2020).

Given that pollen is a trigger of asthma attacks and seasonal allergies, climate change is expected to substantially increase the prevalence of allergies and the frequency of asthma attacks (Anenberg et al. 2017; Neumann et al. 2019). This is particularly concerning in states like Illinois, where asthma prevalence is high among African Americans, women, and low-income communities (IDPH 2018a).

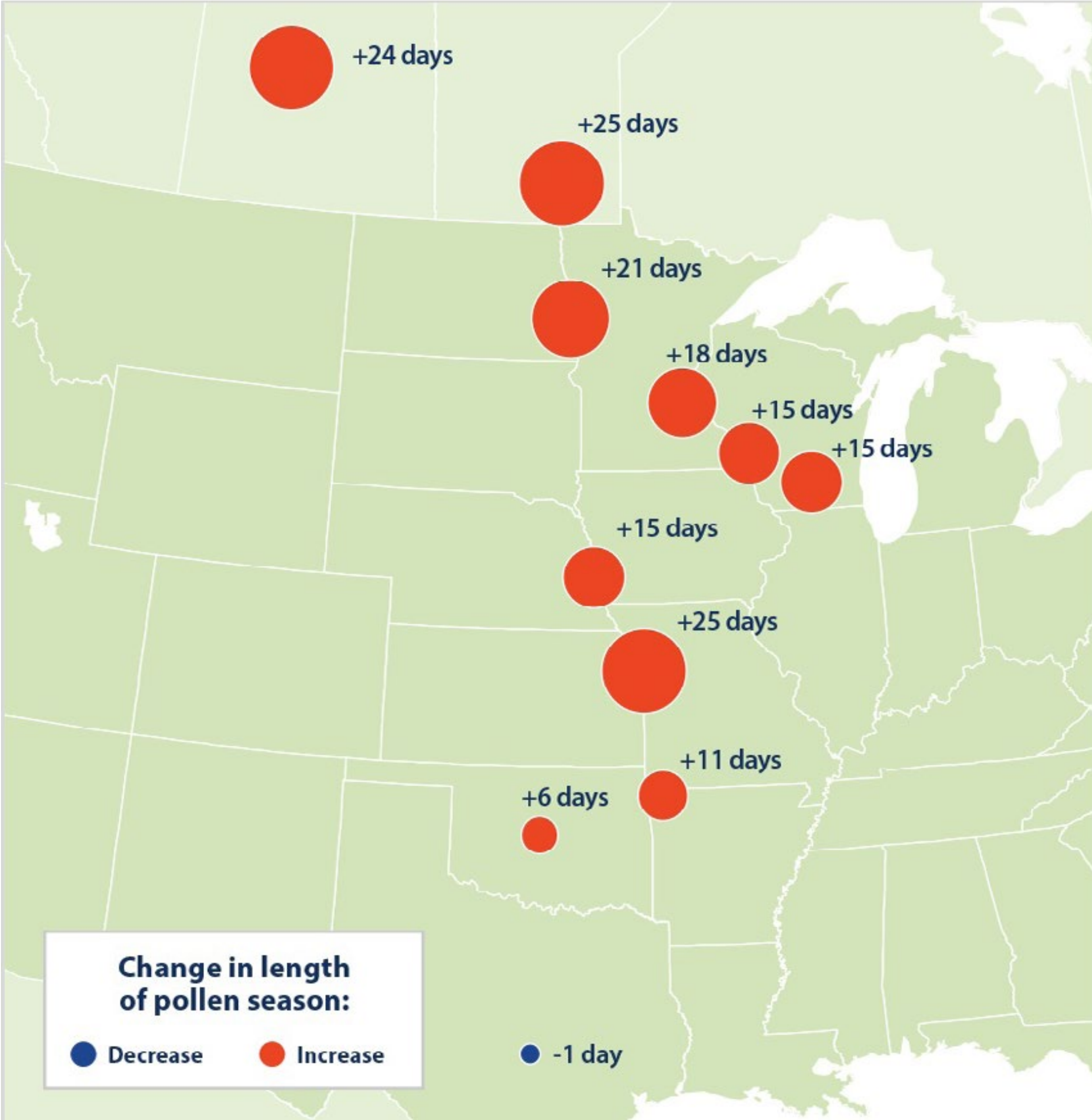

Figure 5.6 Increase in the duration of ragweed pollen season at 11 locations between 1995 and 2015. The red circles represent a longer pollen season and bigger circles indicate larger changes.
Source: Ziska et al. 2011.

Ozone pollution

Ozone pollution is generated in the atmosphere by heat, sunlight, and chemicals (such as volatile organic compounds and nitrogen oxides) produced by the burning of fossil fuels to power cars and factories (Figure 5.7) (EPA 2020b). Rising temperatures are increasing the concentration of ozone pollution (USGCRP 2018), worsening associated respiratory health conditions (Crimmins et al. 2016). According to the American Lung Association, ozone has increased in many American cities owing to record-breaking temperatures over the past few years. The Association's 2020 *State of the Air* report found that Chicago was the 16th most polluted city in the nation in terms of ozone, experiencing around 19 unhealthy ozone days per year on average between 2016 and 2018 (American Lung Association 2020).

Those with a respiratory health condition such as asthma, chronic obstructive pulmonary disorder (COPD), emphysema, and chronic bronchitis are most impacted by ozone pollution. However, high ozone levels can also trigger problems such as coughing, throat irritation, and airway inflammation for those with healthy lungs. In the greater Chicago region, high ozone has the potential to impact significant numbers of people, including over 140,000 children and over 670,000 adults who have been diagnosed with asthma and more than 510,000 people who have been diagnosed with COPD (American Lung Association 2020). Children, older adults, and outside workers are at a higher risk for respiratory health problems than other groups of people based on their physiology and employment (Zhang et al. 2019). People of color are more likely to

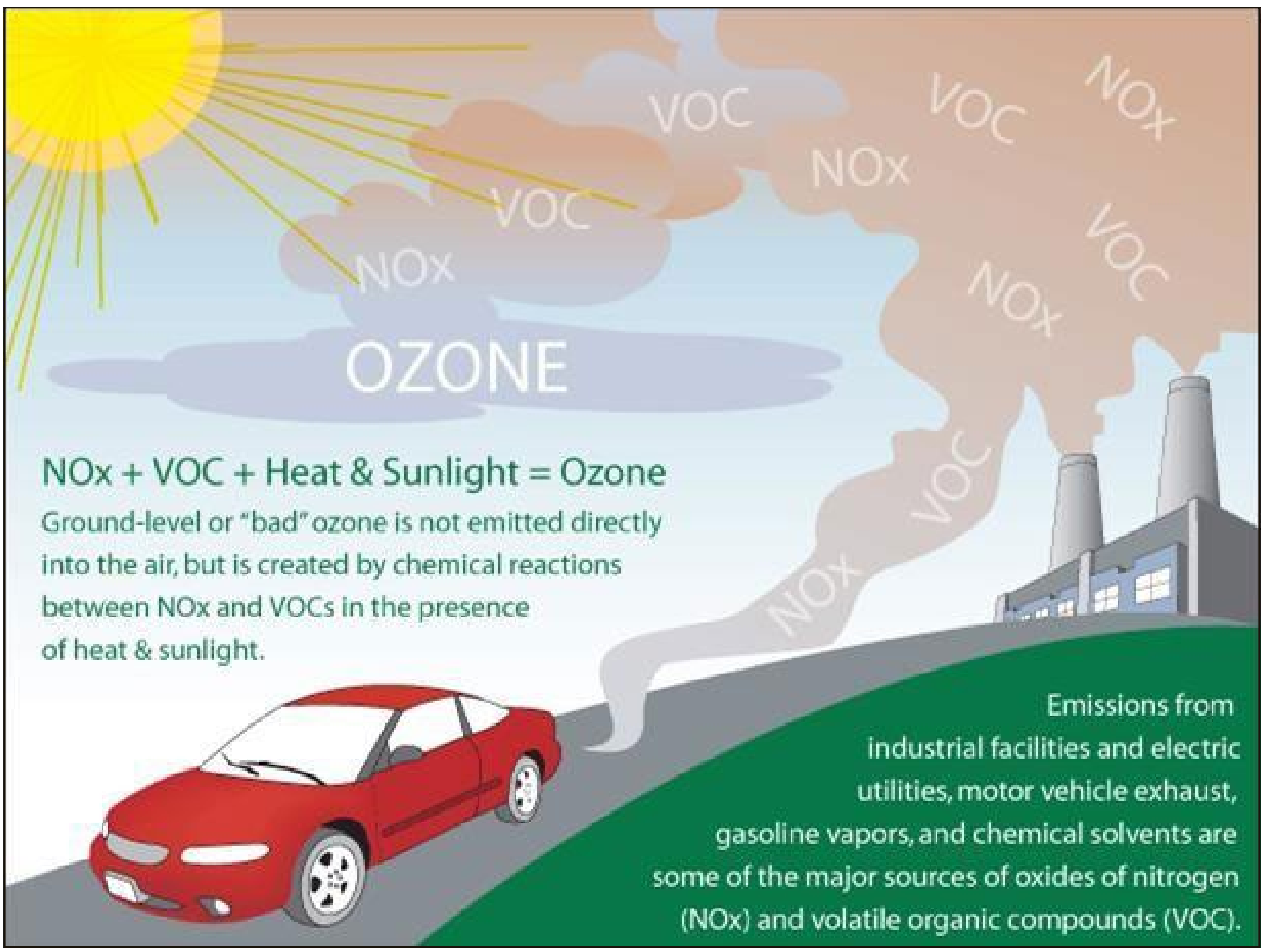

Figure 5.7 Ozone production in the atmosphere. **Source:** EPA 2020b.

live in areas with more air pollution, which places them at greater risk as well (Clark et al. 2017).

Vector-borne diseases

A considerable share of disease worldwide is due to vector-borne diseases, or diseases that result from an infection transmitted to humans and other animals via disease vectors, such as mosquitoes, ticks, fleas, mites, bugs, and lice. Vectors can carry pathogens or microorganisms that cause disease. The pathogens that can be transmitted by specific vectors differ by vector species, and only a proportion of vectors will carry pathogens.

In general, warmer temperatures are predicted to increase the risk of vector-borne diseases. However, the way temperature impacts vector-borne disease transmission is not always straightforward, because each species thrives under unique weather conditions. For instance, when either the mosquito or the disease it carries is close to its ideal temperature for reproduction or transmission, a further increase in temperature can reduce the spread of that disease (Mordecai et al. 2017; Paaijmans et al. 2009). While significant research has been completed over the past two decades to understand the implications of climate change on vector-borne diseases in the tropics (Mordecai et al. 2013; Mordecai et al. 2017), much less is known about the effects of climate change in temperate areas, like Illinois. Temperate areas could potentially be exposed to more intensive transmission of vector-borne diseases that already exist there, as well as to invasions of new vectors and diseases (Mordecai et al. 2017; Ogden et al. 2006; Ogden et al. 2014).

A significant concern is that Illinois has recently experienced emergences of new tick-borne disease agents and has seen a rise in the public health burden of tick-borne diseases associated with range expansions of several species from the north and south.

As noted in Chapter 2, temperature has increased and is expected to continue increasing across all seasons in Illinois. Mild winters have become more frequent, and snow cover has decreased. Soil temperatures in all seasons have also increased, and soils in most of Illinois now remain unfrozen for a longer period of time during the cold season. These trends favor the survival of disease vectors over the winter. In addition, the increase in extreme rainfall events has led to an increase in flooding frequency. As a result of this change in precipitation, the occurrence of long-term drought has diminished during the winter and spring, while shorter term droughts have become more common and summers are projected to become drier (see Chapter 2). Here we highlight how some of these changes are likely to affect mosquitoes and ticks and the diseases they spread.

Figure 5.8 *Aedes albopictus* mosquito. **Source:** CDC 2019d.

Mosquitoes and the infections they transmit to people in Illinois

Milder winter temperatures could be a major factor for the establishment and spread of mosquitoes and enhance the survival of species that are already here. For instance, *Aedes aegypti* and *Aedes albopictus* are two invasive species of mosquitoes that can transmit dengue, chikungunya, and Zika viruses. A major concern is the potential for these mosquitoes to expand their geographic range and be able to survive in more northern areas. *Aedes albopictus*—also referred to as the Asian tiger mosquito—already appears firmly established in southern Illinois and has been increasing in abundance in central Illinois in recent years (Stone et al. 2020). It is also found in Chicago during summertime, although this is likely the result of human-assisted transport or trade (e.g., in waste tires). Studies of the Asian tiger mosquito soon after it became established in the United States suggested that its range would eventually include all areas where January average temperatures were above 32°F and that it would be present during the summertime in areas where the average January temperature was greater than 23°F (Nawrocki and Hawley 1987). Even by that crude measure, warming winter temperatures will allow for a further northward spread.

West Nile virus (WNV) was introduced to Illinois in 1999 and is by far the most prevalent mosquito-borne disease in Illinois and the United States (McDonald et al. 2019). Illinois has consistently had among the highest West Nile virus infection rates in the country over the past two decades. The major mosquitoes that transmit WNV in Illinois are *Culex pipiens* and *Culex restuans*. These mosquitoes enter a dormant state during the winter and those that successfully survive until spring can infect birds with WNV. When other mosquitoes bite infected birds, they can themselves get infected and spread the infection to people. With warmer winters, a larger proportion of female mosquitoes survive, yielding larger mosquito populations and causing WNV circulation to ramp up faster and earlier in the spring. A greater incidence of WNV disease among people has been shown to occur in the months following warm winters (Hahn et al. 2015; Keyel et al. 2019). The number of days that are suitable for the replication of WNV in various cities in the United States has been increasing since the 1970s (Langer et al. 2018). An earlier start to the transmission season for WNV in Illinois is expected to lead to more circulation of the virus between mosquitoes and birds in summer, with more opportunities for transmission to humans in late summer and fall.

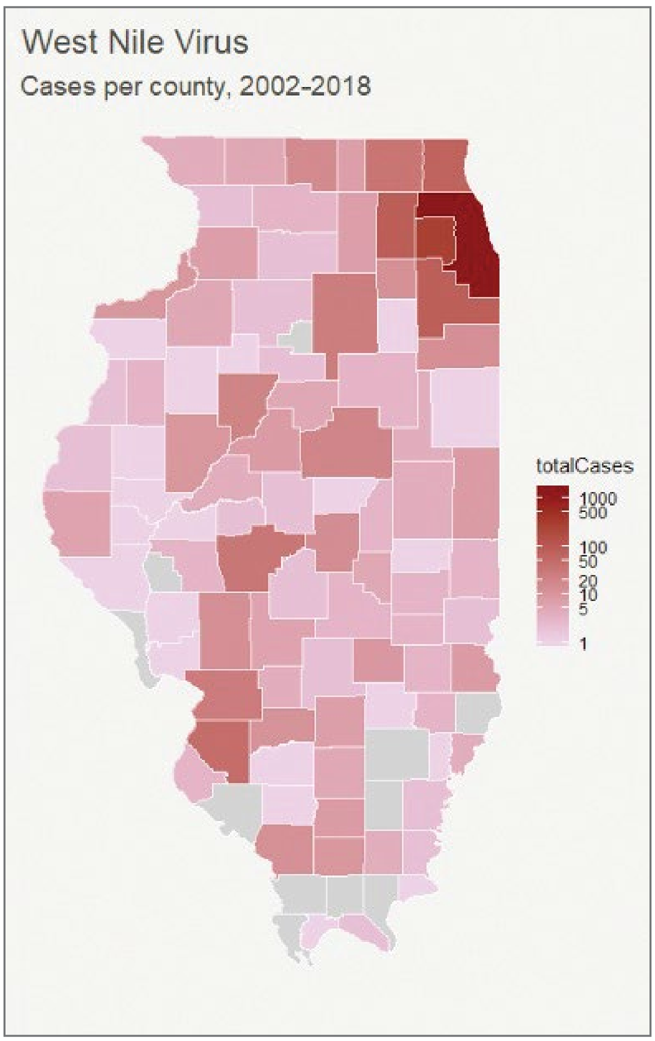

Figure 5.9 West Nile virus human cases per county. While the total number of cases is highest in Cook County, West Nile is present throughout the state. **Source:** IDPH.

Although mosquitoes typically rely on rainfall, *C. pipiens* reproduces best in drought conditions. The year in the last decade with the highest West Nile Virus cases in Illinois was 2012, which was also the last year with an extended drought. Likewise, St. Louis encephalitis epidemics (also transmitted by *C. pipiens*) have occurred during drought conditions (Shand et al. 2016; Valdez et al. 2017). Given that precipitation is increasing in Illinois and that heavy rains are becoming more frequent, it is not clear whether WNV infections will increase (due to higher temperatures and more intense droughts), decrease (due to less frequent droughts), or stay the same. Further complicating efforts to predict the future intensity of WNV in Illinois is that while frequent, heavy rainfall can suppress adult mosquito production and WNV transmission, more intermittent flushing of aquatic habitats can actually elevate disease risk (Koval and Vazquez-Prokopec 2018). It is possible then that the shift in Illinois away from long-term droughts to shorter periods of drought could increase West Nile transmission in the state, though this is an area that needs further research.

Rising temperatures and urbanization: Expanding geographic range

The urban heat island effect may make large urban centers, including Chicago, more prone to the invasion and establishment of species that otherwise could not live there. The yellow fever mosquito, *A. aegypti*, is very effective at transmitting dengue, a potentially fatal infection. That mosquito thrives in tropical and sub-tropical areas and is established in Texas and Florida. However, it can also be introduced by humans (e.g., transport of tires) and, thus, establish populations during the summer months beyond those areas and throughout the United States. Projected changes in temperature and urbanization suggest that, by 2050, the area within the United States that is suitable for this species will have increased to encompass a larger part of the southeast. Furthermore, Cook County is forecasted as being moderately suitable (Kraemer et al. 2019). Controlling *A. aegypti* and other disease-carrying mosquitoes as they migrate north toward Illinois will be a major public health challenge.

Ticks and the infections they transmit to people in Illinois

For ticks, milder winter temperatures could also be a major factor in the establishment, spread, and enhanced survival of species that are already established in Illinois, such as the deer tick (*Ixodes scapularis*), which transmits Lyme disease and is expanding southward through Illinois. The most convincing data for tick species expanding their ranges in Illinois in recent decades has been obtained for the lone star tick, *A. americanum*, and the Gulf Coast tick, *A. maculatum.* The lone star tick can transmit the diseases ehrlichiosis and tularemia (CDC 2018a), as well as Heartland virus. Heartland virus is an emerging virus in the United States, with infection often requiring hospitalization and sometimes resulting in death (Brault et al. 2018). The first two human cases in Illinois occurred in 2018, and the virus has subsequently been found in these ticks in Illinois as well (Tuten et al. 2020). Ehrlichiosis can cause fevers, chills, headaches, nausea, vomiting, diarrhea, and a rash. It can be treated with an antibiotic, but if treatment is delayed, ehrlichiosis can sometimes cause severe illness, such as damage to the brain or nervous system, respiratory failure, organ failure, and death (CDC 2018c). Tularemia may cause several different types of illnesses depending on how and where the bacteria enters the body. The most common form of tularemia from a tick is a skin ulcer at the site of the tick bite. Along with the ulcer, there can be fevers, chills, headaches, and swollen and painful lymph glands (CDC 2018d). The Gulf Coast tick can transmit a spotted fever similar to Rocky Mountain spotted fever, but not as severe (CDC 2018a). The first sign is a dark scab at the site of the tick bite, followed by the possible development of a fever, headache, muscle aches, and a rash (CDC 2019b). This tick and this pathogen were recently documented as being established in southern Illinois (Phillips et al. 2020). The range expansion of lone star ticks in particular over the past 50 years is consistent with a gradually warming environment (Sonenshine 2018). Human Lyme disease, caused by a bacterium transmitted by the blacklegged tick, *Ixodes scapularis*, has been increasing in Illinois as well, though whether this is due to climate change or other environmental changes is not clear.

Milder temperatures in winter (e.g., leading to increased soil temperatures) could improve tick survival and that of their hosts. Increases in temperature and warmer winters have been linked to higher abundances (Kaizer et al. 2015), possibly due to increased survival of hosts, as well as the shortening of tick development times and the overall life cycle. This is consistent with the observed numbers of tick-borne infections in Illinois (Figure 5.10). On the other hand, snow seems to insulate against low winter temperatures (though this does not always appear to be the case) (Burtis et al. 2016). As snowfall and the persistence of snowpack in Illinois are projected to decrease in the future, it is an open question whether this will affect the survival rates of ticks in winter, given the overall increase in winter temperatures.

The factors that determine the spread of ticks and the diseases that they carry are not fully understood, but tick abundance can be affected by factors such as

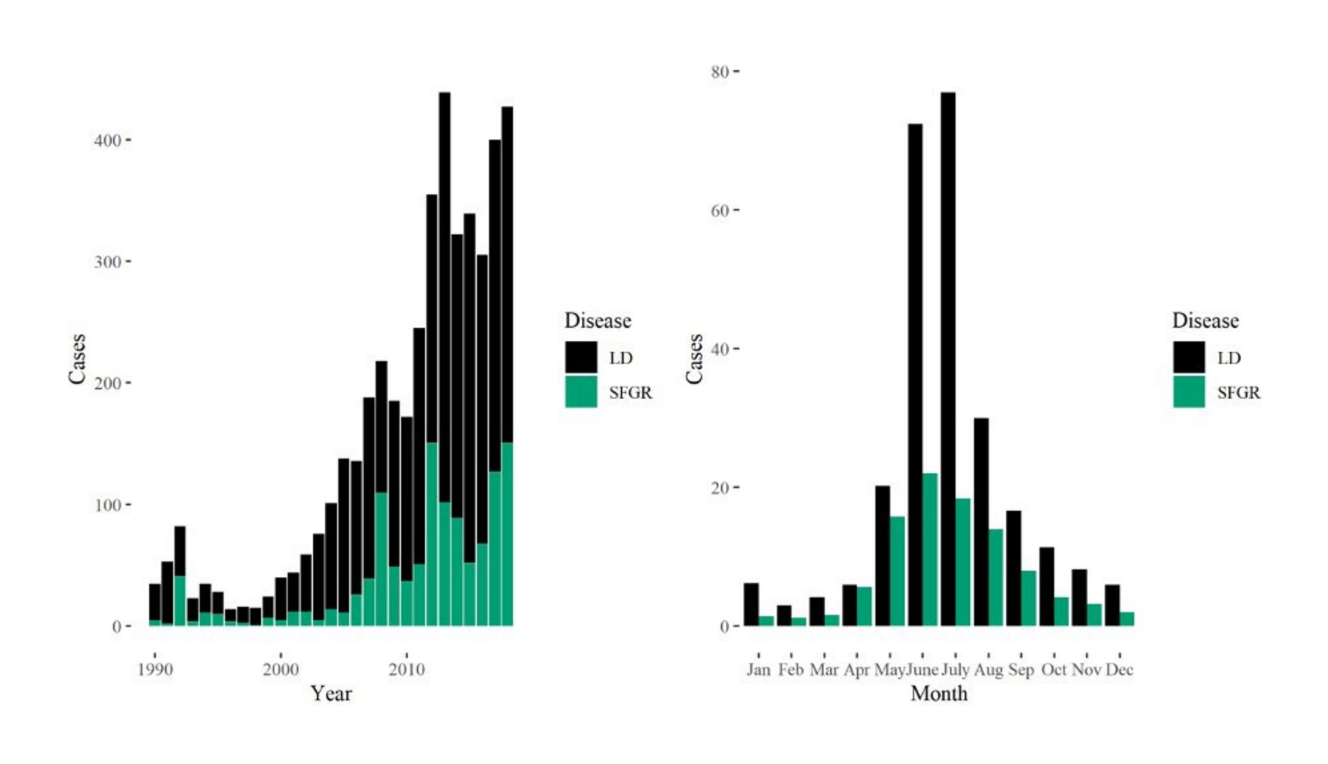

Figure 5.10 Reported human cases in Illinois of two common tick-borne illnesses, Lyme disease (LD) and spotted fever group rickettsial disease (SFGR) by year for the period 1990–2018 (left); and the average number of cases over a 5-year period per month for these diseases in Illinois (right). **Sources:** Illinois Department of Public Health 2018b, 2018c.

temperature, precipitation, reforestation and the spread of invasive plants in natural areas, size of deer populations (hosts to ticks), and the occurrence of forest fires. Given the ways that these factors interact with one another, it is difficult to predict how further changes in temperature and precipitation will change abundance, behavior, and life cycle, which are all critical to public health and pathogen transmission. Occupational, physiological, and behavioral factors can also increase the risk of a vector-borne disease. People who work outside, participate in outdoor activities such as hiking and hunting, and live near vectors and their habitats are at higher risk for infection (Crimmins et al. 2016).

Mental health

Climate change is leading to more frequent and severe extreme weather events, impacting mental health and well-being, as depicted in Figure 5.11. Mental health effects can be direct or indirect, deriving from acute or chronic weather conditions (Berry et al. 2010). Major weather disasters like a flood, wildfire, or extreme heat can directly impact mental health by causing emotional distress and trauma, which can lead to post-traumatic stress disorder (PTSD), depression, anxiety, hopelessness, helplessness, aggression, denial, apathy, and even suicide (Berry et al. 2010). People may be displaced from their homes, suffer a loss of emotional belonging and physical property, encounter a disruption of social connections and business operations, experience the financial stress of rebuilding homes and businesses, witness people harmed and landscapes destroyed, and endure an uncertain future, which may all result in the initiation and intensification of mental health conditions (Crimmins et al. 2016). These impacts can become chronic problems. In a mental health survey conducted between five and eight months after Hurricane Katrina and again one year later, the percent of those identified with a mental health condition increased over time. Twelve years after the event, mental health professionals are still seeing

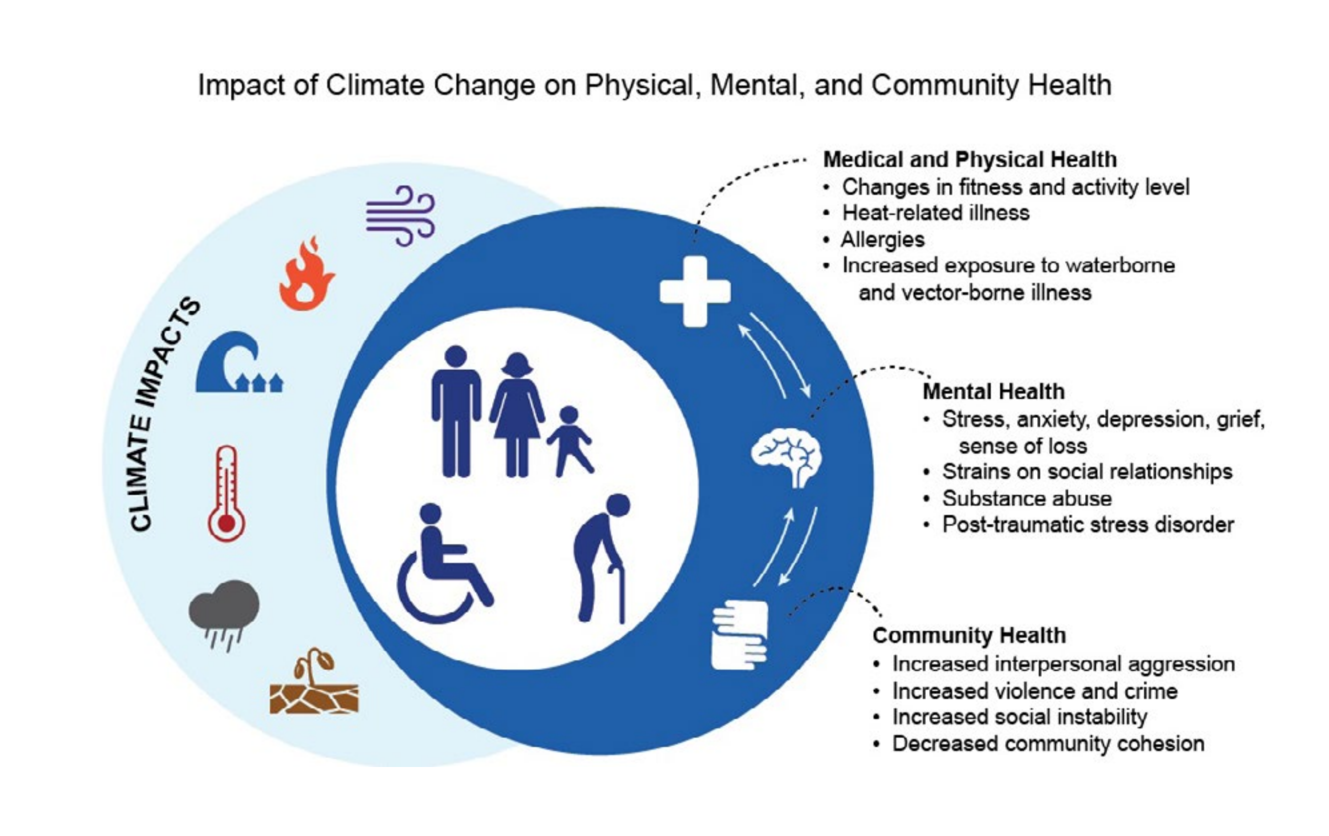

Figure 5.11 The impact of climate change on physical, mental, and community health. **Source:** Crimmins et al. 2016.

PTSD and cognitive difficulties (Kessler et al. 2008; Raker et al. 2019).

Farmers and mental health

Mental health researchers have identified farmers as a group that may be at risk for mental health challenges as a result of climate change (Berry et al. 2011a; Berry et al. 2011b; Hogan et al. 2011; Howard et al. 2020). According to a recent report by the CDC, farmers are the most likely to die by suicide among occupational groups (Peterson et al. 2020). They face long hours, heavy workloads, financial risks, and social isolation. They also rely on the weather for productive crop yields, and climate change is causing weather to be more unpredictable and extreme. For example, during the spring 2019 flooding that devastated the Midwest, only 35% of corn and 14% of soybeans were planted by the end of May in Illinois. In contrast, over the previous five years, 95% of corn and 70% of soybeans were planted by the end of May (NASS 2019). As Chapter 4 of this report identifies, farmers will have to manage a number of adverse climate impacts. Psychologically, these changes and challenges can lead to anxiety and stress.

Existing mental illnesses

The National Alliance on Mental Illness (NAMI) Chicago reported that nearly 40% of adults in Illinois ages 18 and older have experienced poor mental health, almost 17% of Illinois adults were living with a mental illness, and slightly over 3% were living with a serious mental illness (NAMI Chicago 2015). People with existing mental illnesses or using medications to treat a variety of mental health conditions are at a higher risk of experiencing adverse mental health outcomes due to an extreme weather event (Berry et al. 2010). The relationships between exposure to climate-related disasters and mental health outcomes are poorly understood and likely nonlinear, meaning the mental health outcomes can continue to present themselves and change after the exposure. People with PTSD, depression, anxiety, or sleep difficulties can experience exacerbated symptoms when preparing for, during, and after an extreme weather event. If transportation, healthcare, or communications infrastructure is damaged from an extreme weather event, this can also leave those with mental illnesses unable to access care and lead to more negative mental health outcomes (Crimmins et al. 2016). Finally, a number of medications used to treat mental illnesses interfere with the body's ability to regulate temperature, making patients more sensitive to heat and susceptible to heat-related illnesses (Martin-Latry et al. 2007). Other populations at a greater risk of poor mental health outcomes from climate-related events include children, women, pregnant and postpartum women, the elderly, low-income communities, immigrants, veterans, those from indigenous communities or tribes, the homeless, those with limited mobility, emergency workers, and first responders (Crimmins et al. 2016).

Violence

A report by researchers at the U.S. Department of Justice found that interpersonal and intrapersonal violence increase with higher temperature (Lauritsen and White 2014). On a national level, rates of household crimes, aggravated assault, rape and sexual assault victimization, and intimate partner violence were all higher during summers than other seasons. High heat days during summer months further highlight this association. Crime, domestic violence, rape, and disorderly conduct incidents were found to be higher during warmer temperatures in Philadelphia (Schinasi and Hamra 2017). Thus, the continued warming of the Illinois climate may result in increases in interpersonal violence.

Eco-Anxiety

Eco-anxiety is a chronic fear of environmental doom that can lead to an increase of anxiety (Clayton et al. 2017). The mental health impacts following disasters described above are acute consequences, while gradual environmental changes and degradation can result in chronic psychological consequences (Clayton et al. 2017). The increasing risk of injuries and other physical health conditions, such as increased susceptibility to heat stress, exposure to water- and vector-borne diseases, and more frequent and severe flooding events, can exacerbate anxiety (Clayton 2020). More frequent and severe extreme weather events will damage the natural and social environments upon which communities depend for their livelihoods, health, cultural connectedness, and well-being. Furthermore, the anticipation of future climate change impacts on health can compound anxiety and psychological distress (Fritze et al. 2008). The perception and threat of climate change can have negative mental health effects. As more people recognize climate change as an environmental and health issue (e.g., via exposure through media channels or personal experience with an extreme weather event), trauma and anxiety disorders may heighten with the uncertain anticipation of a reoccurrence or an episode occurring for the first time.

Economic impact of the health effects from climate change

The National Oceanic and Atmospheric Administration (NOAA) has catalogued national and statewide weather and climate events since 1980 that led to economic damages in excess of one billion dollars (NOAA 2020c), often spread across multiple states within the United States. According to these estimates, Illinois ranks fourth in the frequency of billion-dollar events (NOAA 2020a; 2020b). From 1980–2020, there were 89 climate events with total costs (across all states) exceeding one billion dollars that impacted parts of Illinois, along with neighboring states. These events included 60 severe storms (67.4% of the total), 11 drought events (12.4%), 11 winter storms/freezes (12.3%), and six floods (6.7%). The economic damages specific to Illinois that were associated with these events are estimated to be $38.4 billion (adjusted for inflation). All of these events are associated with adverse health outcomes, but the billion-dollar disaster assessments do not take into account healthcare costs and the economic losses due to deaths (Smith and Katz 2013). Considering this and the paucity of Illinois-specific assessments of the economic impact of climate-sensitive health outcomes, it is instructive to learn from studies in other parts of the country.

There is growing evidence of the economic burden of direct health impacts associated with extreme temperature. Two separate studies in California (Knowlton et al. 2011) and Wisconsin (Limaye et al. 2019) identified two prolonged, record-breaking heatwaves and estimated the costs of deaths and illness. The 'value of statistical life' approach was used to quantify the costs of deaths; cost estimates available from the Healthcare Cost and Utilization Project (HCUP), run by the Agency for Healthcare Research and Quality, was used to quantify the cost of illness associated with hospital admissions, emergency department visits, and outpatient visits attributable to the heatwaves. The estimated health cost for California was $5.4 billion (in 2008 dollars), and for Wisconsin was $251 million (in 2018 dollars). The primary difference in these health cost estimates between the two locations is due to the larger population in California that was exposed to the heat wave.

In another study, the costs of excess all-cause mortality, hospital admissions, and emergency department visits attributable to exposure to cold temperature were estimated for the Minneapolis/St. Paul Twin Cities metropolitan area. The estimated health cost for the Twin Cities is $8.2 billion per year (2016 dollars) (Liu et al. 2019), which is relevant for Illinois given the high frequency of winter storms and freezing events. These costs may be expected to decrease as the Illinois climate continues to warm. However, this study also estimated annual health costs of $1.17 billion per year attributable to high temperature exposure, which could increase as the climate warms. Another study utilized health insurance data to project an additional 21,000–28,000 emergency department visits in the United States for hyperthermia in 2050, with an associated cost of $6–$52 million (2015 dollars) (Lay et al. 2018). According to this study, the Midwest region would experience the highest rate of increase in heat-related emergency department visits in 2050. Besides the direct health impact from exposure to high temperature, the U.S. Environmental Protection Agency (EPA) estimates a reduction in working hours, particularly in outdoor labor-intensive industries, due to increases in summer temperature (EPA 2017). These estimates project a reduction in labor productivity across all counties in Illinois, to varying degrees, with significant economic consequences. Under the higher scenario (RCP 8.5), impacts of extreme temperatures in the Midwest are expected to be $9.8 billion for premature mortality and lost labor in the year 2050 (Angel et al. 2018).

The incidence of Lyme disease in Illinois may continue to increase as the climate warms, which could also result in an increase in the associated healthcare costs in the coming years. Recent estimates using health insurance records of individuals under 65 years found the mean annual cost of all Lyme disease–related hospitalizations to be $15,638 per hospitalization (2016 dollars) (Schwartz et al. 2020). The overall annual healthcare costs for a person with Lyme disease are estimated to be $2,968 greater than for a comparable individual without the illness (Adrion et al. 2015).

Few analyses have estimated the overall economic impacts of flooding on health and healthcare systems in the Midwest. Some studies have looked at costs of components of the total health costs related to flooding. Analysis of morbidity data on CSO events and mortality associated with flooding and heavy precipitation in Ohio produced a cost estimate of $82.8 million (2018 dollars) for one year (Limaye et al. 2019). Flooding can exacerbate mold and dampness inside buildings, leading to potentially adverse health outcomes. A national analysis estimated the health cost associated with asthma attributable to indoor mold and dampness to be $3.5 billion (Mudarri and Fisk 2007).

Attributing adverse health outcomes to weather events and the changing climate is complex, limiting the development of economic assessments of health impacts associated with these events. Routine health surveillance systems contain a variety of clinical diagnoses codes that indicate health outcomes associated with environmental exposures (e.g., temperature, flood, storm, pollution). But estimates of adverse outcomes solely based on tracking these diagnoses codes could underestimate the actual health burden. As an example, there is an annual estimate for the United States of 733 deaths for which exposure to heat is recorded as a cause of death (based on analysis of mortality data from the National Center for Health Statistics for 2004–2018) (Vaidyanathan et al. 2020). Compared with this estimate based on surveillance data, a separate statistical analysis of all-cause mortality estimated an annual average of 3,590 excess deaths attributable to extreme heat for the United States (Gasparrini et al. 2015). Thus, cost of illness studies related to extreme weather/climate events could depend on the underlying epidemiologic methodology used to ascertain the number of individuals impacted. Strengthening health surveillance systems and accounting for contributions of weather factors to disease burden estimates would improve our ability to estimate the economic impacts of climate change on health.

There is growing evidence of the health benefits from a wide range of climate mitigation and adaptation strategies. The Climate Change Impacts and Risk Analysis (CIRA) project by the U.S. EPA estimates substantial economic benefits from global greenhouse mitigation strategies that will reduce the summer temperature and ozone concentrations in the future compared with the business-as-usual scenario (Bell et al. 2017). The extent of economic damages to healthcare systems from extreme weather events are substantial (Texas Hospital Association 2017). The Fourth National Climate Assessment highlighted the potential economic benefits from engineering redesign to hospitals that ensure uninterrupted healthcare services during and after such events (Ebi et al. 2018). Health interventions in the form of early heat warning systems are shown to be cost-effective solutions in reducing heat-related adverse health outcomes (Ebi et al. 2004). Such collaborations between health departments and weather forecast offices are becoming common in many parts of the United States (Metzger et al. 2010; Wellenius et al. 2017).

Recommendations for climate and health adaptation measures

The field of public health as well as other professional sectors can prepare for the health effects from climate change to minimize adverse outcomes. The public health sector can incorporate climate change into public health planning, inform physicians and nurses about the health effects and utilize them as key messengers, and implement strategies through a climate and health equity lens. Urban planners, engineers, architects, landscape architects, and ecologists can use built and nature-based solutions to protect public health.

Incorporate climate change into public health planning

Public health planning encompasses a variety of activities, including planning programs to address specific health concerns and prioritizing current and future health needs at the local, state, and national levels (Issel 2009). The CDC has developed the BRACE framework (Building Resilience Against Climate Effects) to support the incorporation of climate change preparedness into activities of health departments (CDC 2019a). Illinois has been a recipient of funds from CDC's Climate Ready Cities and States Initiative to implement that framework in Illinois.[3] The most recent *State Health Assessment* for Illinois was completed in 2016 and identified behavioral health, chronic disease, and maternal and child health as the health priorities through a data-informed and stakeholder engagement process (IDPH 2016). The health effects from climate change intersect all public health programs—infectious and communicable disease control, environmental health services, chronic disease and injury prevention and control, public health emergency preparedness, clinical services and health care systems, and even maternal, child, adolescent, and family health (Frumkin et al. 2008; Rudolph et al. 2018). The field of public health can integrate climate change into existing work in all of these programs. For example, long-term monitoring

3 More information on the BRACE framework in Illinois can be found at this link: https://braceillinois.uic.edu/

and surveillance of mosquito- and tick-borne diseases (e.g., the IDPH-funded statewide tick and tick-borne disease surveillance program through the Illinois Natural History Survey Medical Entomology Lab, which performs active surveillance, trains public health personnel, and accepts citizen tick submissions), can be combined with meteorological data and used to develop disease forecasts. In addition, studies on vectors and climate change mitigation measures can ensure that implementation of green infrastructure projects occur in a manner that prevents accidental increases in vectors. Chronic disease and injury prevention and control can combine environmental data, meteorological forecasts, and information on disease incidence to develop models that forecast triggers for those who are at high risk of respiratory health issues.

Utilize physicians and nurses as key messengers

Nurses are the most trusted profession in the United States, and medical doctors are the third most trusted (Gallup News Service 2019). The majority of physicians and nurses agree that climate change impacts health but do not believe they have the resources or skills to respond (Polivka et al. 2012; Villella 2011). Nurses and physicians can incorporate climate change into their practice by informing patients of the connection between their personal health and climate change, how to reduce the impact, and actions they can take to help mitigate climate change. Medical and nursing schools can integrate climate change into their curricula; continuing medical education activities for nurses and physicians can include topics on climate change and health; and academic climate change and health experts can partner with healthcare systems to provide trainings and conferences and seminars for physicians and nurses.

Implement strategies through a climate and health equity lens

Climate change disproportionately impacts people who have low health equity, those who do not have adequate opportunities to be as healthy as possible. People who have low health equity are often from low-income communities and communities of color. They are more likely to have asthma, self-report fair or poor health, live in communities with fewer green and blue spaces, and be exposed to more air pollution (CDC 2018b, 2018e; Clark et al. 2017; Marshall and Gonzalez-Meler 2016). These pre-existing conditions make these groups the most vulnerable to the health impacts from climate change and the least prepared to manage and recover from any devastating climate-related event. Using a climate and health equity lens, public health professionals and organizations can advance health equity and climate resilience within existing programs, for example, by including climate, health, and equity language and data in public health plans, budgets, and assessments (Rudolph et al. 2018).

Use built and nature-based solutions to protect and promote public health

A partnership between the public health sector and non-health sectors can improve both climate change resilience and health outcomes through built and nature-based solutions. The built environment is the part of the physical environment that is made by humans (Perdue et al. 2003). Nature-based solutions are approaches to protect, sustainably manage, and restore natural or modified ecosystems while providing human well-being and biodiversity benefits (Cohen-Shacham et al. 2016). Expertise for both of these strategies falls outside the scope of public health but has a large impact on health. Built and nature-based solutions include expanding urban tree cover, green roofs, white roofs, parks, safe and accessible bike lanes and public transportation, bioswales, rain gardens, and forest, wetland, and prairie restoration. These strategies can help cool down communities, improve air quality, and mitigate floods, which reduce the risk of heat-related illness, exacerbated respiratory health conditions, and mold exposure (Younger et al. 2008). They also encourage more physical activity, which helps cardiovascular health, increases social capital, and improves mental health (Younger et al. 2008).

Chicago Greenprint

The Nature Conservancy created Chicago Greenprint to identify where nature-based solutions can help alleviate challenges related to climate change in Cook County's communities, especially in those neighborhoods that are particularly vulnerable to climate change impacts. Chicago Greenprint is a mapping tool that analyzes multiple layers of data to determine which neighborhoods are at highest risk of flooding, poor air quality, and excessive heat. It also considers data on which areas are home to high concentrations of youth, older adults, and low to moderate income families, who are most at risk from these impacts. The tool can be used by communities and other stakeholders to understand the risks they face and to identify areas that could benefit from incorporating green infrastructure, such as rain gardens, bioswales, and additional greenspace.

To learn more about Chicago Greenprint and to access the tool, please visit: https://storymaps.arcgis.com/stories/696655807ab54c2881f7b57aa145c717

Knowledge and research gaps

In order to improve our understanding of the adverse public health impacts from climate change and the most effective strategies to reduce them, more knowledge and research are required in the following areas:

- **Evidence-based public health strategies for addressing climate change**
  Evidence-based public health practice involves applying evidence-based medicine frameworks to public health. An evidence-based approach to public health and climate change will provide access to more and better information on best practices, a higher likelihood of successful prevention programs and policies, greater workforce productivity, and more efficient use of public and private resources.

- **Cost-benefit analysis of climate and health adaptation strategies in Illinois**
  Between 2000 and 2009, six climate-related events in the U.S. resulted in $14 billion in health costs (Knowlton et al. 2011). In 2012 alone, the harmful health impacts of 10 climate-sensitive events in 11 states cost $10 billion (Limaye et al. 2019). Understanding the cost of the health impacts from climate change in Illinois and the cost of implementing strategies to reduce the health impacts from climate change will give decision makers a data-driven tool to make informed decisions and act.

- **Climate and health communications**
  Seventy-two percent of Americans believe climate change is happening and 61% think it will harm people in the United States, but only 56% think it is already harming people in the United States now or will within 10 years and only 43% think it will harm them personally (Yale Program on Climate Change Communication 2020). There is a disconnect between knowing that climate change is happening and understanding how it can personally affect us. Effective communications are needed about scientific research that links local impacts of a changing climate to health. More effective communications about climate and health specific to Illinois communities are needed, given that localizing the impacts of climate change is critical to communicating them (Evans et al. 2014; Kiwanuka-Tondo and Pettiway 2017; Schroth et al. 2014; Sheppard et al. 2011).

- **Relationship between climate change and vector-borne diseases**
  The relationships between climate change and vector-borne diseases are extremely complex. Thus, there is a need to better understand the relationships to inform strategies to reduce the number of vector-borne disease cases, morbidity, and mortality in Illinois.

- **Relationship between climate change and mental health**
  The relationship between climate change and mental health is a burgeoning field of research that needs continued support. There is also a need to better understand how climate solutions can positively benefit mental health.

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CHAPTER 6

Climate Change Impacts on Ecosystems

Key Messages

1. The ecosystems of Illinois have always been dynamic, responding to changes in climate through shifts in the abundance and composition of plants and wildlife. At least two key factors, however, differentiate the current situation from the past: the rate of climate change is much more rapid than in the past and the natural ecosystems remaining in the state are isolated due to widespread land conversion. Both factors will greatly hinder the ability of native plants and animals to adapt or migrate.
2. Projected changes in climate—warmer and wetter winters and springs, followed by hotter and drier summers—are likely to enhance conditions for some native species in Illinois, including trees such as sweetgum, post oak, and hackberry, and birds such as the prothonotary warbler. At the same time, conditions are likely to become less suitable for other native species, such as the Ohio buckeye, basswood, and quaking aspen.
3. Changes in climate will likely provide advantages to pathogenic insects like the emerald ash borer and invasive, non-native plant species, such as Amur honeysuckle, Johnson grass, oriental bittersweet, and Japanese stilt grass.
4. Warmer winter temperatures will reduce ice cover on Illinois lakes, which may affect key fish species such as walleye during spawning. Heavy winter and spring rains may reduce habitat for some species, such as largemouth bass and Louisiana waterthrush, and threaten habitat suitability for native mussels and bottom-dwelling aquatic invertebrates.
5. Climate change interacts with and amplifies impacts of other stresses such as habitat degradation, and ecosystems that are already stressed will be less resilient. For example, native grasslands in Illinois are already impacted by numerous invasive species, and degradation by invasive species is expected to be exacerbated by a warmer climate, with adverse effects for wildlife that depend on these habitats, such as grassland birds.
6. In Illinois, lands that remain in a natural or semi-natural condition are mostly in private ownership. Managing these lands effectively in a changing climate will require cooperation among private landowners, land trusts, and natural resource agencies.
7. Conserving intact and biologically rich natural ecosystems, initiating large-scale restoration projects, and managing connectivity among these areas will help safeguard native plants and wildlife and enhance their ability to adapt to changing conditions or migrate to more suitable habitats. Native ecosystems are inherently more resilient to climate change than highly managed systems (e.g., tree plantations). Conserving and restoring natural ecosystems also sequesters carbon, which is important for mitigating climate change.

Introduction

Driving through Illinois today, passing vast fields of corn and soybeans that dominate a landscape dotted with scattered towns and cities, it may be difficult to imagine that the state was once a rich mosaic of forests, wetlands, extensive prairies, and waters teeming with wildlife. Commencing with Euro-American settlement in the early 1800s, these incredibly diverse habitats began to give way to greatly simplified systems of human design. Nearly all arable lands in Illinois have been converted to agriculture: less than 20% of the original forested area remains, less than 0.1% of prairies remain (Iverson 1988), and over 90% of wetlands have been drained (Dahl 1990). At present, less than 0.07% of land in Illinois remains in an undegraded state.

Yet change is a fundamental characteristic of the state's ecosystems. Even the most casual observer is familiar with the seasonal changes of a temperate forest during the course of a year, from the dormant winter months to renewed growth in spring and a luxuriant summer appearance followed by the colors of autumn. Change is even more pronounced when viewed over longer time frames. Following the last ice age, Illinois experienced a brief tundra phase, followed by a period dominated by spruce and fir and then spruce and pine forests (King 1981). Gradually, deciduous forest entered the region, with oak and hickory becoming dominant around 8,000 years ago. Prairie species later expanded, forming a Prairie Peninsula extending east to Ohio. This was followed by the emergence of more open wooded habitats that, along with grasslands, were maintained by fire, periodic droughts, and grazing animals (Taft et al. 2009).

Environmental change is not unusual. In fact, it may be the most natural feature of the world we live in. The difference today is the rapid pace of change. As detailed in Chapter 2, we have entered a period of unprecedented, human-caused warming. Not only are the direct effects of climate change concerning, but so too are the ways that climate change tends to interact with or amplify other environmental stresses. For example, the effects of climate change may further compromise the ability of native plant species to cope with competition from invasive, non-native species (Gieisztowt et al. 2020), such as the emerald ash borer, carp, and stilt grass.

Here, we discuss climate change as it relates to several of the state's main ecosystem types, including forests, wetlands, freshwater rivers and lakes, and grasslands.

Table 6.1 Terms Used in This Chapter and Their Definitions

Biodiversity	The variety of life on Earth, from genes to species to ecosystems.
Disturbance	Both natural and human-mediated processes (e.g., fire, flooding) that may affect plants, animals, and their habitats. Disturbances differ in frequency, intensity, and duration. Infrequent disturbance of low intensity and short duration can have negligible impacts on ecosystems. As frequency, intensity, and duration increase, damage and degradation are more likely.
Ecological restoration	The process of assisting the recovery of an ecosystem that has been degraded, damaged, or destroyed.
Ecoregion	A relatively large unit of land or water containing a geographically distinct assemblage of species, natural communities, and environmental conditions.
Ecosystem	A biological community of interacting organisms and their physical environment.
Habitat fragmentation	An outcome of habitat destruction and degradation resulting in the isolation of remaining natural lands. When pronounced, formation of isolated habitat islands disrupts species interactions and limits the potential for species migration.
Resilience	Capacity of a natural system to endure and recover from disturbances.

For each ecosystem type, we begin by briefly tracing its historical and current status in Illinois, followed by a discussion of anticipated effects of climate change and management recommendations to mitigate these effects. We conclude with a list of key knowledge and research gaps that should be addressed to support efforts to manage for resilient ecosystems and enhance climate change mitigation.


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Forests

Key Points

- Projected changes in climate—warmer, wetter springs followed by hotter, drier summers—are likely to increase habitat suitability for some tree species in Illinois, while decreasing habitat suitability for others. Trends will vary by region but, in general, the identity and abundance of individual tree species will shift. Even so, overall tree species diversity is likely to be maintained because of variable topography and soils among the forested portions of the state.

- Many of the tree species found in Illinois, such as basswood, Ohio buckeye, and quaking aspen, are poorly adapted to the warm, drier summer conditions that are projected. However, management factors such as rotation length and harvesting intensity can also influence changes in species presence and growth rates.

- Changes in climate will likely have varying effects on the proliferation of non-native plants already occurring in the state's forests. Warmer temperatures may increase the number of new, non-native species, as plants such as kudzu and Chinese privet expand their ranges northward.

At the time of the first Euro-American settlements in Illinois during the early 1800s, forest covered about 42% of the land area (Figure 6.1). Most forests at that time differed from many current forest stands due to their exposure to occasional fires. Open, fire-maintained woodland and savanna habitats, intermediate in structure and composition between forest and prairie and dominated by fire-tolerant oaks, were common at that time. In contrast, fire-sensitive species, such as sugar maple, were favored in parts of the landscape protected from fire. According to early surveyor records, sugar maple was scarce compared with its current abundance, providing evidence that fire was a widespread and regular phenomenon.

Fire suppression, forest clearing, livestock grazing, and infestations of non-native species have, to varying degrees, altered Illinois forests since settlement. Following a period of intensive harvest, particularly from 1860 to 1900, forest area in Illinois reached its minimum extent around 1920, with 8.5% coverage statewide. During the next 100 years, forest land cover increased by about 60% (Taft et al. 2009; USDA 2019). This trend can be partially attributed to a reduction in cattle grazing and the conversion of pastures and cropland to forest.

Current forest area is 31.7% of the extent at the time of pre-Euro-American settlement, and only about 0.1% of the acreage at the time of settlement remains in a relatively undegraded condition (IDNR 2008). Most forest in Illinois (83%) occurs on private lands, followed by federal (8%), local government (5%), and state (4%) land holdings (USDA 2019). Of the current total forest area, most is classified as upland habitat and just under 20% is bottomland forest and swamp. Most acreage is classified as oak-hickory (68%), followed by elm-ash-soft maple-cottonwood (24%).

Due to fire suppression, open woodland and savanna habitats, with their species-rich ground-layer floras, have become quite scarce. Oak regeneration is limited by ongoing changes in the understories of

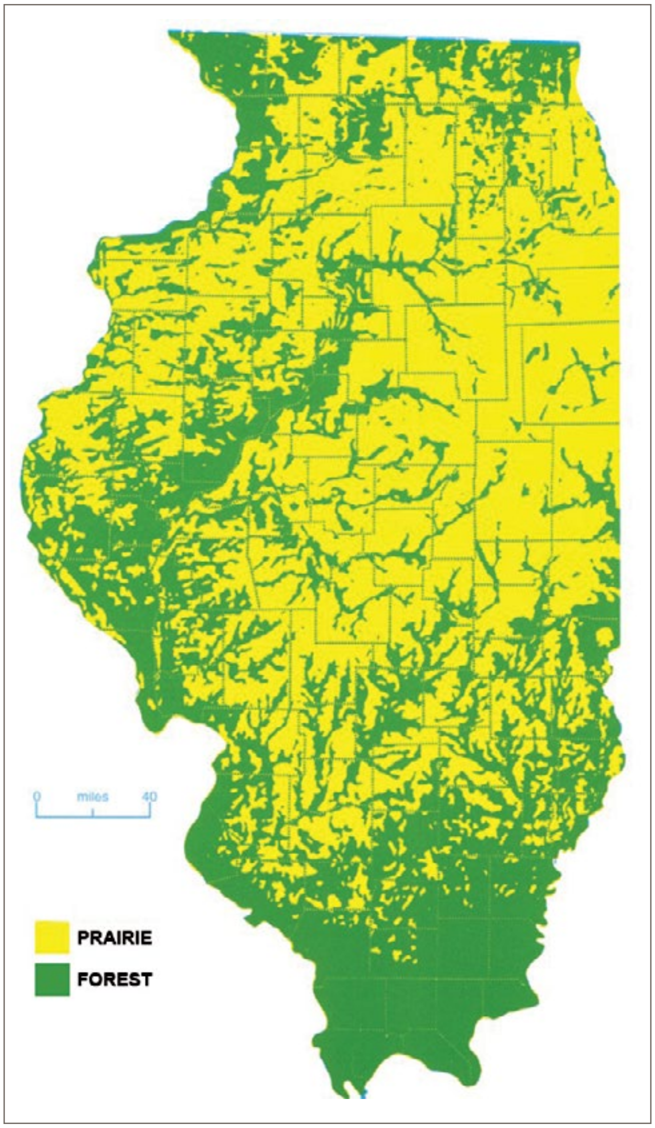

Figure 6.1 The distribution of prairie and forest in Illinois at the time of Euro-American settlement, c. 1820. **Source:** Adapted from Anderson 1991.

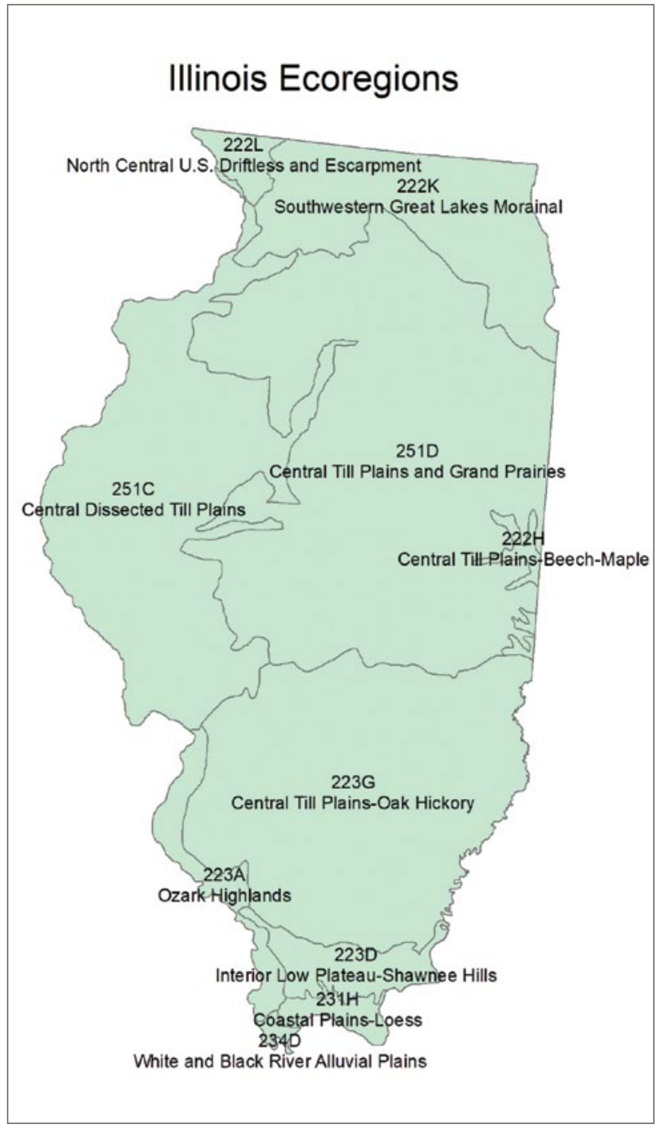

Figure 6.2 Map of Illinois ecoregions. **Source:** Bailey 1980.

many remaining stands, such as the increased abundance of non-oak species whose shade inhibits oaks (Taft et al. 2009). Fire absence is leading to the possibility of a general replacement of oaks in forest canopies by more shade-tolerant species, and the changing climate will likely have a compounding influence on this outcome.

Climate-related effects on Illinois forest ecosystems

Over the next 100 years, forests will be shaped by the responses of tree species to climate change as mediated by local conditions, with effects varying among species and even individuals of the same species. The potential futures for tree species throughout the eastern United States have been modeled in recent years to better understand how specific species will be impacted by climate change (Iverson et al. 2019a, b; Peters et al. 2019). To provide an assessment specific to Illinois, a new analysis was completed to summarize potential tree species responses from these models for the 10 primary ecoregions in the state (Figure 6.2). A snapshot of the results from the new analysis is shown below in Table 6.2, Table 6.3, and Table 6.4; additional information can be accessed in the supplemental material.

In the new analysis, two variables were evaluated: capability and importance value (IV). Capability is a measure of a species' ability to cope or persist given projected climatic changes in relation to the species' current abundance, adaptability, and species' modeled potential to different habitats suitability under the higher scenario (RCP8.5). In this analysis, capability is ranked into five classes from very good to very poor. The importance value is a measure of a current species' importance ranging from 0 to a maximum of 100 for a monoculture, based on tree size, tree density, and areal coverage within an ecoregion. In addition to these two variables, the analysis also considered tree species with the potential to survive in the state under future climate conditions. At least some of these species may migrate into the area naturally within 100 years or could be considered for proactive planting (Iverson et al. 2019a; Prasad et al. 2016).

A total of 113 tree species were evaluated, of which 87 were native species and seven were non-native species (Siberian elm, Norway maple, Scotch pine, ailanthus, paulownia, white mulberry, and Norway spruce) currently found on the forest inventory plots within Illinois. Another 19 species were not currently detected within the plots but do potentially have suitable habitat appearing in the state by around 2100 due to climate change. Based on the importance value metric, the top species in the state are white oak, sugar maple, American elm, yellow poplar, and black oak (Table 6.4). There are north–south variations in the rankings, as would be expected. For example, yellow poplar and sassafras occur almost exclusively in the southern ecoregions, while bur oak and quaking aspen occur primarily in the northern portion of the state.

The number of species recorded by forest inventory plots ranged from 34 in the northwest corner of the state to 70–73 at the southern tip of the state. Of these, the total number of common species, with importance values greater than 10, ranged from 17 in the Southwestern Great Lakes Morainal to a highly diverse 59 species in the furthest south ecoregion, the White and Black River Alluvial Plains. In other words, tree diversity roughly increases north to south, with the species-rich White and Black River Alluvial Plains/Coastal Plains-Loess ecoregions having unique habitats interspersed among the upland forests more typical of the Shawnee Hills region. Data on the total number of tree species detected and the total number of species with importance values over 10 (IV>10) within each ecoregion are shown in Table 6.2. This table also includes information on the number of species within each capability class and species that may find suitable habitat in the region within the next 100 years. Table 6.3 provides data on the current amount of forested, agricultural, and developed land cover in each of the ecoregions, which is useful for understanding the prevalence of forest compared with other land cover types in each geographic area.

Because the capability classes depend on the current abundances of species along with the modeled projection of climate change impacts, species that are relatively uncommon within an ecoregion are more likely to have poor or very poor capability. Across all ecoregions, there are roughly equivalent numbers of species with good or very good capability (average of 21.0) vs. species with poor or very poor capability (21.5), and an average of 11.8 species with fair capability (Table 6.2). Southern ecoregions are once again expected to fare well, with 31–34 species that have good or fair capability to cope or persist under a changed climate.

With respect to those species for which the future climate may lead to an expansion of suitable habitat in Illinois, the models show a range of 11 to 21 new species appearing in the state by 2100. Of these, a subset may potentially migrate naturally into the ecoregion from locations further south within the next 100 years (i.e., the "Natural migration within 100 years" category in Table 6.2). On average, a little over half (7.8 out of 14.6) of the species with habitat potentially appearing would have at least a small chance of entering via natural migration (Table 6.2). These species could be evaluated first for their potential value in proactive plantings in response to climate change (i.e., assisted migration), as they

Table 6.2 Summary of Number of Species Currently Present and Within Each Capability Class Under the Higher Scenario

	North Central U.S. Driftless and Escarpment	Southwestern Great Lakes Morainal	Central Till Plains and Grand Prairies	Central Dissected Till Plains	Central Till Plains-Beech-Maple	Central Till Plains-Oak Hickory	Ozark Highlands	Interior Low Plateau-Shawnee Hills	White and Black River Alluvial Plains/ Coastal Plains-Loess	Average
Number of Tree Species										
Total Present on Plots	34	47	63	64	46	68	66	73	70	59.0
No. of Species with IV>10	24	17	20	32	28	39	50	51	59	35.6
Very Good Capability	4	0	0	3	0	1	7	15	14	4.9
Good Capability	11	13	10	16	14	23	22	19	17	16.1
Fair Capability	5	6	15	11	9	11	18	18	13	11.8
Poor Capability	5	10	19	12	10	15	9	4	12	10.7
Very Poor Capability	6	10	14	15	11	12	7	12	10	10.8
Suitable New Habitat	16	16	13	15	13	14	12	11	21	14.6
Natural Migration Within 100 yrs.	12	11	6	10	8	5	5	3	10	7.8

Table 6.3 Forest, Agriculture, and Developed Land Cover Percentages by Illinois Ecoregion as of 2016

	North Central U.S. Driftless and Escarpment	Southwestern Great Lakes Morainal	Central Till Plains and Grand Prairies	Central Dissected Till Plains	Central Till Plains-Beech-Maple	Central Till Plains-Oak Hickory	Ozark Highlands	Interior Low Plateau-Shawnee Hills	White and Black River Alluvial Plains/ Coastal Plains-Loess	Average
Land Cover (%)										
Forest	30.0	10.6	6.1	23.2	23.3	22.5	35.7	61.0	35.6	27.6
Agriculture	61.4	51.0	84.2	65.8	63.7	67.3	43.0	30.8	52.2	57.7
Developed	5.5	35.0	8.5	6.8	10.9	7.7	13.5	5.1	5.9	11.0

presumably have the best chance of survival. The other species with new suitable habitat developing by the year 2100 will not necessarily migrate naturally into the region within 100 years but could also be candidates for assisted migration. More detailed information on the specific species that fall into these classes is presented in Table 6.4 below and in Supplemental Table 6.2.

Table 6.4 Information on Capability Rankings for Specific Tree Species by Ecoregion

Tree Species	North Central U.S. Driftless and Escarpment	Southwestern Great Lakes Morainal	Central Till Plains and Grand Prairies	Central Dissected Till Plains	Central Till Plains-Beech-Maple	Central Till Plains-Oak Hickory	Ozark Highlands	Interior Low Plateau-Shawnee Hills	White and Black River Alluvial Plains/Coastal Plains-Loess
white oak	VG	P	P	F	F	F	F	F	G
sugar maple	G	F	F	VG	F	VG	G	F	F
American elm	F	G	F	F	G	G	G	VG	VG
yellow-poplar	NH+	NH	P	NH*	F	P	F	F	F
black oak	G	F	P	P	P	F	F	F	F
pignut hickory	NH+	NH#	P	P	VP	P	P	P	P
boxelder	F	F	F	G	G	F	G	VG	VG
silver maple	G	G	G	G	G	G	VG	F	G
green ash	G	F	G	G	G	G	G	G	G
black cherry	P	VP	VP	P	VP	P	F	G	F
hackberry	VG	G	G	VG	G	F	VG	VG	G
black walnut	P	P	P	G	G	F	G	F	P
northern red oak	VG	G	P	F	F	P	F	G	VG
sweetgum	-	NH	G	NH*	G	G	VG	VG	VG
sassafras	NH+	NH#	P	P	P	P	P	F	F
white ash	F	F	P	F	P	F	F	F	F
eastern redcedar	G	G	G	G	G	G	VG	VG	VG
shagbark hickory	F	VP	F	P	P	P	F	F	F
black willow	NH#	P	VP	VP	NH#	VP	P	F	P
post oak	NH*	NH*	G	G	NH*	G	VG	VG	VG
slippery elm	F	G	F	F	P	G	VG	VG	VG
winged elm	-	NH+	NH*	NH*	NH*	G	G	VG	VG
honey locust	G	G	F	VG	G	G	G	VG	G
sycamore	NH*	G	P	P	F	F	G	VG	VG
bitternut hickory	VG	G	G	G	F	G	VG	VG	VG
shortleaf pine	-	-	-	-	-	P	F	G	G
shingle oak	NH*	NH*	P	P	VP	P	P	F	P
American basswood	P	VP	VP	VP	VP	VP	VP	VP	VP
eastern cottonwood	G	G	F	F	G	P	F	VP	P
red maple	NH*	P	F	G	F	G	G	VG	VG
black locust	G	P	P	F	G	P	F	G	F
pin oak	-	F	VP	VP	VP	VP	P	VP	VP
mockernut hickory	NH*	NH+	F	G	P	G	G	VG	G

Key for Capability Ratings

VG	Very Good	NH	New habitat for species by 2100
G	Good	NH*	Some likelihood of migration into the ecoregion within 100 years under either a lower or a higher scenario
F	Fair	NH+	Potential to migrate into the ecoregion under only the higher scenario (RCP8.5)
P	Poor	NH#	Likely already present but not detected in inventory plots
VP	Very Poor	Unk	Unknown status

This table presents information for the 33 most prevalent native tree species, listed in order of statewide importance value. For information on the importance values for species by ecoregion and information on all 113 species evaluated in this analysis, please see Supplemental Table 6.2.

Based on an assessment of statewide capability, the top ranked species that would be expected to cope or persist well in the changing climate are sweetgum, winged elm, and post oak, followed closely by cherrybark oak, hackberry, eastern red cedar, bitternut hickory, and honey locust. Some species currently ranked with the highest importance values within the state, including white oak, black oak, yellow poplar, and pignut hickory, have poor to fair capability rankings for most of the ecoregions. The capability of some species to persist in a changing climate varies by ecoregion. For example, American elm has better capability in southern Illinois than in northern ecoregions (although this assumes resistance to Dutch elm disease), while sugar maple has much greater capability ratings in northern regions. Many species currently present in the state are ranked very low in terms of their capability to persist (see species within the very poor capability class in Table 6.4 and Supplemental Table 6.2). Most often, these species are quite uncommon to start with, meaning few individuals are likely to find refuge in suitable habitat with favorable climate conditions in the coming decades. However, even some species that currently are relatively common have lower future capabilities, including pignut hickory, black willow, American basswood, pin oak, chinkapin oak, eastern white pine, quaking aspen, Ohio buckeye, and pawpaw.

These results suggest that many species in oak-hickory stands, the predominant cover type in Illinois, will have fair-to-good capabilities, with some notable exceptions (e.g., pignut hickory, chinkapin oak and, for some ecoregions, white and black oak). However, some shade-tolerant and moisture-loving species (e.g., maples) in those habitats that can outcompete oaks are also projected to have fair-to-good capabilities. Thus, outcomes will hinge in part on how forests are managed and whether they are managed to favor particular combinations of species. Many species ranked with some of the highest and lowest capabilities are trees of lower slope, terrace, and floodplain forests—habitats where we might expect notable shifts in species composition because of expected highly fluctuating moisture regimes. As such, these bottomland and lower-slope habitats may trend toward a composition that includes more honey locust, silver maple, bitternut hickory, sweetgum, and hackberry and less pin oak, basswood, and pawpaw.

Response of other forest species

Populations of understory and ground-layer plants in forests are greatly influenced by light and moisture availability and likely will also be affected by climate change. Species adapted to abundant sunlight may benefit if fires increase in frequency and create a more open forest structure, but they would likely decline in the absence of fire and increased shading by the overstory. If sunlight is not limiting, warm-season plants that thrive during the summer will have an advantage over cool-season species, since climate change is projected to increase average temperatures. These include the grasses of savanna and open woodland habitats, which also occur in prairies.

Many of the rarest plant species in Illinois are species found in the northern ecoregions and occur in Illinois at the southernmost extent of their midwestern ranges (e.g., Canada yew, yellow birch, bunchberry, various orchids, ferns and fern allies). These species typically have persisted in specialized habitats, such as forest seeps, cooler north-facing forested slopes, and canyon walls. Because many of these species are likely boreal relicts from a former time, they are likely to be at risk from a warmer climate and the likelihood of increasingly severe summer droughts. Certain invasive, non-native species such as Amur honeysuckle, oriental bittersweet, and Japanese stilt grass could also become more problematic because they are likely to benefit from longer growing seasons and milder winters.

While wildlife species are generally more mobile than plants and may potentially be able to migrate in response to climate change, they are also at risk of negative impacts. The ability of wildlife to migrate may be hindered by a lack of suitable habitat in the absence of adequate natural corridors to facilitate movement or if the specific forest ecosystems on which they depend are degraded or diminished in size. There is also a risk of disrupted species interactions, particularly between pollinator and host-plant species.

Recommendations

Efforts to maintain Illinois' forests in the face of climate change are important because these ecosystems provide critical habitat to native flora and fauna, as well as numerous other benefits like clean air and water and recreational opportunities. Conserving and restoring forests in the state also has the potential to contribute to both sequestering carbon emissions and building more resilience to climate change. Support for the formation of large forest conservation areas and corridors through both private and public consortia will be needed to maintain and enhance forest health and biodiversity in the state.

Effectively addressing the impacts of climate change on forests in Illinois will also require coordinated management, restoration, and protection plans informed by habitat monitoring. Many specific management practices can be included within these plans to foster habitat integrity and the maintenance of characteristic forest types in Illinois. For example, the use of prescribed fire will be necessary to facilitate and promote the maintenance of oak-dominated habitats and the highly diverse ground-story species associated with them. Under some circumstances, silvicultural practices, including innovative harvesting techniques, may be needed to achieve goals for maintaining oak-hickory predominance in upland stands. Where habitat fragmentation is particularly pronounced, assisted migration may be needed to advance or establish species whose suitable habitat is shifting into more northern areas. Vigilant invasive species control will also be needed to maintain ecosystem integrity in most forest stands.


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Wetlands

Key Points

- The most important climate-related impacts to wetlands will be driven by changes in water balance, including the increased likelihood of summer drought and increased frequency and severity of floods.

- Increased summer drying will impact small and ephemeral wetlands and wetland-dependent species, such as many amphibians, by decreasing wetland area and water permanence.

- Riparian wetlands will be impacted by the increased frequency and severity of major floods. Tree species composition in forested wetlands along watercourses will shift toward species that are more tolerant of prolonged flooding. Increased flooding intensity is also likely to decrease the amount of time that water is stored in wetlands, thus decreasing the ability of wetlands to cleanse water of sediments and nutrients.

- Restoration of wetlands along rivers and streams will become increasingly important as a climate change adaptation strategy to manage high volumes of runoff associated with episodic, intense storms and to mitigate downstream flood risks.

Illinois is home to several types of wooded and herbaceous-dominated wetlands. Fens and bogs are characterized by the accumulation of organic matter called peat and occur primarily in northeastern

Illinois. Fens are wet meadows continually recharged by alkaline groundwater, whereas bogs are formed from fens that lack water outlets, leading to acidic soil conditions and a further accumulation of peat. Marshes and wet meadows, which are dominated by herbaceous (non-woody) plants, occur in depressions along the borders of lakes and ponds and in the floodplains of streams throughout Illinois. Deeper waters support communities of submerged and floating vegetation. Wooded wetlands include bald cypress swamps in southern Illinois and forested wetlands bordering streams throughout the state.

Wetlands are estimated to have once covered about 23% of Illinois, but 85–90% of the original wetland area in the state has been destroyed by drainage and land-use changes (Dahl 1990). Wetland losses have been particularly severe in central Illinois due to drainage for agriculture. The wetlands remaining in Illinois face a number of additional stresses, including hydrological alterations, nutrient runoff from agricultural fields, and invasive plant species, such as reed canary grass, giant reed, hybrid cattail, and purple loosestrife.

6Climate-related effects on Illinois wetlands

The types of species present in wetlands and the natural processes that occur there depend strongly on the quantity, quality, and timing of water inputs. Seasonal patterns of water flow and depth determine wetland type, plant productivity, and species composition. Water flow and depth also control the benefits that wetlands provide to society, including water storage and flood attenuation, carbon storage, and water quality improvements. Changes in the water balance resulting from climate change, including the increased likelihood and severity of extreme drought and flood events (see Chapter 2), will cause important changes in wetlands. Projecting specific changes to seasonal patterns of water flow, including both increased and decreased water availability and the resulting impacts on wetlands, also depends on local geomorphological and ecological conditions.

Increased summer drying

Decreases in summer precipitation and increased evapotranspiration will amplify the risk of short-term summer droughts. Although water levels naturally fluctuate seasonally in most Illinois wetlands, more rapid or prolonged water drawdowns during the summer months could negatively affect many wetland organisms. Without soil saturation, wetlands disappear. As a consequence of soil drying and increased oxygen availability in the soil, soil organic matter decomposes more rapidly and the carbon stored there is lost to the atmosphere. The risk of drying is especially severe for depressional wetlands with small contributing watersheds, simply because they receive water from a very limited area (Junk et al. 2013), and for bogs, which are dependent on a balance between precipitation and evapotranspiration to keep the upper soil layers saturated (Moore et al. 1997). Depressional wetlands are most common in northeastern Illinois, and many harbor rare plants that might be threatened by changes to seasonal precipitation patterns.

Wetland drying has several consequences for wetland-dependent organisms. With less water, wetland area shrinks and non-wetland plant species replace wetland species. Many species of insects and amphibians are dependent on small, seasonally flooded wetlands for breeding and will suffer reproductive failure if wetlands dry before juvenile stages reach maturity. Water drawdown will also affect migrating and breeding birds in Illinois. For example, migrating shorebirds are dependent on shallow water and open mudflat wetlands (Potter et al. 2007). Water drawdowns in late summer and autumn expose formerly inundated sediments, increasing the area of mudflat habitat available for shorebirds during the southward fall migration. In contrast, predicted increases in spring flooding would have the opposite effect, reducing the amount of mudflat and shallow water habitat available for shorebirds during the northward spring migration.

Increased flooding

Average precipitation is expected to increase in Illinois during winter and spring (see Chapter 2).

Because much of this increase will be delivered during major rain events, the risk of flooding will increase. Whereas wetlands with small watersheds may be at greatest risk for drying in late summer, riverine wetlands with large contributing watersheds are at higher risk from flooding. Seasonal patterns of flooding shape the ecology of floodplain wetlands, with major floods eliminating plant species that cannot tolerate inundation. The prolonged inundation of soils prevents oxygen from reaching plant roots, leading to severely reduced growth, and eventually, plant death. Although most wetland plants can tolerate stressful soil conditions temporarily, long-duration flooding is much more stressful for plants found in areas that typically flood only intermittently, including many floodplain tree species. Historic flooding patterns have led to shallow rooting for some floodplain species, which amplifies moisture stress in floodplains relative to uplands, where plant roots tend to be deeper. Thus, the alternating stresses of flooding and drought, both of which are likely to increase with climate change, are likely to have severe impacts in floodplains.

The increased frequency and intensity of major floods in Illinois will alter biodiversity in floodplain wetlands. Flooding tends to limit non-wetland tree species more strongly than it promotes wetland species, resulting in a shift favoring a small number of flood-tolerant species, likely at the expense of overall species diversity. Because tree seedlings are more susceptible to flooding than adult trees, flooding can hinder forest recovery and regrowth. Thus, increased flood severity will make wetland restoration and reforestation efforts more challenging, as planted trees may suffer increased mortality.

Although changes in average precipitation will impact wetlands, the most pronounced effects will result from changes in the variability and timing of precipitation, plus the increased likelihood of extreme events (see Chapter 2). Large die-offs occur periodically in response to extreme weather events, and tree mortality increases sharply in floodplain wetlands during years with extreme flooding. For example, the 1993 flood on the Mississippi River resulted in a 57% decrease in the number of trees in Upper Mississippi River floodplains (Yin et al. 2009).

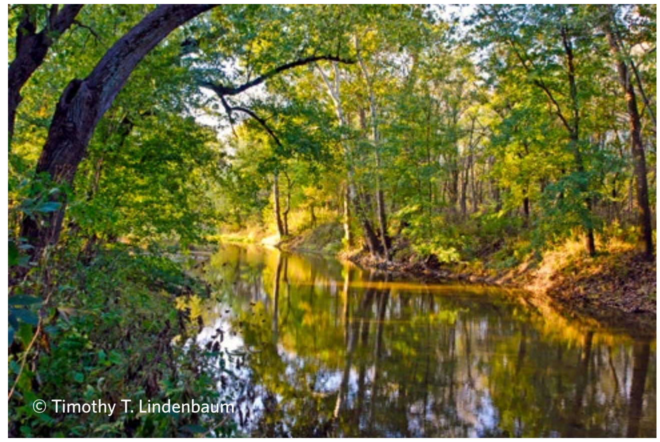
More intense flooding will also diminish the capacity of wetlands to provide benefits to people. Water quality improvement occurs when shallow water flows slowly through a wetland, allowing sediments to drop out and nutrients to be removed by microbes and taken up by plants. Conversely, extreme flooding decreases contact between polluted water, plants, and soils, allowing contaminants in the water to pass through wetlands unimpeded, negatively affecting downstream water quality. This is especially true for urban areas where water flows rapidly across impervious surfaces and flows rapidly through urban wetlands. Efforts to restore urban wetlands and install green infrastructure, like bioswales and rain gardens, can help to partially ameliorate this issue and restore the absorptive capacity of urban soils.

Net effects of climate change on Illinois wetlands

The overall impact of climate change on Illinois wetlands is difficult to predict; species will be differentially affected, and impacts to specific wetlands will depend on both location and human responses to altered seasonal patterns of flooding and drying. Wetlands are also impacted by many non-climate-related stresses, such as nutrient runoff, invasive species, and altered hydrology. Furthermore, non-climate stresses may also be impacted by climate change. For example, if fertilizer application rates are increased for corn and soybean crop production as an adaptive measure to climate change, nutrient runoff may further increase. Changes in wetland water balance will inevitably lead to shifts in species composition and alteration of ecosystem functions. However, the ultimate effect of climate change on Illinois wetlands depends, in large part, on human responses. If climate-induced changes to the water cycle make it increasingly difficult to manage large volumes of runoff, then landowners might convert certain cropland areas to wetlands. As the water storage function of wetlands becomes increasingly important for mitigating flood risks, there might be greater incentives to restore wetlands, potentially increasing total wetland area in the state (Garris et al. 2015).

Recommendations

Mitigating climate-related impacts to Illinois wetlands will require an adaptive approach that incorporates monitoring, the alleviation of non-climate–related stresses, and large-scale restoration efforts to increase both the acreage and floodwater storage capacity of the state's wetlands. Detecting and adapting to changing conditions will be impossible without adequate knowledge of baseline conditions. Long-term monitoring programs such as the Illinois Critical Trends Assessment Program, updated national and regional wetland inventories, and large-scale assessments of ecological condition (e.g., EPA 2016) will provide critical baseline data for detecting changes over the next century. Such efforts should be supported and expanded. Large-scale restoration efforts, such as The Nature Conservancy's Emiquon Preserve on the Illinois River, provide critical habitat, floodwater storage, and water quality improvement currently lacking in the state after two centuries of wetland destruction. Efforts to ramp up wetland restoration would help alleviate flood risks associated with increasingly large storm events (Hey and Philippi 1995), while reducing nutrient export to the Mississippi River and the Gulf of Mexico (Mitsch et al. 2001). Increasing the resilience of wetlands to climate-related effects will require reducing non-climate stresses. Finally, planning for wetland responses to climate change also requires anticipating catastrophes, such as industrial waste or sewage spills or repeated weather-related events that limit time for wetland recovery between successive disturbances—events that could push ecosystems beyond the limits of recovery (Zedler 2010).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Streams, rivers, lakes, and ponds

Key Points

- As a result of climate change, air temperatures in Illinois are projected to increase and short-duration heatwaves are expected to become more common and more intense, resulting in higher average water temperatures. Warmer water temperatures will alter the growth, survival, and reproduction of aquatic species, as well as predator–prey relationships. Models suggest that warmer water will reduce habitat availability and competitive abilities for cold and cool water fishes but maintain or increase habitat availability and enhance competitive abilities for warm water fishes.

- Increasing annual precipitation, coupled with more extreme precipitation events, is likely to result in higher average flow rates and more flooding. Higher peak flows are expected to favor stronger swimmers while resulting in challenges for weak swimmers, like bottom-oriented fish. Increased peak flows will also impact aquatic habitats by causing substrate removal and transporting many species downstream to unfavorable habitats.

- Climate change is likely to cause increased periods of drought in Illinois, which could reduce freshwater habitat connectivity.

The freshwaters of Illinois are diverse, including large rivers, small streams, lakes, ponds, and human-created reservoirs. Illinois is home to over 180 native fishes, 1,800 aquatic macroinvertebrate species (mostly insects), and over 180 mollusk species.

Freshwater resources in Illinois have been negatively impacted by numerous stresses over time. During the late 1800s and early 1900s, millions of pounds of fish were extracted from the Illinois River and Euro-American settlers harvested enormous quantities of mussels for the button trade. Activities such as agriculture, dam construction, and urbanization have greatly altered many aspects of freshwater habitats in Illinois, including water temperature, flow patterns, and nutrient content. In particular, extensive agricultural production has had the following impacts: (1) expansive use of tile drainage in fields has lowered the water table and resulted in the input of excess nutrients; (2) removal of streamside vegetation has led to an increase in stream temperature and fine sediments and a decrease in the amount of woody material in streams that fish use for shelter; and (3) channelization of agricultural land for flood control has increased peak stream flows. Dam construction to facilitate navigation, prevent flooding, and provide recreation has been another factor that has altered freshwater habitats by changing free-flowing rivers into slow-moving impoundments. Approximately 25% of the surface waters in Illinois have been disconnected from their floodplains due to levee construction, particularly in urban areas. Approximately 22 different invasive fishes (e.g., bigheaded carp) have also been introduced into Illinois, along with many exotic invertebrates (e.g., rusty crayfish) (Burr and Page 2009) that compete with native species.

As a result of these stresses, freshwater communities in Illinois have experienced alarming declines in species abundance and distribution. Most Illinois watersheds have experienced at least a 25% decline in the number of species of mussels, and almost 75% of native mussels in Illinois are either extinct, protected at the state or federal level, or have unstable populations (DeWalt et al. 2009). Declines and extinctions of aquatic insects have occurred primarily in large rivers and flowing water habitats that historically ran through former prairies. Almost 40% of native fishes in Illinois have experienced a reduction in range and abundance, with severe declines in distribution occurring for many species, and approximately 10 fish species have been extirpated (Burr and Page 2009). Declines in native fish communities also have concurrent impacts on mussel populations, as many mussel species rely on fish hosts as part of their reproductive cycle.

Climate-related effects on Illinois freshwater ecosystems

Water temperature

Water temperature is one of the most important environmental factors in aquatic ecosystems, directly influencing the growth, survival, and reproductive output of many aquatic organisms. Based on historical data and climate models (see Chapter 2), summer nighttime air temperatures in Illinois have increased around 2°F over the past century. By late century, mean air temperatures are projected to increase by as much as 8–9°F under a higher scenario (RCP8.5). This increase in air temperature will, in turn, have pronounced impacts on water temperatures.

Increased water temperatures in aquatic habitats will alter the growth, survival, and reproductive output of many aquatic organisms, as well as their distributions. Increasing temperatures will also increase the rate that cold-blooded organisms like fish and mussels consume energy, which could result in smaller individuals and negatively influence reproduction. Energetic constraints occur at different temperatures, depending on the species. Increased water temperatures may first impact species that prefer cold and cool waters (Table 6.5), impairing their swimming performance, which, in turn, could reduce their ability to obtain food. For example, walleye—a popular cool water fish species found in many Midwestern lakes—is adapted to a relatively narrow temperature range and could be displaced by warm water fishes, like largemouth bass, with a warmer climate (Hansen et al. 2017). In lakes where both cool water northern pike and warm water largemouth bass exist, it is expected that increasing temperatures will reduce the growth of northern pike, while having little effect on the growth of its

Table 6.5 Examples of Fish Species in Illinois that Thrive in Cool and Cold Water

Illinois Cool and Cold-water Fishes		
Native		**Introduced/non-native**
Blacknose dace	Mottled sculpin	Brook trout
Brown bullhead	Northern hog sucker	Brown trout
Cisco (state-endangered)	Northern pike	Chinook salmon
Common shiner	Pumpkinseed	Coho salmon
Creek chub	Rock bass	Muskellunge
Golden redhorse	Silver redhorse	Pink salmon
Johnny darter	Smallmouth bass	Rainbow trout
Lake trout	Walleye	Sauger
Lake whitefish	White sucker	Striped bass
Longnose dace	Yellow perch	

Climate change will reduce habitat suitability for many of these species. **Sources:** INHS 2017; Mohseni et al. 2014

competitor, largemouth bass. Increased metabolic requirements for both species can result in higher demand for prey, including bluegill and yellow perch, potentially changing predator-prey relationships and species abundances (Breeggemann et al. 2016). Freshwater mussels can also suffer from rising temperatures due to their limited mobility, although climate impacts on mussels are largely unstudied.

In addition to increases in average temperatures, heatwaves are predicted to become both more intense and more frequent (see Chapter 2), and the impacts of heatwaves on shaping the performance and distribution of aquatic species could be significant. Short-term extreme heat can greatly increase energy consumption rates for aquatic organisms and may result in mortality. Heatwaves can also cause irreversible physiological effects, such as oxidative damage (Kaur et al. 2005) and prolonged elevation of stress hormones (Peterson and Small 2005). As a result, although most brief heatwaves may not directly cause death, fish still could suffer from impaired locomotion, growth, and reproduction over the long term. Furthermore, increasingly intense and frequent heatwaves will likely impact not only cold or cool water species, but also warm water fish (Peterson and Small 2005). The consequences of heatwaves will likely be exacerbated by other human impacts. For example, the removal of riverbank cover and the channelization of streams and rivers—common in agricultural regions—can result in reduced temperature variability in aquatic habitats, eliminating cool-water refuges for some fish species.

Even though the deeper portions of lakes and reservoirs in Illinois may experience relatively small increases in summer temperatures due to climate change, this is unlikely to be the case in the shallow portions of these waterbodies (Höök et al. 2019). With higher air and surface temperature, an increased duration of summer thermal stratification, caused by temperature-related differences in water density, is expected for many lakes and reservoirs in Illinois (Höök et al. 2019). When water is stratified, there is little dissolved oxygen exchange between the upper and lower water layers, resulting in extended periods of low oxygen in the deeper portions of a lake. If this extended period of low oxygen is coupled with algae blooms due to excess nutrient runoff (i.e., phosphorous and nitrogen), low oxygen conditions in deep water layers could expand in both extent and magnitude. Thus, deep water species could be further impacted, accompanied by changes in the community structure of lakes and reservoirs.

Flow

Future precipitation patterns are expected to become more extreme, resulting in more heavy rainfall events along with more consecutive dry days (see Chapter 2). Thus, we expect to see more floods and higher average streamflow in Illinois in the future. Conversely, an increase in the number of consecutive dry days, potentially coupled with greater water demand for irrigation and municipal use, will lessen groundwater recharge to surface waters. Increased temperature and evaporation may also reduce minimum flows during drought periods.

Water velocity and seasonal flooding are key factors dictating the abundance and distribution of stream fish. From an evolutionary perspective, the reproductive strategies of many aquatic organisms are tied to the timing of seasonal floods, and several aspects of reproductive events, such as the timing of spawning and larval survival, are tied to historical flow regimes. Any changes in the timing or magnitude of flow can therefore directly translate to impaired survival and reproduction for many organisms.

More extreme peak flows can negatively impact some aquatic species. For all fish, swimming ability varies across water velocity, with species varying in their preferred swimming speeds. Some species, such as predators, are often considered to be strong swimmers, while some more bottom-oriented fish may be considered weak swimmers. When more extreme peak flows are coupled with reduced muscle performance, which occurs with high water temperature, flows could exceed the swimming ability of some fishes and force individuals to move to areas with more favorable flow. Reduced intervals between extreme flow events may not allow sufficient time for freshwater mussels to recover from the negative impacts related to high flow events. Under extreme conditions, increased flow rate can dislodge benthic invertebrates and transport organisms to unsuitable habitats downstream.

In addition to these direct impacts, altered flow rates can indirectly affect freshwater organisms. For example, increased peak flows can alter habitat due to scouring, resulting in shifts of submerged plants and sediments, indirectly changing distributions of fish and invertebrates. Higher peak flows, coupled with higher temperature, could also facilitate additional nutrient runoff from surrounding watersheds, intensifying algal blooms, reducing water clarity and dissolved oxygen concentrations, and potentially leading to displacement or even mortality for many aquatic species.

Extended periods of drought can lower water levels, reducing the ability of aquatic organisms to move and potentially cutting off access to feeding, spawning, or overwintering areas, which would ultimately constrain species distributions and decrease survival. Extreme drawdowns can lead to stranding or drying of aquatic organisms, causing direct mortality, particularly for less mobile species such as aquatic invertebrates. Reduced movement of fishes from drought could result in impaired reproductive output for mussels if larvae cannot associate with the proper fish host. Drought can also disrupt the upstream/downstream movement of nutrients and energy, preventing critical resources from being transported to areas where they are needed.

Owing to alterations in flow regime, Poff and Allan (1995) found that highly variable flow patterns caused the removal of specialist fishes from a stream, resulting in simplified fish communities dominated by generalist species. Bunn and Arthington (2002) predict that rivers experiencing altered flow regimes are more vulnerable to invasion by non-native species. With predicted wide variations in water velocity, more floods, and longer droughts, we expect that changing flow patterns will exceed the tolerance of some fish and aquatic invertebrates, causing displacement of these species.

Recommendations

Extended, uninterrupted data collection is the cornerstone of efforts aimed at distinguishing climate-related trends from background variability and other human-induced stresses. Studies of long-term changes to aquatic ecosystems have documented improvements to fish communities over time (Parker et al. 2015), and Illinois has a long and enviable history of surveys for both fish and aquatic invertebrates. Therefore, current long-term monitoring programs of this sort (e.g., basin surveys carried out by Illinois Department of Natural Resources, long-term monitoring programs on the Illinois and Mississippi Rivers, the Critical Trends Assessment Program) should continue, and ideally be enhanced with additional sampling effort. Monitoring can also help detect the presence of newly arrived invasive species, so that efforts can be initiated to remove individuals and prevent further spread. Aquatic habitat protection at the watershed level will be challenging due to the extent and magnitude of degradation and the predominance of private land ownership. Conservation efforts should therefore focus on the protection of streams with high species diversity and/or the presence of rare species, intact ecosystems, and an abundance of critical habitat for fish and/or mussels, as well as the restoration of headwater areas. Hatchery propagation programs, while challenging, can help to restore mussel populations and should be enhanced.

Climate Change and Birds in Illinois

Birds are the most monitored group of species in the world and, in Illinois, we are already observing changes in bird distributions and behaviors that are likely the result of a warming climate. There are multiple ways that climate change can impact bird populations in the state. Four examples of potential impacts are described here.

Extreme weather events

Increases in heavy rains may be detrimental to several species of birds in Illinois. The Louisiana waterthrush is a migratory warbler that breeds along streams in the southern half of the state. The waterthrush places its nest in stream banks, often among roots and other vegetation. With heavy precipitation, small streams in Illinois are prone to flooding. If water in a stream is flowing bank full, even for a short period, waterthrush nests and their contents will be destroyed. Flash floods can also adversely impact nesting wetland birds. Whereas species such as pied-billed grebe, sandhill crane, American coot, and sora all breed in wetlands, their nests are not constructed to withstand high water. The threat of flooding in wetlands is often compounded by runoff diverted from surrounding development, causing even higher water levels and likely greater destruction of nests.

Early spring onset

As spring arrives earlier, it provides the opportunity for birds to begin breeding sooner in the year. A recent study of prothonotary warblers (pictured) reports that, in southern Illinois, this migratory species is returning and initiating breeding earlier (Hoover and Schelsky 2020). Historically, prothonotary warblers produce one brood of young per year. But with an earlier onset of spring, the species could be able to double brood (i.e., produce two broods per year). This adaptation could potentially benefit populations of this bottomland forest species.

Changing habitats

Habitat loss remains the primary threat to bird populations in the state, and the impacts that climate change will have on avian habitat remain to be seen. For example, longer growing seasons might allow for double cropping of soybean and wheat fields, which may result in the loss of habitats utilized by grassland birds. Conversely, wetter springs may delay planting, thus increasing the amount of time that breeding habitat is available to grassland birds, such as horned larks and upland sandpipers, potentially enhancing their reproductive success.

Range expansion

The majority of bird species in Illinois are migratory, spending their winters in southern locations. It is possible that warming conditions and potential changes in the distribution of habitats might cause some species to expand their distributions in Illinois. Several species are currently expanding north in the state, including the blue grosbeak, fish crow, and black vulture. The factors responsible for this northward expansion are species-specific and numerous, but a warming climate is likely one of them. For some species that are at the southern edge of their breeding distribution in northern Illinois, such as the bobolink and veery, a changing climate may cause the distributions of these species to shift northward and out of the state.

Lake Michigan

Key Points

- Lake Michigan's response to climate change is complex and difficult to predict with certainty due to the three-dimensional thermal structure and currents in the system, as well as non-climate, anthropogenic changes to the ecosystem (i.e., introductions of non-native invasive species).

- Warmer water is likely to result in summer stratification that begins earlier in the year and lasts longer, as well as related changes in the spatial distribution of fish. Cold water species will probably spend more time offshore, and warm-water species may become more widespread. Warmer water may also increase opportunities for additional invasive species to become established.

- Because precipitation and evaporation are both expected to increase in the Great Lakes Basin, water levels in Lake Michigan may increase or decrease, depending on the relative magnitude of change in these processes. Changes in lake levels will affect habitat availability for nearshore species and species dependent on tributary access for spawning.

Lake Michigan is a large system connected hydrologically to the rest of the Great Lakes through Lake Huron (Larson and Schaetzl 2001). The Illinois portion of Lake Michigan measures 1,576 square miles and represents approximately 60% of Illinois' surface water. Benefits provided by Lake Michigan include drinking water for more than 10 million people (including 6.6 million people in Chicago and other

Illinois municipalities), recreational and commercial fisheries, beaches, shipping, and industrial uses.

Prior to European exploration and settlement, human impacts were limited to minor levels of fish harvest by several Native American groups. Euro-American settlement and human population growth led to large-scale changes in land use in the region (e.g., logging, agriculture, dams), affecting tributaries and their watersheds. Spawning habitat for migratory fish (e.g., lake sturgeon, white sucker) was greatly reduced due to dams and eroded sediment that covered spawning habitat. Commercial fishing had a large impact on several species, including some deep-water ciscoes native to the Great Lakes. Four species were eliminated from Lake Michigan due to overfishing, and two are now extinct. Commercial fishing also greatly reduced populations of other species, such as lake sturgeon and lake trout.

Compared with other large lakes around the world, Lake Michigan is relatively young, so it contains a comparatively low number of native fish species. Non-native species gained access to Lake Michigan through canals and the ballast water of ocean-going vessels, among other sources. There are currently over 180 non-native plant and animal species documented in the Great Lakes. Although most have minimal impacts, some have completely restructured the ecosystem. For instance, by the late 1950s, non-native sea lamprey had eliminated lake trout, the most important native top predator. Non-native alewife outcompeted many native plankton-eating fish and became abundant in the absence of predators, at times forcing beach closures due to their periodic mass die-offs. Non-native mussels, initially zebra mussels, and more recently, quagga mussels, have proliferated and driven Lake Michigan to a nutrient-poor state by limiting overall productivity in the lake. While they consume planktonic algae, these mussels rarely transfer productivity to the rest of the food web because they are seldom consumed by predators. As a result, annual spring algal blooms have been eliminated, likely due to a lack of sufficient suspended nutrients, with the exception of short-duration storm events. In the future, new invasive species will likely continue to impact Lake Michigan. Of particular concern is the threat of bigheaded carp invasion via the Illinois River and the Chicago Sanitary and Ship Canal.

Many of the changes in Lake Michigan over the last two centuries were unanticipated. Such changes are especially challenging given the complexity of policy and decision-making involving many state, tribal, federal, and international organizations in the management of the Lake Michigan ecosystem for multiple benefits and a broad range of stakeholders. While Illinois' small tributaries can have important local impacts on Lake Michigan, watershed impacts in other states and Canada can also substantially affect fish and invertebrate communities in the lake, requiring management over a large geographic area. Managing the fisheries segment of Lake Michigan requires balancing numerous considerations and interests. For example, while native lake trout are beginning to recover, they are dependent on non-native prey fish (alewife, rainbow smelt, and round goby). In addition, non-native salmonids were stocked in the 1960s, initially to take advantage of abundant alewife prey, and some of these have become highly desired by anglers and represent valuable components of the current recreational fishery. Thus, current management represents a balance between restoring native species, managing food webs, and providing recreational opportunities, all in the context of an unnaturally nutrient-poor system.

Climate-related effects on Lake Michigan

Because of the vast scale of ecosystem change experienced by Lake Michigan, disentangling the impact of a changing climate on plants and animals is exceptionally difficult. Many of the species that were important 100 years ago are gone or have largely been replaced. There is evidence that surface waters are warming and average ice cover is decreasing (Figure 6.3), which has led to reduced shoreline protection and more erosion during winter months.

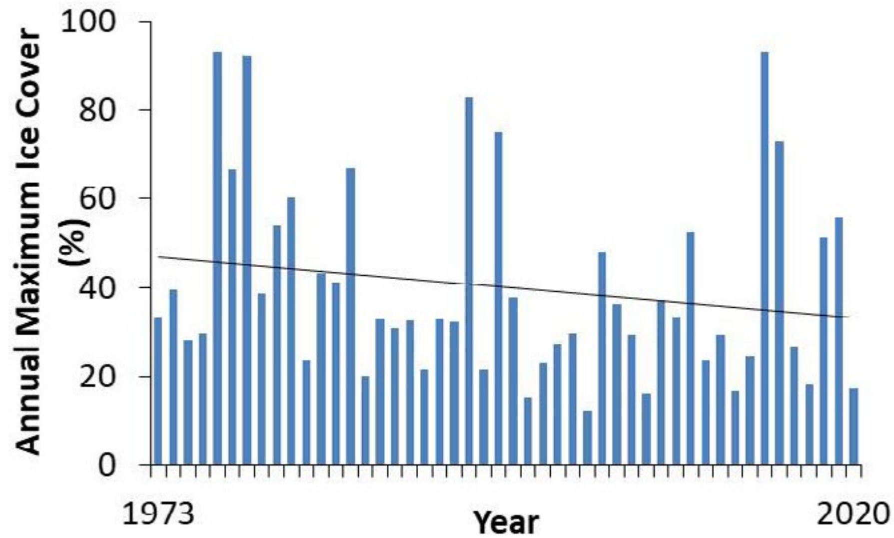

Figure 6.3 Annual maximum ice cover on Lake Michigan, 1973–2020, with average trend (solid line).
Source: NOAA-GLERL 2020.

Earlier and longer summer stratification

Summer stratification, in which a warm surface layer is separated from deep cold water, is an important characteristic of Lake Michigan, and plays a key role in species distribution and seasonal food web dynamics. For example, during the summer while the lake is stratified, cold-water predators must retreat to deeper water and are unable to forage on nearshore prey species. As a result of climate change, summer stratification is likely to occur earlier in the year and last longer. Historically, Lake Michigan is stratified from approximately June to October, with some variation depending on the year. The spatial distribution of fish is also likely to change—cold water species will probably spend more time offshore and warm-water species may be more widespread.

Increased precipitation and evaporation

Annual precipitation and evaporation, within the lake and in the watershed, are both expected to increase in the Great Lakes Basin with climate change (Wuebbles et al. 2019). Depending on the relative magnitude of change in these processes, water levels may increase or decrease, changing habitat availability for nearshore species and species that are dependent on tributary access for spawning. Projected precipitation increases may also provide nutrient "pulses" nearshore when runoff increases tributary flow, but the impact of these events is uncertain. While increased nutrient loads from tributaries are likely to increase productivity, such increases may be limited to nearshore waters due to the abundance of quagga mussels. These impacts would be especially important in areas outside Illinois with larger tributaries, but Illinois waters may be indirectly affected.

Warmer water temperatures

Spawning periods for fish may change as water temperatures increase earlier in the spring (affecting species such as yellow perch and alewife) or cool later in the fall (affecting species like lake trout and whitefish). The resulting impacts on production and survival of young fish are unclear. For example, early-life survival of spring-spawning fish often depends on energy reserves in the winter months—earlier spawning and hatch timing would allow additional time for growth and obtaining energy reserves, which could improve survival. On the other hand, if prey are not available for newly hatched fish, they may starve before their first winter.

Impacts on non-native species

More frequent floods and warmer water temperatures resulting from climate change are also likely to result in non-native species having additional impacts on Lake Michigan, through either new introductions or increases in existing populations. The following examples of possible scenarios highlight the complexity of projecting changes, even changes that may have very important consequences.

- The most important prey fish for salmon and trout is alewife. While the survival of young alewife is highly variable, it tends to be higher in warmer years. If climate change leads to increased survival of young alewife and increased alewife abundances, trout and salmon populations may benefit. However, warmer water may also cause trout and salmon to eat more prey, reducing alewife survival to adulthood. If increased predation outpaces increases in alewife production, the alewife population could collapse, in turn leading to a collapse of trout and salmon populations. Also, if competitors for larval alewife (e.g., juvenile yellow perch) increase in abundance, survival may decline if warm years become more common. Alewife also affect the ecosystem by driving the abundance and types of zooplankton present in the lake. If climate change increases alewife numbers, plankton communities may become less abundant and dominated by smaller species, thus negatively impacting other fish that are dependent on plankton, including most juvenile fish species.

- Because the proliferation of quagga mussels has reduced nutrient availability for the base of the water-column food web (plants and algae), productivity has become an important driver of ecosystem dynamics and management of Lake Michigan. The impact of climate change on nutrient fluxes and their impacts is a complex issue with several possible outcomes. Longer stratification periods (Figure 6.4a), when warmer surface water is separated from cooler water below by a narrow band called the thermocline, may keep algae in the warm, upper layer of the lake and away from most of the deep-water mussel biomass.

  Due to a lack of mixing between upper and lower water layers during the stratified period, mussels in deep water do not filter water in the surface layer, which could possibly increase water-column productivity. Conversely, longer summer stratification could decrease water-column productivity by limiting mixing that helps to distribute benthic nutrients across the lake. More phosphorus for algal growth comes from the resuspension of sediment during mixing than from tributary inputs lake-wide. However, mixing may increase in winter months because, as winter temperatures increase and ice cover decreases, wind is more effective at driving currents that can facilitate the movement of nutrients and algae throughout the lake (Figure 6.4b). Projecting productivity impacts would also require accounting for a number of other potential changes, such as shifts in mussel filtering rates, the frequency of sediment resuspension, and the degree of light penetration. Overall, climate change increases uncertainty about productivity dynamics and how to manage them in Lake Michigan.

Recommendations

The capacity for Lake Michigan's fisheries to continue delivering benefits to people in the face of uncertainty can be improved by managing for multiple species of economic importance, so that potential poor performance by one species might be buffered by strong performance of another. Management should strive for a diverse fishery with several sport fish species and improve various sources of natural reproduction sites (i.e., multiple spawning reefs) where possible. Similarly, restoring native plankton-eating fish, like cisco, may provide alternate prey sources if alewife survival and abundance declines.

Although Illinois contains just a small portion of the Lake Michigan watershed (approximately 0.2%), managing runoff to the lake is still important. This is due in part to stormwater flow reversals of the Chicago River system, when intense rain events can cause the Chicago River to flow into Lake Michigan (see Chapter 3). Furthermore, runoff from small tributaries north of Chicago can also bring excess

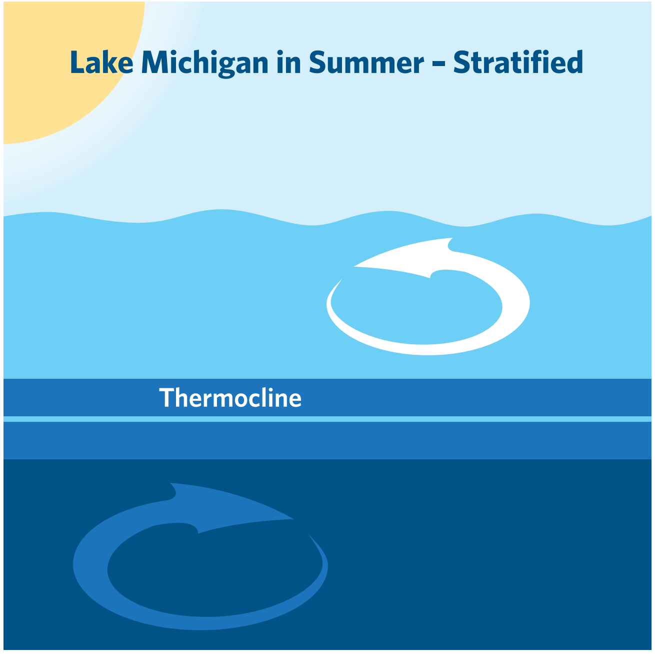

Figure 6.4a Diagram of summer stratification in Lake Michigan. Lake Michigan is stratified from approximately June to October when the sun warms surface water temperatures and causes density variations, leading cooler water to settle toward the bottom of the lake below the warmer surface. Due to a lack of mixing between layers during the stratified period, mussels in deep water do not filter water in the surface layer.

Figure 6.4b Diagram of unstratified Lake Michigan. During unstratified, ice-free periods, mixing can occur throughout the entire lake, allowing nutrients and algae to be widely distributed. In this phase, filtering by all mussels, even those dwelling in deep water, can sequester nutrients from throughout the lake.

nutrients and contaminants to the lake. While these flows are relatively insignificant on a lake-wide scale, they can have significant local impacts for swimming, boating, and other uses in the Illinois portion of the lake. Basin-wide, whole-watershed approaches to management can help reduce localized impacts of excessive nutrient and contaminant runoff.

Because of the complex, interjurisdictional nature of Lake Michigan and the broader Great Lakes ecosystem, communication across management agencies and organizations is paramount, especially in the face of climate change. Clear goals and objectives, coupled with accountability, are important for the co-management of Lake Michigan. In many cases, this is already occurring (e.g., cooperative fisheries management under the Great Lakes Fishery Commission). Finally, continued monitoring is fundamentally important for preparing managers to respond to major changes (e.g., reductions in alewife prey abundance) in a timely manner.

Grasslands

Key Points

- Changes in climate will affect grassland vegetation largely by shifting the amount and seasonal pattern of precipitation and soil water availability.
- Increased summer temperatures and evaporation may negatively affect grasslands by increasing loss of soil moisture, which will lead to decreased plant growth and reproduction.
- Native prairie plants adapted to survive periodic droughts and warmer temperatures will likely fare better than species not adapted to these conditions.
- Restoring prairie at landscape scales and forward-thinking management will be necessary to conserve native plants and wildlife and build resilience to climate change impacts.

Grasslands are plant communities dominated by grasses and other herbaceous vegetation, with few to no trees or shrubs. They contain a surprising amount of biological diversity, providing habitat to a variety of plants, birds, mammals, insects, and other wildlife. The vegetation structure of grasslands reduces water runoff from precipitation, slows soil erosion, and retains soil moisture for long periods of time. Like forests, grasslands capture atmospheric carbon through the process of photosynthesis. Although grasslands have been highly altered by humans and are generally not as highly valued as other ecosystems, humans depend on grasslands to provide livestock feed and forage, as well as a multitude of recreation, education, cultural, and research opportunities.

Historically, much of the Midwest was once covered by tallgrass prairies (Figure 6.5), which are dominated by deep-rooted perennial grasses and forbs (flowering herbaceous plants). They are botanically diverse—even small prairies (less than 25 acres) frequently support more than 100 plant species. Several types of tallgrass prairie are found in Illinois, characterized by different vegetation. Variations are largely a function of differences in soils and geography.

At the time of Euro-American settlement, tallgrass prairie covered over half of Illinois, or approximately 21 million acres (Figure 6.1). Between 1840 and 1900, most of the tallgrass prairie in Illinois was converted to other land uses, primarily agricultural. Because deep, fertile prairie soil made these ecosystems particularly desirable for agricultural conversion, tallgrass prairie is one of the most endangered ecosystems in the world (Noss et al. 1996).

Some patches of prairie did escape the plow; small, widely scattered remnants exist in pioneer cemeteries, along railroads, and in areas unsuitable for agriculture (e.g., sandy soils, steep slopes). The Illinois Natural Areas Inventory estimated that about 2,400 acres of high-quality prairie exists at about 250 sites across the state, representing less than 0.01 percent of the original prairie (Taft et al. 2009).

Currently, most grasslands in Illinois are not prairie, but rather lands generally associated with agriculture, formed either directly or indirectly by people. These cultural grasslands include pastures, hayfields, fallow fields, lawns, road and railroad rights-of-way, and reclaimed surface mines, as well as restored prairie and other grassland planted into former row-crop agricultural fields. Cultural grasslands are generally dominated by non-native plants, such as smooth brome and tall fescue, and contain fewer species than prairie (Spyreas et al. 2004). They cover about 4.1 million acres, or 11.5% of the land area in Illinois (NASS 2019). Many of these large agricultural grasslands are the last strongholds for declining native grassland bird species (Walk and Warner 2000).

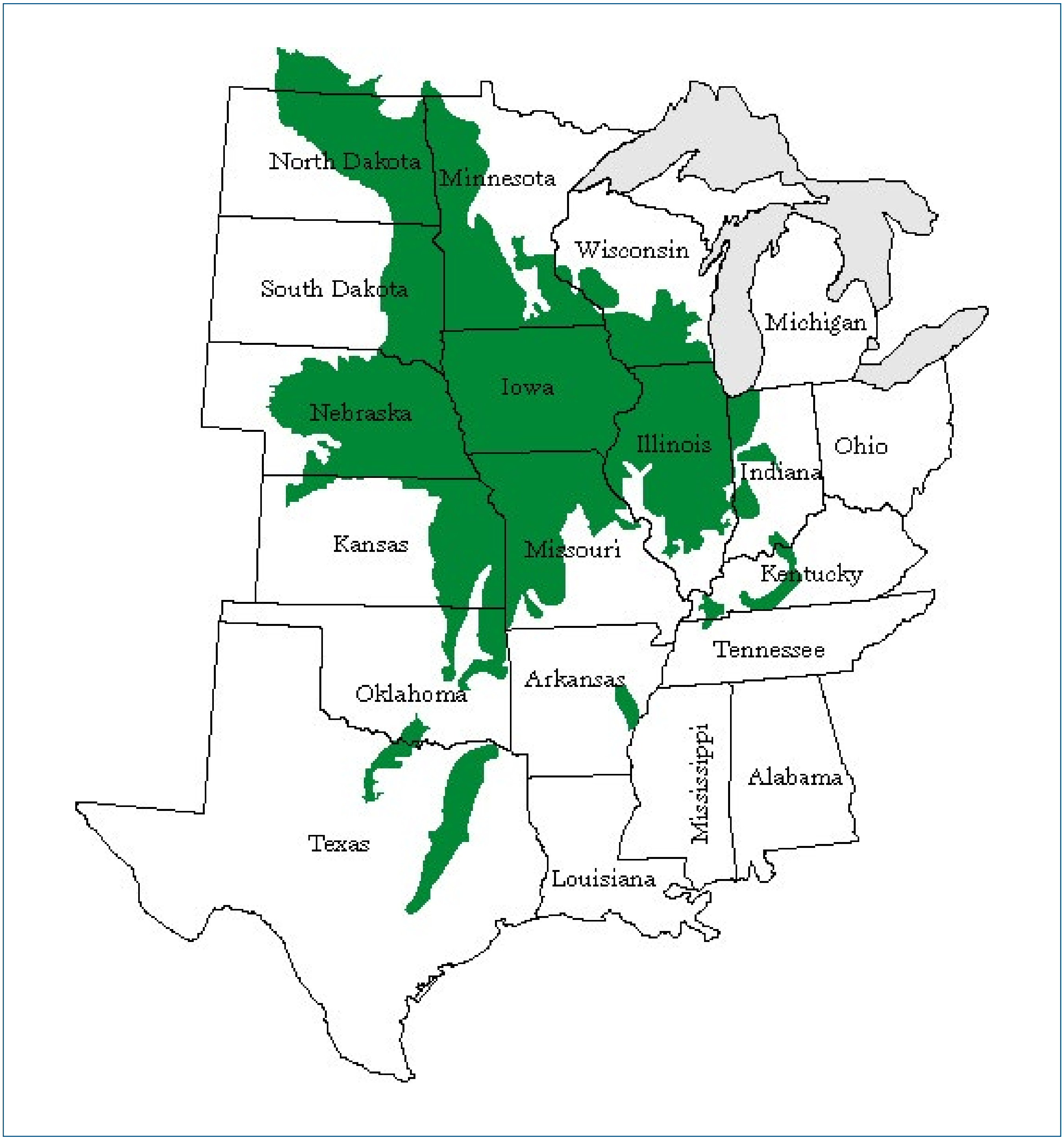

Figure 6.5 Historic distribution of tallgrass prairie in North America. **Source:** Map by Lynne Hawkinson-Smith, adapted from Anderson 1991.

Climate-related effects on Illinois grassland ecosystems

Changes in precipitation

Climate change will affect plants largely by shifting the amount and seasonal pattern of water available in the soil (Knapp et al. 2008). Water availability limits plant growth in almost all terrestrial ecosystems, and grasslands are highly responsive to changes in water availability. Most grasslands in Illinois have relatively abundant soil moisture relative to demand. Generally, frequent low-intensity rain events throughout the growing season keep soil moist enough to maintain vegetation in an unstressed state. Plants experience water stress due to either limited or excess water availability, which leads to significant reduction in rates of photosynthesis and growth.

Fewer and heavier rain events are expected to amplify fluctuations in soil water content. This might decrease shallow soil moisture (0–20" deep) and increase deep soil moisture (20–40" deep). Most grasses and forbs draw water from shallow soil; shrubs are able to draw water from deeper layers. Prolonged dry periods between rain events will dry upper layers of soil and lead to an increase in the length and occurrence of drought stress. Excess water will most likely percolate to deep soil layers or be lost to groundwater or runoff.

Changes in rainfall patterns might favor the growth of plant species better adapted to dry conditions (Knapp et al. 2008). Prairie plants such as big bluestem, prairie milkweed, Illinois bundleflower, rough blazing star, little bluestem, and Indian grass all exhibit drought tolerance. Some non-native species like smooth brome are also tolerant of dry conditions. Recurrent drying of upper soil layers will negatively affect plants that depend on frequent low-intensity rainfall events for growth, reproduction, and survival. Fewer but heavier rainfall events will likely reduce plant and soil microbial growth as a result of prolonged periods of low soil moisture. This could negatively impact wildlife and livestock that rely on highly productive grasslands.

Soils that developed under prairie are some of the most fertile and productive in the world, but the vital nutrients they contain, like nitrogen, are dependent on available water. Stable soil moisture throughout the growing season ensures the availability of nitrogen, but severe drought interspersed between heavy rainfall events may produce pulses in soil nutrients that change the composition of vegetation. Available soil nitrogen increases during drought periods when plant absorption is suppressed. Consequently, the availability of soil moisture will coincide with high nitrogen levels during rainfall events after drought. Plant species that can survive and recover most rapidly from drought will benefit the most from available nitrogen (Gebauer and Ehleringer 2000). Plants stressed by drought conditions may recover slowly or die, and space they leave behind might be filled by weedy, non-native, or undesirable plant species, including common ragweed, lamb's quarters, horseweed, wild carrot, common peppergrass, sweet clover, and wild parsnip.

Severe multiyear droughts can substantially modify species composition (Breshears et al. 2005). Evidence from the 1930s illustrates that plant species with deep roots, high water-use efficiency, or growth patterns that match the seasonality of precipitation likely will fare the best during protracted droughts.

Increases in temperature

Temperature regulates rates of chemical reactions in both soils and plants and drives water and energy flows between the land and atmosphere. Warming has been found to increase growth in terrestrial plants by alleviating low temperature limits on growth, extending the growing season, and increasing nutrients like nitrogen, provided enough water is available (Lin et al. 2010). In contrast, warming may reduce plant growth by increasing evapotranspiration, reducing soil water availability (Sherry et al. 2008), and decreasing plant water-use efficiency. The resulting water stress often reduces plant growth in the absence of compensating changes in precipitation.

Generalizations about grassland responses to changes in temperature are tempered by observations that plant responses to warming are species specific. Woody plants generally show a more consistent response to warming than do herbaceous species (Lin et al. 2010). Warm-season species, like native prairie grasses, will likely be favored in a warming environment over cool-season species, which includes most wildflowers, shrubs, trees, and non-native grasses in Illinois (Knapp et al. 2008). Other factors, though, such as increased atmospheric carbon dioxide, will favor cool-season species (Morgan et al. 2007).

Response to changes in atmospheric carbon dioxide

Carbon dioxide is both a greenhouse gas contributing to global climate change and a compound that is vital to life itself. Plants use carbon dioxide and energy from the sun to make their own food in the chemical process of photosynthesis. Elevated levels of atmospheric carbon dioxide increase rates of photosynthesis, carbon assimilation, and plant growth, but effects are limited by the amount and seasonal distribution of precipitation and soil water availability. Warming and higher levels of carbon dioxide should lead to earlier and more rapid plant growth in grasslands dominated by winter precipitation because warming will reduce temperature limitations on both growth and growth responses to carbon dioxide. Tree and shrub abundance in grasslands is anticipated to increase because increased carbon dioxide enhances photosynthesis and growth in these species (Ratajczak et al. 2012).

Fire response

Fire is an important factor in the maintenance and persistence of prairie because fire affects the vegetation composition, favoring fire-tolerant over fire-intolerant species. Across North America, wildfire activity is projected to increase as the climate warms and dries (Pechony and Shindell 2010). Thus, more frequent prairie wildfires may occur, provided there are enough fuels and ignition sources. Owing to the extremely fragmented nature of prairies in Illinois, it remains to be seen whether wildfires will become more frequent in the state. Notably, prescribed fires are distinct from wildfires and are used by land managers as an important conservation tool to maintain and restore prairies.

Non-native plant response

Non-native species present challenges to the maintenance and management of grasslands. Disturbances that suppress or eliminate dominant or native grassland species will provide more opportunities for the growth and spread of non-native plants. Many non-native plants are invasive weeds, and they often share traits that contribute to their capacity to grow quickly, increase in abundance, rapidly shift or extend ranges, and exploit habitat openings at the expense of native species. Flowering times and abundance in some invasive species have changed and increased in response to warmer temperatures, allowing them to compete directly with native species for insect pollinators. Excess nutrients such as nitrogen and more frequent droughts are anticipated to favor invasive species, especially when dominant natives are suppressed by disturbances (Dukes and Mooney 1999). Johnsongrass is a pernicious weed that is common across southern Illinois and will very likely continue to spread northward and invade grasslands as temperatures increase.

Wildlife response

Habitat loss and degradation remains the main stressor to birds, mammals, insects, and other animals that utilize or depend on grasslands, but climate change could exacerbate stress and loss. Grassland-dependent birds, like eastern meadowlark, Henslow's sparrow, dickcissel, and grasshopper sparrow continue to decline (Walk et al. 2010). Direct or indirect climate change impacts to these species remain to be seen. Warmer winters might increase whitetail deer survival rates that lead to population increases. Conversely, warmer, drier summers might increase transmission of diseases like bluetongue and epizootic hemorrhagic disease in deer, leading to population decreases. Insects and other invertebrates represent most of the faunal diversity in grasslands and play substantial roles in processes such as nutrient cycling and pollination. Insect communities are also highly dependent on plant diversity and production. Warming temperatures may affect the timing of biological events. For example, the life cycles of butterflies and caterpillar host or nectar plants might become misaligned. If plants grow or flower earlier than usual, caterpillars or adults may have little to eat by the time they emerge. Changes in plant abundance or forage quality due to increased precipitation or drought conditions will negatively impact herbivores, such as grasshoppers and other groups that feed on plants.

Recommendations

Mitigating climate-related impacts to grasslands in Illinois will require an adaptive approach that incorporates continued protection of native prairie, active management, biological monitoring, and restoration of large, botanically diverse grasslands.

Illinois has a long and robust history of identifying and protecting prairie through the Illinois Natural Areas Inventory and Illinois Nature Preserves Commission. Land dedicated as nature preserves is protected in perpetuity. Continued efforts are needed to protect native prairie, buffer existing reserves, and provide connectivity among them.

Protection efforts will be of limited value if grasslands are not adequately managed. The use of prescribed fire is essential, but mechanical and chemical methods will also be needed to control non-native plants as well as trees and shrubs in prairies. The management and persistence of agricultural grasslands is highly dependent on economic and social factors. Most of these grasslands are in private ownership, and government programs that provide assistance and incentives, like the Conservation Reserve Program, could be a good strategy to maintain and expand grasslands in Illinois.

Deliberate action to restore prairie is needed. The land that historically supported prairie is still here, albeit intensively managed and used to grow corn, soybeans, and other crops. The highly fragmented nature of protected prairies and abundance of non-native plants greatly limits the natural ability of prairie plants to colonize suitable sites. Local, state, and federal agencies, as well as non-governmental organizations, should continue to prioritize prairie conservation, reconstruction, and management. Large-scale restoration projects by The Nature Conservancy at Nachusa Grasslands and Kankakee Sands Preserve, the USDA Forest Service at Midewin National Tallgrass Prairie, and other regional initiatives provide critical habitat to grassland-dependent plants and wildlife and opportunities to study and refine the techniques and knowledge needed to successfully restore prairie.

Finally, monitoring grasslands will be important to detect and respond to alterations in condition as the climate changes. Long-term monitoring programs such as the Critical Trends Assessment Program will provide critical baseline data for detecting changes in plant, insect, and bird assemblages over the next century.


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Knowledge and research gaps

Native ecosystems in Illinois play important roles in reducing the adverse effects of climate change, in addition to providing many other benefits to people. Given the widespread conversion of these ecosystems to other land uses in Illinois, the first priority must be to reduce current rates of ecosystem destruction and degradation in the state. In addition, ecological restoration will increasingly become a priority. There is still much to be learned about the factors that contribute to restoration success and, because this process is expensive, it will require adequate investment in research and implementation.

Given the many sources of uncertainty associated with climate change, a so-called adaptive approach to restoration and management is recommended. This involves the implementation of climate change adaptation and mitigation strategies, followed by targeted monitoring to provide an informative feedback loop and a basis for improving these strategies. Management actions aimed at enhancing the resilience of an ecosystem, such as eliminating pollution sources or managing invasive species, are likely to be robust regardless of the climate future. Other strategies that are more focused on a particular aspect of climate change or a particular plant or wildlife species, such as translocating a species to an area where it does not currently occur but is predicted to thrive in the future, have higher levels of uncertainty. Yet, such actions may be necessary to accommodate range shifts among species. As with ecological restoration, a lack of information should not be construed as a rationale for inaction. Rather, it underscores the need for an adaptive approach and learning-by-doing. The following areas of research can help to inform and improve management strategies for Illinois' ecosystems in a changing climate.

- **Baseline data**
  There is a critical need for baseline data on the condition of natural ecosystems in Illinois, including the distribution of plants and animals, as well as the environmental stresses facing them. Gaining reliable knowledge about the effects of climate change and other environmental stresses will require building upon baseline information gathered from ongoing trend assessments.

- **Integrated hydrologic and climate models**
  Incorporating outputs from landscape-scale hydrological models into climate change projections is needed to forecast impacts on wetlands and floodplains and to manage these systems accordingly.

- **Species-specific climate impacts**
  The effects of climate change on individual species are mostly unknown, as are the interaction or competitive effects of multiple species under various ecological conditions. Research on the ways that plants and animals cope with climate changes, like altered precipitation patterns and increasing temperatures, will do much to inform natural resource management decisions.

- **Best practices and guidance for restoration**
  Ecological restoration will be necessary to mitigate the effects of climate change, and studies that examine the factors contributing to the success of restoring different ecosystem types are needed. Also sorely needed is more guidance on seed sourcing for restoration, given a changing climate, and a robust native seed market.

- **Social science research on landowner responses to climate change**
  Human responses to climate change, especially those of private landowners, will be fundamental to determining how native ecosystems and the lands that surround them are managed. Social science research is urgently needed to advance our understanding of human values, priorities, and beliefs in this context.

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Supplemental Materials

- To access a list of common and scientific species names used in this chapter, please visit: https://doi.org/10.13012/B2IDB-9049988_V1

- To access the supplemental materials for the Forests section, please visit: https://doi.org/10.13012/B2IDB-3459813_V1

CHAPTER 7

Knowledge and Research Priorities

This assessment provides localized climate projections and information on how climate change is likely to impact the hydrology, agriculture, public health, and natural ecosystems of Illinois. The critical insights contained in this report can be used by lawmakers, government agencies, nonprofits, businesses, landowners, and farmers to develop plans to both mitigate and build resilience to a diverse array of adverse impacts from climate change.

However, additional research would be beneficial to decrease uncertainty and improve predictive capabilities, which is important for ensuring that adequate and effective strategies are developed to respond to climate change. The highest priority recommendations are described below, grouped by chapter, to provide a comprehensive summary of knowledge and research priorities. Additional details related to these recommendations, as well as other high-priority research recommendations, may be found at the end of chapters two through six.

Chapter 2. Regional climate change in Illinois and surrounding states

We know with a high degree of certainty that climate change is occurring as a result of rising greenhouse gas concentrations. However, the certainty with which particular impacts will occur as a result of climate change differs, especially at the local level. Future changes in climate variables that are directly tied to temperature have the highest level of confidence, including virtually certain global increases in atmospheric water vapor and extreme precipitation. Research should target climate issues with the most uncertainty. Three particular focus areas are recommended:

- **High-spatial-resolution climate simulations.** The development of very-high-spatial-resolution (4-km or finer grid spacing) climate model simulations over climate timescales (decades) would be beneficial. Such high-resolution simulations would resolve convective clouds and land cover heterogeneity and provide more robust simulations of heatwaves, severe thunderstorms, and extreme precipitation.
- **Refined climate modeling for hot summer days.** Further research is needed to improve our understanding of the phenomena responsible for the lack of an observed trend in hot summer days. All climate model simulations project an increase in hot summer days and warm summer nights. While an upward trend in warm summer nights has been observed, an upward trend for hot summer days has not been observed in Illinois or over most of the Midwest. Thus, there is greater uncertainty about future projections of increased numbers of hot summer days.
- **Coupled land–lake atmosphere modeling.** The development of integrated models of atmosphere, land, and the Great Lakes will improve both the utility of weather forecasts and long–term climate projections and associated impacts on hydrometeorological extremes, agriculture, ecosystems, engineering design, human health, and socioeconomic systems in the Midwest and Great Lakes region.

Chapter 3. Climate change impacts on hydrology and water resources

As noted above, the assessment of climate impacts for successful planning and water resource management increasingly requires higher resolution projections of all relevant variables. Other important research focus areas include:

- **Updated rainfall frequency studies.** Due to the projected increase of heavy precipitation in Illinois, updated rainfall frequency estimates are recommended every 15 years, applying nonstationary statistical frequency estimation methodology and using additional rainfall gauge data as they become available in the future. New methods for nonstationary precipitation frequency analysis show promise but exhibit significant variability in space and time, so additional research is recommended. Future projected, downscaled, and de-biased precipitation data should also be analyzed using nonstationary methods.

- **Improve urban flooding data and adaptive management strategies.** Comparative analysis and quantitative assessment of tools that could be used to study the effects of projected increases in storm intensity would facilitate long-term planning and the development of sustainable infrastructure and management approaches. Decades of insufficient funding have left many areas of the state with out-of-date flood hazard data; additional funding is needed to update the hazard maps. Research is needed to evaluate strategies for linking conventional stormwater infrastructure with distributed green infrastructure to optimally mitigate both local and regional flooding risks, while also maximizing co-benefits to people and nature.

- **Quantify contributions of different factors to riverine nutrient loading.** Additional research is needed to quantify the contributions of different factors that influence nutrient loading in rivers and their interactions in diverse settings. While it is well established that large nutrient-loading episodes are associated with storm/flood events, it is not known to what degree climate change will increase nutrient loading or affect the success of crop management and other practices (e.g., wetland restoration) in reducing nutrient loads. Studying the effects of climate change on riverine nutrients is particularly relevant for the Illinois Nutrient Loss Reduction Strategy (NLRS).

- **Advance and integrate emerging sensing systems and prediction.** With the rapid decline in the cost of sensing technologies, sensor miniaturization, and the emergence of new measurement platforms such as drones and low-earth-orbiting satellites, it is now possible to obtain environmental observations at a higher frequency and much higher spatial density. However, data from these technologies have highly varied coverage and resolution in both space and time, and they have not been closely integrated with existing data sources or synthesized to assess climate change at regional scales. These data are also facilitating the emergence of a new generation of models capable of prediction at extremely high resolution. New research is needed to advance data management and predictive capabilities—both for operational decisions and scientific explorations—using machine learning/artificial intelligence approaches based in effective model–data integration.

- **Expand research to guide water-use planning and management.** Knowledge gaps regarding how water resources will be affected by climate change create important challenges for planning and management. Research is needed to guide the sustainable management of drinking water from both surface and sub-surface sources, based on projected changes to availability and replenishment capacities. Furthermore, research is needed to improve understanding of climate change impacts on irrigation demand and water quality—especially changes in the loading of nutrients, sediment, and other contaminants from both urban and agricultural areas.

Chapter 4. Climate change impacts on agriculture

Additional information would be useful to refine the understanding of how climate change will impact Illinois' agricultural sector. The large number of factors involved and their interactions can complicate efforts to project how climate change will specifically alter production. For instance, there are outstanding uncertainties regarding the ability of technological progress on crop yields to keep pace with climate change and climate extremes. A systems approach for research would facilitate a better understanding of the vulnerabilities of Illinois' agricultural system to climate change. Important knowledge and research focus areas include:

- **Crop technology.** Recent research suggests that, if past technological gains continue during the 21st century, this could mitigate future yield losses from climate change; however, more research on this topic is needed, and such advances will require significant new investments. More research and investment could be focused on developing specific traits to take advantage of and make crops more resilient to changing climate conditions. For example, genotypes vary in sensitivity to CO_2, which could be exploited to identify key genes and adapt crops for improved performance in future growing conditions.

- **Complex plant responses to increasing CO_2 emissions.** One of the greatest uncertainties about climate change relates to interactions between elevated CO_2 and other abiotic and biotic factors. More experiments with combined stresses and different management practices are needed. Given the demand for both food and fuel production, additional studies on C_4 crops are also needed. Future experiments should also consider multiple levels of elevated CO_2 to inform projections of agricultural performance in the latter half of the century, as field studies have not yet included experimental treatments of elevated CO_2 greater than 600 ppm.

- **Research in understudied areas.** Two areas of agriculture with the least information today and, thus, the greatest future uncertainty, are how pests and diseases and specialty crops will be impacted by climate change. The scientific understanding of climate change impacts on insect pests, pathogens, and weeds is limited, as is knowledge about the interactions of these organisms within complex agricultural landscapes. There is also a critical lack of information about the impacts of increased variability and extreme weather events on horticultural crops.

- **Climate mitigation potential of farming practices.** Agriculture has the ability to partially mitigate future climate change through carbon sequestration in soil and perennial vegetation, improved nutrient-use efficiency of fertilizers, and reduced methane emissions from ruminant livestock and manure. However, more research is needed to quantify the impacts of such mitigation measures. It is also necessary to develop effective policies and regulations to ensure widespread adoption of best practices.

- **Social science research on vulnerability and adaptation in rural communities.** Social science research is required to improve understanding of the vulnerability of rural communities—of which the agricultural sector is an important component. Social science research is also important for the development of strategies to enhance adaptive capacity and resilience and overcome barriers to the adoption of new strategies.

Chapter 5. Climate change impacts on public health

The field of public health must prepare for the impacts of climate change to minimize adverse health outcomes, especially in vulnerable communities. To that end, knowledge of projected climate change impacts can be incorporated into public health planning, and public health strategies can be implemented through a climate lens. However, to improve understanding of the public health impacts of climate change and design the most effective strategies to reduce them, more research is required in the following areas:

- **Evidence-based public health strategies.** An evidence-based approach to public health and climate change will provide access to better information on best practices, a higher likelihood of successful prevention programs and policies, greater workforce productivity, and more efficient use of public and private resources.

- **Cost-benefit analysis of climate and health adaptation strategies.** Understanding the cost of health impacts from climate change in Illinois, as well as the cost of implementing strategies to reduce adverse health impacts, will give decision makers data-driven tools to make informed decisions and take action.

- **Climate and health communications.** There is a disconnect between knowing that climate change is happening and understanding how it can personally affect us. Localizing the impacts of climate change is critical to communicating them; messaging about climate change and health should be targeted to specific Illinois communities. More effective communications are needed about scientific research that links local impacts of a changing climate to health.

- **Vector-borne diseases.** The relationships between climate change and vector-borne diseases are extremely complex. Research is needed to better understand these relationships and inform strategies designed to reduce the number of vector-borne disease cases, morbidity, and mortality in Illinois.

- **Mental health.** The relationship between climate change and mental health is a burgeoning field of research that needs continued support. There is also a need to better understand how different climate solutions can positively benefit mental health.

Chapter 6. Climate change impacts on ecosystems

Native ecosystems in Illinois play important roles in reducing the adverse effects of climate change and provide many other benefits to people. Given the widespread conversion of these ecosystems to other land uses in Illinois, the first priority must be to reduce current rates of ecosystem destruction and degradation in the state. In addition, ecological restoration will increasingly become a priority. There is still much to be learned about the factors that contribute to restoration success and, because this process is expensive, it will require substantial investment in research and implementation. The following areas of research can help to inform and improve management strategies for Illinois' ecosystems in a changing climate:

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References

Chapter 1

Anderson, R.C., 1991: Illinois Prairies: A Historical Perspective. *Our Living Heritage: The Biological Resources of Illinois*, L.M. Page and M.R. Jeffords, Eds., Illinois Natural History Survey Bulletin, **34**, 4, 384-391.

Dahl, T.E., 1990: Wetlands Losses in the United States 1780's to 1980's. U.S. Department of the Interior, Fish and Wildlife Service, Washington, D.C., USA, 13 pp.

Hayhoe, K., D.J. Wuebbles, D.R. Easterling, D.W. Fahey, S. Doherty, J. Kossin, W. Sweet, R. Vose, and M. Wehner, 2018: Our Changing Climate. In *Impacts, Risks, and Adaptation in the United States: Fourth National Climate Assessment, Volume II* [Reidmiller, D.R., C.W. Avery, D.R. Easterling, K.E. Kunkel, K.L.M. Lewis, T.K. Maycock, and B.C. Stewart, Eds.]. U.S. Global Change Research Program, Washington, D.C., USA, 72–144, doi 10.7930/NCA4.2018.CH2.

Illinois Department of Agriculture, n.d.: Facts about Illinois Agriculture. Accessed 1 December 2020, https://www2.illinois.gov/sites/agr/About/Pages/Facts-About-Illinois-Agriculture.aspx.

Illinois Department of Natural Resources (IDNR), n.d.: The National Flood Insurance Program (NFIP). Accessed 1 December 2020, https://www2.illinois.gov/dnr/WaterResources/Pages/nfip.aspx.

IPCC, 2013: Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change [Stocker, T.F., D. Qin, G.-K. Plattner, M. Tignor, S.K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex, and P.M. Midgley, Eds.]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 1535 pp.

Janssen, E., D.J. Wuebbles, K.E. Kunkel, S.C. Olsen, and A. Goodman, 2014: Observational- and model-based trends and projections of extreme precipitation over the contiguous United States. *Earth's Future*, **2**, 2, 99–112.

Knutti, R., J. Sedláček, B.M. Sanderson, R. Lorenz, E.M. Fischer, and V. Eyring, 2017: A climate model projection weighting scheme accounting for performance and interdependence. *Geophys. Res. Lett.*, **44**, 1909–1918, https://doi.org/10.1002/2016GL072012.

Melillo, J.M., T.C. Richmond, and G.W. Yohe, Eds., 2014: Climate Change Impacts in the United States: The Third National Climate Assessment. U.S. Global Change Research Program, 841 pp., doi:10.7930/J0Z31WJ2.

NOAA, 2020: Climate at a Glance: Global Time Series. Accessed 6 May 2020, https://www.ncdc.noaa.gov/cag/global/time-series.

Pierce, D.W., D.R. Cayan, and B.L. Thrasher, 2014: Statistical downscaling using localized constructed analogs (LOCA). *J. Hydrometeorol.*, **15**, 2558–2585, https://doi.org/10.1175/JHM-D-14-0082.1.

Riahi, K., and Coauthors, 2011: RCP 8.5 – A scenario of comparatively high greenhouse gas emissions. *Clim. Change*, **109**, 33, https://doi.org/10.1007/s10584-011-0149-y.

Sanderson, B.M., M. Wehner, and R. Knutti, 2017: Skill and independence weighting for multi-model assessments, *Geosci. Model Dev.*, **10**, 2379–2395, https://doi.org/10.5194/gmd-10-2379-2017.

Schnitkey, G., 2020: Profitability and acreage shifts between corn and soybeans in Illinois. *Farmdoc Daily*, **10**, 44, Department of Agricultural and Consumer Economics, University of Illinois at Urbana-Champaign, Accessed 6 May 2020, https://farmdocdaily.illinois.edu/2020/03/profitability-and-acreage-shifts-between-corn-and-soybeans-in-Illinois.html.

Suloway, L., and M. Hubbell, 1994: Wetland resources of Illinois: an analysis and atlas. Illinois Natural History Survey Special Publication 15, 88 pp.

Thomson, A.M., and Coauthors, 2011: RCP4.5: A pathway for stabilization of radiative forcing by 2100. *Clim. Change*, **109**, 77, https://doi.org/10.1007/s10584-011-0151-4.

USGCRP, 2017: Climate Science Special Report: Fourth National Climate Assessment, Volume I [Wuebbles, D.J., D.W. Fahey, K.A. Hibbard, D.J. Dokken, B.C. Stewart, and T.K. Maycock, Eds.]. U.S. Global Change Research Program, Washington, D.C., USA, 475 pp., doi: 10.7930/J0J964J6.

USGCRP, 2018: Impacts, Risks, and Adaptation in the United States: Fourth National Climate Assessment, Volume II: Report-in-Brief [Reidmiller, D.R., C.W. Avery, D.R. Easterling, K.E. Kunkel, K.L.M. Lewis, T.K. Maycock, and B.C. Stewart, Eds.]. U.S. Global Change Research Program, Washington, D.C., USA, 186 pp., doi: 10.7930/NCA4.2018.RiB.

van Vuuren, D.P., and Coauthors, 2011: The representative concentration pathways: an overview. *Clim. Change*, **109**, 5, https://doi.org/10.1007/s10584-011-0148-z.

World Meteorological Organization, 2017: WMO Guidelines on the Calculation of Climate Normals (WMO-No. 1203). Geneva, https://library.wmo.int/doc_num.php?explnum_id=4166.

Chapter 2

Angel, J., and Coauthors, 1992: The 1988–1989 Drought in Illinois: Causes, dimensions, and impacts. ISWS Research Report 121, http://hdl.handle.net/2142/75857.

Cook, B.I., R.L. Miller, and R. Seager, 2009: Amplification of the North American "Dust Bowl" drought through human-induced land degradation. *PNAS*, **106**, 13, 4997–5001, https://doi.org/10.1073/pnas.0810200106.

Demaria, E.M.C., J.K. Roundy, S. Wi, and R.N. Palmer, 2016: The effects of climate change on seasonal snowpack and the hydrology of the northeastern and upper Midwest United States. *J. Clim.*, **29**, 6527–6541, https://doi.org/10.1175/JCLI-D-15-0632.1.

Frankson, R., K. Kunkel, S. Champion, B. Stewart, D. Easterling, B. Hall, and J.R. Angel, 2017: Illinois State Climate Summary. *NOAA Technical Report NESDIS* 149-IL, 4 pp.

Hoerling, M., J. Eischeid, A. Kumar, R. Leung, A. Mariotti, K. Mo, S. Schubert, and R. Seager, 2014: Causes and predictability of the 2012 Great Plains drought. *Bull. Amer. Meteor. Soc.*, **95**, 269–282, https://doi.org/10.1175/BAMS-D-13-00055.1.

Sharma, A., and Coauthors, 2018: The need for an integrated land-lake-atmosphere modeling system, exemplified by North America's Great Lakes region. *Earth's Future*, **6**, 10, 1366–1379, https://doi.org/10.1029/2018EF000870.

Sherwood, S., and Coauthors, 2020: A combined assessment of Earth's climate sensitivity. *Rev. Geophys.*, **58**, 4, https://doi.org/10.1029/2019RG000678.

Takle, E., and W. Gutowski, 2020: Iowa's agriculture is losing its Goldilocks climate. *Phys. Today*, **73**, 2, https://doi.org/10.1063/PT.3.4407.

USGCRP, 2017: Climate Science Special Report: Fourth National Climate Assessment, Volume I [Wuebbles, D.J., D.W. Fahey, K.A. Hibbard, D.J. Dokken, B.C. Stewart, and T.K. Maycock, Eds.]. U.S. Global Change Research Program, Washington, D.C., USA, 475 pp., doi: 10.7930/J0J964J6.

Chapter 3

Abrams, D.B., and C. Cullen, 2020: Analysis of Risk to Sandstone Water Supply in the Southwest Suburbs of Chicago. Illinois State Water Survey CR2020-04, Champaign, IL, http://hdl.handle.net/2142/109174.

AGU, 2019: Illinois Flooding Fact Sheet. Accessed 4 February 2021, https://scienceisessential.org/floods-in-the-central-us/.

Ando, A., and Coauthors, 2019: Cures Connections Workshop: New Voices and Pathways to Urban Sustainability. *A Proposed Workshop on Interdisciplinary Sustainable Solutions for Urban Systems in a Changing Climate*, Center for Urban Resilience and Environmental Sustainability, Discovery Partners Institute, Chicago, IL, https://dpi.uillinois.edu/cures-connections/.

Angel, J.R., M. Markus, K.A. Wang, B.M. Kerschner, and S. Singh, 2020: Precipitation Frequency Study for Illinois. Illinois State Water Survey Bulletin 75, Champaign, IL, http://hdl.handle.net/2142/106653.

Angel, J., and Coauthors, 2018: Midwest. In *Impacts, Risks, and Adaptation in the United States: Fourth National Climate Assessment, Volume II* [Reidmiller, D.R., C.W. Avery, D.R. Easterling, K.E. Kunkel, K.L.M. Lewis, T.K. Maycock, and B.C. Stewart, Eds.]. U.S. Global Change Research Program, Washington, D.C., USA, 872–940, doi:10.7930/NCA4.2018.CH21.

Archfield, S.A., R.M. Hirsch, A. Viglione, and G. Blöschl, 2016: Fragmented patterns of flood change across the United States. *Geophy. Res. Lett.*, **43**, 19, 10,232–10,239, doi:10.1002/2016GL070590.

Association of State Floodplain Managers Foundation (ASFPM), 2004: Reducing flood losses: Is the 1% chance flood standard sufficient? *Report of the 2004 Assembly of the Gilbert F. White Flood Policy Forum*, National Academies Keck Center, Washington, D.C., https://www.nrcs.usda.gov/Internet/FSE_DOCUMENTS/16/nrcs143_009401.pdf.

Bell, C., K. Spahr, E. Grubert, J. Stokes-Draut, E. Gallo, J. McCray, and T. Hogue, 2019: Decision making on the gray-green stormwater infrastructure continuum. *J. Sustain. Water Built Environ.*, **5**, 04018016.

Bridges, K., S. Wilson, and R. Perry, 2015: Center pivot irrigation in Illinois 2012 and 2014. Illinois State Water Survey, Map Series 2015-03, Accessed 4 March 2021, https://www.isws.illinois.edu/iswsdocs/maps/ISWSMS2014-03.pdf.

Burlakova, L.E., E.K. Hinchey, A.Y. Karatayev, and L.G. Rudstam, 2018: U.S. EPA Great Lakes National Program Office monitoring of the Laurentian Great Lakes: Insights from 40 years of data collection. *J. Great Lakes Res.*, **44**, 535–538, https://doi.org/10.1016/j.jglr.2018.05.017.

Center for Neighborhood Technology (CNT), 2014: The Prevalence and Cost of Urban Flooding: A Case Study of Cook County, IL. Accessed 4 March 2021, www.cnt.org/publications/the-prevalence-and-cost-of-urban-flooding.

Easterling, D.R., and Coauthors, 2017: Precipitation change in the United States. In *Climate Science Special Report: Fourth National Climate Assessment, Volume I* [Wuebbles, D.J., D.W. Fahey, K.A. Hibbard, D.J. Dokken, Stewart, B.C., and T.K. Maycock, Eds.]. U.S. Global Change Research Program, Washington, D.C., USA, 207–230, doi:10.7930/J0H993CC.

Federal Emergency Management Agency (FEMA), 2020a: Guidelines and Standards for Flood Risk Analysis and Mapping Activities Under the Risk MAP Program. Accessed 14 October 2020, https://www.fema.gov/flood-maps/guidance-partners/guidelines-standards.

Federal Emergency Management Agency (FEMA), 2020b: Coordinated Needs Management Strategy. Accessed 14 October 2020, https://www.fema.gov/flood-maps/tools-resources/risk-map/coordinated-needs-management-strategy.

Federal Emergency Management Agency (FEMA), 2016: Guidance for Flood Risk Analysis and Mapping, Elevation Guidance. https://www.fema.gov/sites/default/files/2020-02/Elevation_Guidance_May_2016.pdf.

First Street Foundation (FSF), 2020a: Technical Methodology Document. Accessed 19 October 2020, https://assets.firststreet.org/uploads/2020/06/FSF_Flood_Model_Technical_Documentation.pdf.

First Street Foundation (FSF), 2020b: Defining America's Growing Risk. Accessed 19 October 2020, https://assets.firststreet.org/uploads/2020/06/first_street_foundation__first_national_flood_risk_assessment.pdf.

Hejazi, M., and M. Markus, 2009: Impacts of urbanization and climate variability on floods in northeastern Illinois. *J. Hydrol. Eng.*, **14**, 6, 606–616.

Hershfield, D.M., 1961: Rainfall frequency atlas of the United States for durations from 30 min to 24 h and return periods from 1 to 100 years. Technical Paper No. 40, Weather Bureau, U.S. Department of Commerce, Washington, D.C..

Hirsch, R., and S. Archfield, 2015: Not higher but more often. *Nat. Clim. Change*, **5**, 198–199, https://doi.org/10.1038/nclimate2551.

Hodson, T.O., and P.J. Terrio, 2020: Trends in nutrient and soil loss in Illinois rivers, 1978–2017. U.S. Geological Survey Scientific Investigations Report 2020–5041, 26 pp., https://doi.org/10.3133/sir20205041.

Hopkins, K.G., N.B. Grimm, and A.M. York, 2018: Influence of governance structure on green stormwater infrastructure investment. *Environ. Sci. Policy*, **84**, 124–133.

Huff, F.A., and J.R. Angel, 1989: Rainfall distributions and hydroclimatic characteristics of heavy rainstorms in Illinois. Illinois State Water Survey Bulletin 70, Champaign, IL, https://www.isws.illinois.edu/pubdoc/B/ISWSB-70.pdf.

Illinois Department of Natural Resources (IDNR), 2020: Illinois Rivers and Streams. Accessed 13 October 2020, https://www2.illinois.gov/dnr/education/Pages/ILRiversStreams.aspx#:~:text=Illinois%20is%20bordered%20by%20880,and%20streams%20within%20its%20borders.

Illinois Environmental Protection Agency (IEPA), 2020: Lake Michigan. Accessed 13 October 2020, https://www2.illinois.gov/epa/topics/water-quality/monitoring/Pages/lake-michigan.aspx.

Illinois Environmental Protection Agency (IEPA), Illinois Department of Ag (IDOA) and University of Illinois Extension, 2015: Illinois Nutrient Loss Reduction Strategy, https://www2.illinois.gov/epa/topics/water-quality/watershed-management/excess-nutrients/Pages/nutrient-loss-reduction-strategy.aspx.

Illinois State Water Survey, 2020a: Groundwater Science: Illinois Water Level Conditions. Accessed 4 February 2021, http://aqueduct.isws.illinois.edu/isws-hydrographs.html?pnum=381643&network=grl,%20last%20accessed%201/11/2021.

Illinois State Water Survey, 2020b: Illinois Floodmaps. Accessed 4 February 2021, https://www.illinoisfloodmaps.org/dfd.aspx.

Jarvie, H.P., L.T. Johnson, A.N. Sharpley, D.R. Smith, D.B. Baker, T.W. Bruulsema, and R. Confesor, 2017: Increased soluble phosphorus loads to Lake Erie: Unintended consequences of conservation practices? *J. Environ. Qual.*, **46**, 123–132, doi:10.2134/jeq2016.07.0248.

Jensen, R.E., M.A. Cialone, R.S. Chapman, B.A. Ebersole, M.E. Anderson, and L. Thomas, 2012: Lake Michigan: Storm Wave and Water Level Modeling. ERDC/CHL TR-12-26, U.S. Army Engineer Research and Development Center, Vicksburg, MS.

Kampbell, D.H., Y.J. An, K.P. Jewell, and J.R. Masoner, 2003: Groundwater quality surrounding Lake Texoma during short-term drought conditions. *Environ. Pollut.*, **125**, 2, 183–191, doi:10.1016/S0269-7491(03)00072-1.

Kelly, W. R., and Coauthors, 2019: Water Supply Planning: Kankakee Watershed Assessment of Water Resources for Water Supply. Illinois State Water Survey Contract Report 2019-07, Champaign, IL, http://hdl.handle.net/2142/104591.

Knapp, H.V., 2005: Analysis of streamflow trends in the Upper Midwest using long-term flow records. In *Impacts of Global Climate Change: Proceedings of the 2005 World Water and Environmental Resources Congress*, Anchorage, AK, 4190–4201.

Knapp, H.V., and Coauthors, 2017: The 2012 Drought in Illinois. Illinois State Water Survey Report of Investigation 123, Champaign, IL, 99 pp., http://www.isws.illinois.edu/pubdoc/RI/ISWSRI-123.pdf.

Kossin, J.P., T. Hall, T. Knutson, K.E. Kunkel, R.J. Trapp, D.E. Waliser, and M.F. Wehner, 2017: Extreme Storms. In C*limate Science Special Report: Fourth National Climate Assessment, Volume 1* [D.J. Wuebbles, D.W. Fahey, K.A. Hibbard, D.J. Dokken, B.C. Stewart, and T.K. Maycock, Eds.]. U.S. Global Change Research Program, Washington, D.C., USA, 257–276, doi:10.7930/J07S7KXX.

Lofgren, B.M., and J. Rouhana, 2016: Physically plausible methods for projecting changes in Great Lakes water levels under climate change scenarios. *J. Hydrometeorol.*, **17**, 2209–2223, doi:10.1175/JHM-D-15-0220.1.

Markus, M., D.J. Wuebbles, X-Z. Liang, K. Hayhoe, D.A.R. Kristovich, 2012: Diagnostic analysis of future climate scenarios applied to urban flooding in the Chicago metropolitan area. *Clim. Change*, **111**, 3, 879–902.

Markus, M., J. Angel, G. Byard, S. McConkey, C. Zhang, X. Cai, M. Notaro, and M. Ashfaq, 2018: Communicating the impacts of projected climate change on heavy rainfall using a weighted ensemble approach. *J. Hydrol. Eng.*, **23**, 4018004, https://doi.org/10.1061/(ASCE)HE.1943-5584.0001614.

McIsaac, G.F., 2019: Nitrate and Total Phosphorus Loads in Illinois Rivers: Update Through the 2017 Water Year. Illinois Nutrient Loss Assessment Strategy Scientific Update, https://www2.illinois.gov/epa/topics/water-quality/watershed-management/excess-nutrients/Documents/NLRS_SCIENCE_ASSESSMENT_UPDATE_2019%20v7_FINAL%20VERSION_web.pdf.

Melby, J.A., N.C. Nadal-Caraballo, Y. Pagan-Albelo, and B.A. Ebersole, 2012: Wave Height and Water Level Variability on Lakes Michigan and St. Clair, U.S. Army Corps of Engineers, TR-12-23, http://greatlakescoast.org/pubs/reports/CHL+TR-12-23.pdf.

Meyer, S.C., B. Dziegielewski, Z. Zhang, D. Abrams, and W.R. Kelly, 2018: Water Demand in the Middle Illinois Water Supply Planning Region, 2010–2060. Illinois State Water Survey Contract Report 2018-06, http://hdl.handle.net/2142/102366.

Meyer, S.C, B. Dziegielewski, Z. Zhang, D. Abrams, and W.R. Kelly, 2019a: Water demand in the Kankakee Water Supply Region, 2010–2060. Illinois State Water Survey Contract Report 2019–01, http://hdl.handle.net/2142/102367.

Meyer, S.C., B. Dziegielewski, Z. Zhang, D. Abrams, and W.R. Kelly, 2019b: Water Demand in the Rock River Water Supply Planning Region, 2010–2060. Illinois State Water Survey Contract Report 2019-02, http://hdl.handle.net/2142/102368.

Miller, W.M., and J.B. Dunn, 2019: Sustainable Urban Systems: Predictive, Interconnected, Resilient, and Evolving (SUSPIRE Conference). Northwestern University, Chicago, IL, https://www.engineeringsustainability.northwestern.edu/documents/suspire_final_report_9.30.20191.pdf.

National Academies of Sciences, Engineering, and Medicine, 2019: Framing the Challenge of Urban Flooding in the United States. The National Academies Press, Washington, D.C., https://doi.org/10.17226/25381.

National Oceanic and Atmospheric Administration (NOAA), 2020: National Centers for Environmental Information, Storm Events Database. Accessed 16 October 2020, https://www.ncdc.noaa.gov/stormevents/.

Natural Resources Conservation Service (NRCS), 2020: National Elevation Dataset. Accessed 19 October 2020, https://www.nrcs.usda.gov/wps/portal/nrcs/detail/national/?&cid=nrcs143_021626.

Naz, B.S., S-C. Kao, M. Ashfaq, D. Rastogi, R. Mei, and L.C. Bowling, 2016: Regional hydrologic response to climate change in the conterminous United States using high resolution hydroclimate simulations. *Global Planet. Change*, *143*, 100–117.

Notaro, M., V. Bennington, and B. Lofgren, 2015: Dynamical downscaling-based projections of Great Lakes water levels. *J. Clim.*, **28**, 9721–9745, doi:10.1175/ JCLI-D-14-00847.1.

Pinter, N., A. Jemberie, J.W.F. Remo, and R.A. Heine, 2008. Flood trends and river engineering on the Mississippi River system. *Geophys. Res. Lett.*, **35**, L23404, doi: 10.1029/2008GL035987.

Pryor, S.C., D. Scavia, C. Downer, M. Gaden, L. Iverson, R. Nordstrom, J. Patz, and G.P. Robertson, 2014: Midwest. In *Climate Change Impacts in the United States: The Third National Climate Assessment* [J.M. Melillo, T.C. Richmond, and G.W. Yohe, Eds.]. U.S. Global Change Research Program, Washington, D.C., USA, 418–440, doi 10.7930/J0J1012N.

Robertson, D.M., and D.A. Saad, 2011: Nutrient inputs to the Laurentian Great Lakes by source and watershed estimated using SPARROW watershed models. *JAWRA*, **47**, 5, 1011–1033, doi:10.1111/j.1752-1688.2011.00574.x.

Robertson, D.M., D.A. Saad, D.E. Christiansen, and D.J. Lorenz, 2016, Simulated impacts of climate change on phosphorus loading to Lake Michigan. *J. Great Lakes Res.*, **42**, 536–548.

Scavia, D., and Coauthors, 2014: Assessing and addressing the re-eutrophication of Lake Erie: Central basin hypoxia. *J. Great Lakes Res.*, **40**, 226–246, doi:10.1016/j.jglr.2014.02.004.

Sharma, A., C. Wasko, and D.P. Lettenmaier, 2018: If precipitation extremes are increasing, why aren't floods? *Water Resour. Res.*, **54**, 8545–8551, https://doi.org/10.1029/2018WR023749.

Theiling, C.H., and J.T. Burant, 2013: Flood inundation mapping for integrated floodplain management: Upper Mississippi River system. *River Res. Appl.*, **29**, 961–78.

U.K. Met Office, n.d.: Water Cycle. Accessed on 4 March 2021, https://www.metoffice.gov.uk/weather/learn-about/met-office-for-schools/other-content/other-resources/water-cycle.

Um, M.J., M. Markus, D. Wuebbles, and Y. Kim, 2016: Projected variations in the regional clustering of precipitation stations around Chicago. *Clim. Res.*, **67**, 2, 151–163.

Um, M.J., Y. Kim, M. Markus, and D.J. Wuebbles, 2017: Modeling nonstationary extreme value distributions with nonlinear functions: an application using multiple CMIP5 precipitation projections for U.S. cities. *J. Hydrol.*, **552**, 396–406.

U.S. Environmental Protection Agency (EPA), 2015: CREAT Climate Scenarios Projection Map. Accessed 21 September 2020, https://www.arcgis.com/apps/MapSeries/index.html?appid=3805293158d54846a29f750d63c6890e.

USGCRP, 2018: Impacts, Risks, and Adaptation in the United States: Fourth National Climate Assessment, Volume II [Reidmiller, D.R., C.W. Avery, D.R. Easterling, K.E. Kunkel, K.L.M. Lewis, T.K. Maycock, and B.C. Stewart, Eds.]. U.S. Global Change Research Program, Washington, D.C., USA, 1515 pp., doi:10.7930/NCA4.2018.

U.S. Geological Survey (USGS), 2020: USGS Water Data for the USA. U.S. Department of the Interior, Washington, D.C., USA, Accessed 3 February 2021, https://waterdata.usgs.gov/nwis.

Whittemore, D.O., K.M. McGregor, and G.A. Marotz, 1989: Effects of variations in recharge on groundwater quality. *J. Hydrol.*, **106**, 1–2, 131–145, doi:10.1016/0022-1694(89)90170-4.

Winkler, J.A., R.W. Arritt, and S.C. Pryor, 2012: Climate projections for the Midwest: Availability, interpretation, and synthesis. In *US National Climate Assessment Midwest Technical Input Report* [J. Winkler, J. Andresen, J. Hatfield, D. Bidwell, and D. Brown (coordinators)]. Great Lakes Integrated Sciences and Assessment (GLISA) Center, http://glisa.umich.edu/media/files/NCA/MTIT_Future.pdf.

Winters, B.A., and Coauthors, 2015: Report for the Urban Flooding Awareness Act. Illinois Department of Natural Resources, Office of Water Resources, https://www.dnr.illinois.gov/WaterResources/Documents/Final_UFAA_Report.pdf.

Wu, Y., S. Liu, and O.I. Abdul-Aziz, 2012: Hydrological effects of the increased CO_2 and climate change in the Upper Mississippi River Basin using a modified SWAT. *Clim. Change* **110**, 3-4, 977–1003.

Wuebbles, D.J., and Coauthors, 2019: An Assessment of the Impacts of Climate Change on the Great Lakes. Environmental Law and Policy Center, 70 pp., www.elpc.org/glclimatechange/.

Chapter 4

Abendroth, L.J., F.E. Miguez, M.J. Castellano, P.R. Carter, C.D. Messina, P.M. Dixon, and J.L. Hatfield, 2021: Lengthening of maize maturity time is not a widespread climate change adaptation strategy in the U.S. Midwest. *Glob. Change Biol.*, https://doi.org/10.1111/gcb.15565.

Ainsworth, E.A., and S.P. Long, 2005: What have we learned from 15 years of free-air CO_2 enrichment (FACE)? A meta-analytic review of the responses of photosynthesis, canopy properties and plant production to rising CO_2. *New Phytol.*, **165**, 2, 351–372.

Ainsworth, E.A., C.R. Yendrek, J.A. Skoneczka, and S.P. Long, 2012: Accelerating yield potential in soybean: Potential targets for biotechnological improvement. *Plant Cell Environ.*, **35**, 1, 38–52.

Angel, J., and Coauthors, 2018: Midwest. In *Impacts, Risks, and Adaptation in the United States: Fourth National Climate Assessment, Volume II* [Reidmiller, D.R., C.W. Avery, D.R. Easterling, K.E. Kunkel, K.L.M. Lewis, T.K. Maycock, and B.C. Stewart, Eds.]. U.S. Global Change Research Program, Washington, D.C., USA, 872–940, doi:10.7930/NCA4.2018.CH21.

Aragon, P., and J.M. Lobo, 2012: Predicted effect of climate change on the invasibility and distribution of the western corn root-worm. *Agric. Forest Entomol.*, **14**, 13–18.

Assefa, Y., and Coauthors, 2016: Yield responses to planting density for US modern corn hybrids: A synthesis-analysis. *Crop Sci.*, **56**, 2802–2817, https://doi.org/10.2135/cropsci2016.04.0215.

Basche, A.D., and O.F. Edelson, 2017: Improving water resilience with more perennially based agriculture. *Agroecol. Sustain. Food Syst.*, **41**, 799–824, https://doi.org/10.1080/21683565.2017.1330795.

Bernabucci, U., L. Colavecchia, P.P. Danieli, L. Basiricò, N. Lacetera, A. Nardone, and B. Ronchi, 2011: Aflatoxin B1 and fumonisin B1 affect the oxidative status of bovine peripheral blood mononuclear cells. *Toxicol. In Vitro*, **25**, 684–691, https://doi.org/10.1016/j.tiv.2011.01.009.

Black, C.K., S.C. Davis, T.W. Hudiburg, C.J. Bernacchi, and E.H. DeLucia, 2017: Elevated CO_2 and temperature increase soil C losses from a soybean-maize ecosystem. *Glob. Change Biol.*, **23**, 1, 435–445.

Bowling, L.C., and Coauthors, 2020: Agricultural impacts of climate change in Indiana and potential adaptations. *Clim. Change*, **163**, 2005–2027, http://dx.doi.org/10.5703/1288284316778.

Burchfield, E., N. Matthews-Pennanen, J. Schoof, and C. Lant, 2020: Changing yields in the Central United States under climate and technological change. *Clim. Change*, **159**, 3, 329–346, https://doi.org/10.1007/s10584-019-02567-7.

Cavero, J., C. Zaragoza, M.L. Suso, and A. Pard, 1999: Competition between maize and *Datura stramonium* in an irrigated field under semi-arid conditions. *Weed Res.*, **39**, 225–240.

Chen, G., and R.R. Weil, 2011: Root growth and yield of maize as affected by soil compaction and cover crops. *Soil Tillage Res.*, **117**, 17–27, doi:10.1016/j.still.2011.08.001.

Coble, K.H., and B.J. Barnett, 2013: Why do we subsidize crop insurance? *Amer. J. of Ag. Econ.*, **95**, 498–504.

Condon, A.G., R.A. Richards, G.J. Rebetzke, and G.D. Farquhar, 2004: Breeding for high water-use efficiency. *J. Exp. Bot.*, **55**, 2447–2460.

Craine, J.M., A. Elmore, and J.P. Angerer, 2017: Long-term declines in dietary nutritional quality for North American cattle. *Environ. Res. Lett.*, **12**, 044019.

Dabney, S.M., J.A. Delgado, and D.W. Reeves, 2001: Using winter cover crops to improve soil and water quality. *Commun. Soil Sci. Plan.*, **32**, 1221–1250, http://dx.doi.org/10.1081/CSS-100104110.

Dantas-Torres, F., B.B. Chomel, and D. Otranto, 2012: Ticks and tick-borne diseases: A One Health perspective. *Trends Parasitol.*, **28**, 10, 437–446.

Davis, A.S., and E.A. Ainsworth, 2012: Weed interference with field-grown soyabean decreases under elevated [CO_2] in a FACE experiment. *Weed Res.*, **52**, 277–285.

Decision Innovation Solutions, 2015: 2015 Illinois Agriculture Economic Contribution Study. https://www.ilsoyadvisor.com/sites/default/files/documents/FINAL-2015-Illinois-agriculture-economic-contribution-study-lowres.pdf.

Dekker, J., 2004: Evolutionary biology of the foxtail (*Setaria*) species group. *Weed Biol. Manage.*, 65–113, https://doi.org/10.1007/978-94-017-0552-3_4.

Delgado, J.A., and Coauthors, 2011: Conservation practices to mitigate and adapt to climate change. *J. Soil Water Conserv.*, **66**, 118A–129A, doi:10.2489/jswc.66.4.188A.

DeLucia, E., and Coauthors, 2019: Are we approaching a water ceiling to maize yields in the United States? *Ecosphere*, **10**, 6, e02773.

Diffenbaugh, N.S., C.H. Krupke, M.A. White, and C.E. Alexander, 2008: Global warming presents new challenges for maize pest management. *Environ. Res. Lett.* **3**, 044007.

Diuk-Wasser, M.A., and Coauthors, 2012: Human risk of infection with *Borrelia burgdorferi*, the Lyme disease agent, in eastern United States. *Amer. J. Trop. Med. Hyg.*, **86**, 2, 320–327, https://doi.org/10.4269/ajtmh.2012.11-0395.

Douglas, M.R., and J.F. Tooker, 2012: Slug (Mollusca: Agriolimacidae, Arionidae) ecology and management in no-till field crops, with an emphasis on the mid-Atlantic region. *J. Integr. Pest Manage.*, **3**, 1, http://dx.doi.org/10.1603/IPM11023.

English-Loeb, G.M., 1990: Plant drought stress and outbreaks of spider mites: a field test. *Ecol.*, **71**, 1401–1411.

Estrada-Peña, A., N. Ayllón, and J. de la Fuente, 2012: Impact of climate trends on tick-borne pathogen transmission. *Front. Physiol*. **3**, 64, https://doi.org/10.3389/fphys.2012.00064.

Fargione, J., and Coauthors, 2018: Natural climate solutions for the United States. *Sci. Adv.*, **4**, 11, https://doi.org/10.1126/sciadv.aat1869.

Fennel, K., and J.M. Testa, 2019: Biogeochemical controls on coastal hypoxia. *Annu. Rev. Mar. Sci.*, **11**, 4.1-4.26, https://doi.org/10.1146/annurev-marine-010318-095138.

Fiener, P., and K. Auerswald, 2003: Effectiveness of grassed waterways in reducing runoff and sediment delivery from agricultural watersheds. *J. Environ. Qual.*, **32**, 927–936.

Finney, D.M., S.E. Eckert, and J.P. Kaye, 2016: Drivers of nitrogen dynamics in ecologically based agriculture revealed by long-term, high frequency field measurements. *Ecol. Appl*. **25**, 2210–2227, doi:10.1890/14-1357.1.

Ford, T., 2020: Climate Change & Agricultural Impacts in Illinois. *Farmdoc Daily*, **10**, 94, Department of Agricultural and Consumer Economics, University of Illinois at Urbana-Champaign, Accessed 26 February 2020, https://farmdocdaily.illinois.edu/2020/05/climate-change-agricultural-impacts-in-illinois.html.

Frank, H.K., 1991: Risk estimation for ochratoxin A in European countries. *IARC Sci. Publ.*, **115**, 321–325.

Gatewood, A.G., and Coauthors, 2009: Climate and tick seasonality predict *Borrelia burgdorferi* genotype distribution. *Appl. Environ. Microbiol.*, **75**, 8, 2476–2483.

Glauber, J.W., 2004: Crop insurance reconsidered. *Amer. J. Agric. Econ.*, **86**, 1179–1195.

Gordon, K., M. Lewis, J. Rogers, and F. Kinniburgh, 2015: Heat in the Heartland: Climate Change and Economic Risk in the Midwest. *Risky Business Project*, http://riskybusiness.org/uploads/files/RBP-Midwest-Report-WEB-1-26-15.pdf.

Gowda, P., J.L. Steiner, C. Olson, M. Boggess, T. Farrigan, and M.A. Grusak, 2018: Agriculture and Rural Communities. In *Impacts, Risks, and Adaptation in the United States: Fourth National Climate Assessment, Volume II* [Reidmiller, D.R., C.W. Avery, D.R. Easterling, K.E. Kunkel, K.L.M. Lewis, T.K. Maycock, and B.C. Stewart, Eds.]. U.S. Global Change Research Program, Washington, D.C., USA, 391–437, doi:10.7930/NCA4.2018.CH10.

Government Accountability Office (GAO), 2014: Better Management of Exposure to Potential Future Losses Is Needed for Federal Flood and Crop Insurance. GAO-15-28, Washington, D.C., https://www.gao.gov/products/GAO-15-28.

Gramig, B.M. and S.D. Yun., 2019: Economic Management and Climatic Challenges Posed by Days Suitable for Field Work in the US Corn Belt. Selected Paper, Agricultural and Applied Economics Association, Annual Meeting, Atlanta, GA, http://dx.doi.org/10.22004/ag.econ.291165.

Grassini, P., K.M. Eskridge, and K.G. Cassman, 2013: Distinguishing between yield advances and yield plateaus in historical crop production trends. *Nat. Commun.*, **4**, 2918, https://doi.org/10.1038/ncomms3918.

Gray, S.B., and S.M. Brady, 2016: Plant developmental responses to climate change. *Dev. Biol.*, **419**, 64–77.

Hatfield, J.L., and J.H. Prueger, 2004: Impacts of changing precipitation patterns on water quality. *J. Soil Water Conserv.*, **59**, 51–58.

Hatfield, J.L., K.J. Boote, A. Kimball, L.H. Ziska, R.C. Izaurralde, D. Ort, A.M. Thomson, and D. Wolfe, 2011: Climate Impacts on Agriculture: Implications for Crop Production. *Agron. J.*, **103**, 2, 351–370, https://doi.org/10.2134/agronj2010.0303.

Hatfield, J.L., R.M. Cruse, and M.D. Tomer, 2013: Convergence of agricultural intensification and climate change in the Midwestern United States: implications for soil and water conservation. *Mar. Freshwater Res.*, **64**, 423–435, http://dx.doi.org/10.1071/MF12164.

Hay, R.K.M., 1995: Harvest index: A review of its use in plant breeding and crop physiology. *Ann. Appl. Biol.*, **126**, 1, https://doi.org/10.1111/j.1744-7348.1995.tb05015.x.

Heap, I., 2014: Herbicide resistant weeds. *Integr. Pest Manage.*, 281–301, https://doi.org/10.1007/978-94-007-7796-5_12.

Heap, I., 2020: The International Herbicide-Resistant Weed Database. Accessed 28 December 2020, www.weedscience.org.

Henry, B., E. Charmley, R. Eckard, J.B. Gaughan, and R. Hegarty, 2012: Livestock production in a changing climate: adaptation and mitigation research in Australia. *Crop Pasture Sci.*, **63**, 3, 191–202.

Hoffman, A.L., A.R. Kemanian, and C.E. Forest, 2020: The response of maize, sorghum, and soybean yield to growing-phase climate revealed with machine learning. *Environ. Res. Lett.*, **15**, 9, https://doi.org/10.1088/1748-9326/ab7b22.

Hudson, B.D., 1994: Soil organic matter and available water capacity. *J. Soil Water Conserv*. **49**, 89–194.

Illinois Department of Agriculture (IDOA), n.d.: Facts about Illinois Agriculture. Accessed 1 December 2020, https://www2.illinois.gov/sites/agr/About/Pages/Facts-About-Illinois-Agriculture.aspx.

Intergovernmental Panel in Climate Change (IPCC), 2007: Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the IPCC, Cambridge University Press, Cambridge, UK.

Jha, M., J.G. Arnold, P.W. Gassman, F. Giorgi, and R.R. Gu, 2006: Climate change sensitivity assessment on Upper Mississippi River Basin streamflows using SWAT. *J. Amer. Water Resour. Assoc.*, **42**, 4, 997–1015.

Jin, Z., E.A. Ainsworth, A.D.B. Leakey, and D.B. Lobell, 2017: Increasing drought and diminishing benefits of elevated carbon dioxide for soybean yields across the US Midwest. *Glob. Change Biol.*, **24**, 2, 1–12, https://doi.org/10.1111/gcb.13946.

Jongejan, F. and G. Uilenberg, 2004: The global importance of ticks. *Parasitology*, **129**, S3–S14, doi:10.1017/S0031182004005967.

Kaye, J.P., and M. Quemada, 2017: Using cover crops to mitigate and adapt to climate change. A review. *Agron. Sustain. Dev.*, **37**, 4, doi: 10.1007/s13593-016-0410-x.

Krakauer, N.Y., 2018: Shifting hardiness zones: trends in annual minimum temperature. *Clim.*, **6**, 1, 15, https://doi.org/10.3390/cli6010015.

Leakey, A.D.B., C.J. Bernacchi, F.G. Dohleman, D.R. Ort, and S.P. Long, 2004: Will photosynthesis of maize (*Zea mays*) in the US Corn Belt increase in future [CO_2] rich atmospheres? An analysis of diurnal courses of CO_2 uptake under free-air concentration enrichment (FACE). *Glob. Change. Biol.*, **10**, 6, 951–962, https://doi.org/10.1111/j.1529-8817.2003.00767.x.

Leakey, A.D.B., M. Uribelarrea, E.A. Ainsworth, S.L. Naidu, A. Rogers, D.R. Ort, and S.P. Long, 2006: photosynthesis, productivity, and yield of maize are not affected by open-air elevation of CO_2 concentration in the absence of drought. *Plant Physiol*, **140**, 2, 779–790, https://doi.org/10.1104/pp.105.073957.

Leakey, A.D.B., E.A. Ainsworth, C.J. Bernacchi, A. Rogers, S.P. Long, and D.R. Ort, 2009: Elevated CO_2 effects on plant carbon, nitrogen, and water relations: six important lessons from FACE. *J. Exp. Bot.*, **60**, 10, 2859–2876, https://doi.org/10.1093/jxb/erp096.

Leakey, A.D.B., and J.A. Lau, 2012: Evolutionary context for understanding and manipulating plant responses to past, present and future atmospheric [CO_2]. *Philos. Trans. R. Soc. Lond. B. Biol. Sci.*, **367**, 613–629, doi:10.1098/rstb.2011.0248.

Léger, E., G. Vourc'h, L. Vial, C. Chevillon, and K.D. McKoy, 2013: Changing distributions of ticks: causes and consequences. *Exp. Appl. Acarol.*, **59**, 219–244, https://doi.org/10.1007/s10493-012-9615-0.

Lemke, A.M., K.G. Kirkham, T.T. Lindenbaum, M.E. Herbert, T.H. Tear, W.L. Perry, and J.R. Herkert, 2011: Evaluating agricultural best management practices in tile-drained subwatersheds of the Mackinaw River, Illinois. *J. Environ. Qual.*, **40**, 1215–1228, doi:10.2134/jeq2010.0119.

Li, Y., K. Guan, G. Schnitkey, E. DeLucia, and B. Peng, 2019: Excessive rainfall leads to maize yield loss of a comparable magnitude to extreme drought in the United States. *Glob. Change Biol.*, **25**, 7, 2325–2337.

Lin, T-S., Jain, A.K., and Kheshgi, H.S., 2021: Worldwide maize and soybean yield response to environmental and management factors over the 20th and 21st centuries, *J. Geophy. Res.: Biogeosci*. (submitted).

Loladze, I., 2014: Hidden shift of the ionome of plants exposed to elevated CO_2 depletes minerals at the base of human nutrition. *eLife*, **3**, 1–29, https://doi.org/10.7554/eLife.02245.001.

Long, S.P., E.A. Ainsworth, A. Rogers, and D.R. Ort, 2004: Rising atmospheric carbon dioxide: plants FACE the future. *Annu. Rev. Plant. Biol.*, **55**, 591–628, https://doi.org/10.1146/annurev.arplant.55.031903.141610.

Lorenz, A.J., T.J. Gustafson, J.G. Coors, and N. de Leon, 2010: Breeding maize for a bioeconomy: a literature survey examining harvest index and stover yield and their relationship to grain yield. *Crop Sci.*, **50**, 1, 1–12, https://doi.org/10.2135/cropsci2009.02.0086.

Medlock, J.M., and Coauthors, 2013: Driving forces for changes in geographical distribution of *Ixodes ricinus* ticks in Europe. *Parasites Vectors*, **6**, 1, https://doi.org/10.1186/1756-3305-6-1.

Miao, R., D. Hennessy, and H. Feng, 2016: The effects of crop insurance subsidies and sodsaver on land-use change. *J. Agric. Resour. Econ.*, **41**, 2, 247–265, http://www.jstor.org/stable/44131337.

Miao, R., M. Khanna, and H. Huang, 2016: Responsiveness of crop yield and acreage to prices and climate. *Amer. J. Agric. Econ.*, **98**, 1, 191–211, https://doi.org/10.1093/ajae/aav025.

Morgan, P.B., G.A. Bollero, R.L. Nelson, F.G. Dohleman, and S.P. Long, 2005: Smaller than predicted increase in aboveground net primary production and yield of field-grown soybean under fully open-air [CO_2] elevation. *Glob. Change. Biol.*, **11**, 10, 1856–1865, https://doi.org/10.1111/j.1365-2486.2005.001017.x.

Myers, S.S., and Coauthors, 2014: Increasing CO_2 threatens human nutrition. *Nature*, **510**, 7503, 139–42, https://doi.org/10.1038/nature13179.

Nardone, A., B. Ronchi, N. Lacetera, M.S. Ranieri, and U. Bernabucci, 2010: Effects of climate changes on animal production and sustainability of livestock systems. *Livestock Sci.*, **130**, 57–69.

National Agricultural Statistics Service (NASS), 2017a: 2017 Census of Agriculture: Specialty Crops Volume 2. United States Department of Agriculture, Washington, D.C., Accessed 23 February 2021, https://www.nass.usda.gov/Publications/AgCensus/2017/Online_Resources/Specialty_Crops/SCROPS.pdf.

National Agricultural Statistics Service (NASS), 2017b: Illinois Agricultural Statistics 2017 Annual Bulletin. United States Department of Agriculture, Washington, D.C..

National Agricultural Statistics Service (NASS), 2019a: Annual crop yields by county. United States Department of Agriculture, Washington, D.C., Accessed 2 December 2020, https://quickstats.nass.usda.gov/.

National Agricultural Statistics Service (NASS), 2019b: Cropland Data Layer 2019. United States Department of Agriculture, Washington, D.C., Accessed 2 December 2020, https://nassgeodata.gmu.edu/CropScape/.

National Agricultural Statistics Service (NASS), 2019c: Illinois Agricultural Statistics 2019 Annual Bulletin. United States Department of Agriculture, Washington, D.C.

National Research Council (NRC) Subcommittee on Environmental Stress, 1981: Effect of Environment on Nutrient Requirements of Domestic Animals. National Academy Press, Washington, D.C., ISBN-10:0-309-03181-8.

Ogden, N.H., S. Mechai, and G. Margos, 2013: Changing geographic ranges of ticks and tick-borne pathogens: drivers, mechanisms and consequences for pathogen diversity. *Front. Cell. Infect. Microbiol.*, **3**, 46, https://doi.org/10.3389/fcimb.2013.00046.

Ottman, M.J., and Coauthors, 2001: Elevated CO_2 increases sorghum biomass under drought conditions. *New Phytol.*, **150**, 2, 261–273, https://doi.org/10.1046/j.1469-8137.2001.00110.x.

Patterson, D.T., 1995: Weeds in a changing climate. *Weed Sci.*, **43**, 4, 685–701, http://www.jstor.org/stable/4045831.

Pimentel, D., L. Lach, R. Zuniga, and D. Morrison, 2000: Environmental and economic costs of nonindigenous species in the United States. *BioSci.*, **50**, 1, 53–65, https://doi.org/10.1641/0006-3568(2000)050[0053:EAECON]2.3.CO;2.

Rabalais, N.N., R.J. Diaz, L.A. Levin, R.E. Turner, D. Gilbert, and J. Zhang, 2010: Dynamics and distribution of natural and human-caused hypoxia. *Biogeosciences*, **7**, 585-619.

Ray, D.K., N.D. Mueller, P.C. West and J.A. Foley, 2013: Yield trends are insufficient to double global crop production by 2050. *PLoS One*, **8**, 6, e66428, https://doi.org/10.1371/journal.pone.0066428.

Reyes, J.J., and E. Elias, 2019: Spatio-temporal variation of crop loss in the United States from 2001 to 2016. *Environ. Res. Lett.*, **14**, 7, https://doi.org/10.1088/1748-9326/ab1ac9.

Reynolds, M., D. Bonnett, S.C. Chapman, R.T. Furbank, Y. Manès, D.E. Mather, and M.A.J. Parry, 2011: Raising yield potential of wheat. I. Overview of a consortium approach and breeding strategies. *J. Exp. Bot.*, **62**, 2, 439–452, https://doi.org/10.1093/jxb/erq311.

Riedell, W.E., and G.R. Sutter, 1995: Soil moisture and survival of western corn rootworm larvae in field plots. *J. Kansas Entomol. Soc.*, **68**, 1, 80–84, https://www.jstor.org/stable/25085563.

Rogers, A., Y. Gibon, M. Stitt, P.B. Morgan, C.J. Bernacchi, D.R. Ort, and S.P. Long, 2006: Increased C availability at elevated carbon dioxide concentration improves N assimilation in a legume. *Plant Cell Environ.*, **29**, 8, 1651–1658, https://doi.org/10.1111/j.1365-3040.2006.01549.x.

Rogers, A., E.A. Ainsworth, and A.D.B. Leakey, 2009: Will elevated carbon dioxide concentration amplify the benefits of nitrogen fixation in legumes? *Plant Physiol.*, **151**, 3, 1009–1016, https://doi.org/10.1104/pp.109.144113.

Ruiz-Vera, U.M., M. Siebers, S.B. Gray, D.W. Drag, D.M. Rosenthal, B.A. Kimball, D.R. Ort, and C.J. Bernacchi, 2013: Global warming can negate the expected CO_2 stimulation in photosynthesis and productivity for soybean grown in the Midwestern United States. *Plant Physiol.*, **162**, 1, 410–423, https://doi.org/10.1104/pp.112.211938.

Schlenker, W., and M.J. Roberts, 2009: Nonlinear temperature effects indicate severe damages to U.S. crop yields under climate change. *PNAS*, **106**, 37, 15594–15598, https://doi.org/10.1073/pnas.0906865106.

Schroeder, J.B., M.E. Gray, S.T. Ratcliffe, R.E. Estes, and S.P. Long, 2006: Effects of elevated CO_2 and O_3 on a variant of the western corn rootworm (Coleoptera: Chrysomelidae). *Environ. Entomol.*, **35**, 3, 637–644, https://doi.org/10.1603/0046-225X-35.3.637.

Schwartz, J., 2019: A Wet Year Causes Farm Woes Far Beyond the Floodplains. *The New York Times*, November 21, 2019, Accessed 1 December 2020, https://www.nytimes.com/2019/11/21/climate/farms-climate-change-crops.html.

Slattery, R.A., and D.R. Ort, 2019: Carbon assimilation in crops at high temperatures. *Plant Cell Environ.*, **42**, 2750–2758, https://doi.org/10.1111/pce.13572.

Song, Y., A.K. Jain, and G.F. McIsaac, 2013: Implementation of dynamic crop growth processes into a land surface model: evaluation of energy, water and carbon fluxes under corn and soybean rotation. *Biogeosciences*, **10**, 8039–8066, http://doi.org/10.5194/bg-10-8039-2013.

Stiers, J., 2017: Illinois: The Great Pumpkin State. Illinois Farm Bureau Partners, Accessed 12 February 2021, https://www.ilfbpartners.com/family/illinois-the-great-pumpkin-state/.

Thomey, M.L., R.A. Slattery, C.J. Bernacchi, I.H. Köhler, and D.R. Ort, 2019: Yield response of field-grown soybean exposed to heat waves under current and elevated [CO_2]. *Glob. Change Biol.*, **25**, 12, 4352–4368, https://doi.org/10.1111/gcb.14796.

Thornton, P.K., J. van de Steeg, A. Notenbaert, and M. Herrero, 2009: The impacts of climate change on livestock and livestock systems in developing countries: A review of what we know and what we need to know. *Agric. Syst.*, **101**, 3, 113–127, https://doi.org/10.1016/j.agsy.2009.05.002.

Todey, D., 2020: Record wetness and the impact on U.S. Midwest/Plains agriculture growing season 2019. In State of the Climate 2019: Regional Climates [Bissolli, P., C. Ganter, T. Li, A. Mekonnen, and A. Sánchez-Lugo, Eds.]. *Bull. Amer. Meteor. Soc.*, **101**, 8, S334–S335, https://doi.org/10.1175/2020BAMSStateoftheClimate_Chapter7.1.

Tubiello, F.N., J.F. Soussana, and S.M. Howden, 2007: Crop and pasture response to climate change. *PNAS*, **104**, 50, 19686–19690, https://doi.org/10.1073/pnas.0701728104.

Uilenberg, G., 1995: International collaborative research: significance of tick-borne hemoparasitic diseases to world animal health. *Vet. Parasitol.*, **57**, 1–3, 19–41, https://doi.org/10.1016/0304-4017(94)03107-8.

USDA Economic Research Service (UDSA-ERS), 2019: U.S. and State Farm Income and Wealth Statistics. Accessed 3 March 2021, https://www.ers.usda.gov/data-products/farm-income-and-wealth-statistics/.

Zavala, J.A., C.L. Casteel, E.H. Delucia, and M.R. Berenbaum, 2008: Anthropogenic increase in carbon dioxide compromises plant defense against invasive insects. *PNAS*, **105**, 13, 5129–5133, https://doi.org/10.1073/pnas.0800568105.

Zavala, J.A., L. Gog, and R. Giacometti, 2017: Anthropogenic increase in carbon dioxide modifies plant–insect interactions. *Ann. Appl. Biol.*, **170**, 68–77, https://doi.org/10.1111/aab.12319.

Zhou, W., and Coauthors, 2020: Connections between the hydrological cycle and crop yield in the rainfed U.S. Corn Belt. *J. Hydrol.*, **590**, 125398.

Ziska, L.H., 2001: Changes in competitive ability between a C_4 crop and a C_3 weed with elevated carbon dioxide. *Weed Sci.*, **49**, 622–627, https://doi.org/10.1614/0043-1745(2001)049[0622:CICABA]2.0.CO;2.

Ziska, L.H., and L.L. McConnell, 2016: Climate change, carbon dioxide, and pest biology: monitor, mitigate, manage. *J. Agric. Food Chem.*, **64**, 1, 6–12, https://doi.org/10.1021/jf506101h.

Chapter 5

Adalja, A.A., M. Watson, N. Bouri, K. Minton, R.C. Morhard, and E.S. Toner, 2014: Absorbing citywide patient surge during Hurricane Sandy: a case study in accommodating multiple hospital evacuations. *Ann. Emerg. Med.*, **64**, 1, 66–73.

Adrion, E.R., J. Aucott, K.W. Lemke, and J.P. Weiner, 2015: Health care costs, utilization and patterns of care following Lyme disease. *PLoS One*, **10**, 2, e0116767.

American Lung Association, 2020: State of the Air 2020. Accessed 1 February 2021, https://www.stateoftheair.org/assets/SOTA-2020.pdf.

Anenberg, S.C., K.R. Weinberger, H. Roman, J.E. Neumann, A. Crimmins, N. Fann, J. Martinich, and P.L. Kinney, 2017: Impacts of oak pollen on allergic asthma in the United States and potential influence of future climate change. *Geohealth*, **1**, 80–92.

Angel, J., and Coauthors, 2018: Midwest. In *Impacts, Risks, and Adaptation in the United States: Fourth National Climate Assessment, Volume II* [Reidmiller, D.R. C.W. Avery, D.R. Easterling, K.E. Kunkel, K.L.M. Lewis, T.K. Maycock, and B.C. Stewart, Eds.]. U.S. Global Change Research Program, Washington, D.C., USA, 872–940, doi:10.7930/NCA4.2018.CH21.

Auld, H., D. MacIver, and J. Klaassen, 2004: Heavy rainfall and waterborne disease outbreaks: the Walkerton example. *J. Toxicol. Environ. Health. A.*, **67**, 1879–1887.

Bell, M.D., J. Phelan, T.F. Blett, D. Landers, A.M. Nahlik, G. Van Houtven, C. Davis, C.M. Clark, and J. Hewitt, 2017: A framework to quantify the strength of ecological links between an environmental stressor and final ecosystem services. *Ecosphere*, **8**, e01806.

Berry, H.L., K. Bowen, and T. Kjellstrom, 2010: Climate change and mental health: a causal pathways framework. *Int. J. Public Health*, **55**, 123–132.

Berry, H.L., A. Hogan, S.P. Ng, and A. Parkinson, 2011a: Farmer health and adaptive capacity in the face of climate change and variability. Part 1: Health as a contributor to adaptive capacity and as an outcome from pressures coping with climate related adversities. *Int. J. Environ. Res. Public Health*, **8**, 10 4039–4054.

Berry, H.L., A. Hogan, J. Owen, D. Rickwood, and L. Fragar, 2011b: Climate change and farmers' mental health: risks and responses. *Asia Pac. J. Public Health*, **23**, 119S–132.

Brault, A.C., H.M. Savage, N.K. Duggal, R.J. Eisen, and J.E. Staples, 2018: Heartland virus epidemiology, vector association, and disease potential. *Viruses*, **10**, 9, 498.

Bruce Grey Owen Sound Health Unit, 2000: The Investigative Report of the Walkerton Outbreak of Waterborne Gastroenteritis, 1–58.

Burtis, J.C., R.S. Ostfeld, J.B. Yavitt, and T.J. Fahey, 2016: The relationship between soil arthropods and the overwinter survival of *Ixodes scapularis* (Acari: Ixodidae) under manipulated snow cover. *J. Med. Entomol.*, **53**, 225–229.

CDC, 2008: Nonfatal, unintentional, non-fire-related carbon monoxide exposures—United States, 2004–2006. *Morb. Mortal. Wkly. Rep.*, **57**, 896–899.

CDC, 2018a: Tickborne Diseases of the United States: A Reference Manual for Health Care Providers. Accessed 27 January 2021, https://www.cdc.gov/ticks/tickbornediseases/TickborneDiseases-P.pdf.

CDC, 2018b: Behavioral Risk Factor Surveillance System Asthma Prevalence Data. Accessed 27 January 2021, https://www.cdc.gov/asthma/brfss/2018/default.html.

CDC, 2018c: Ehrlichiosis. Accessed 27 January 2021, https://www.cdc.gov/ehrlichiosis/index.html.

CDC, 2018d: Tularemia. Accessed 27 January 2021, https://www.cdc.gov/tularemia/index.html.

CDC, 2018e: Summary Health Statistics: National Health Interview Survey, 2018. Accessed 27 January 2021, https://ftp.cdc.gov/pub/Health_Statistics/NCHS/NHIS/SHS/2018_SHS_Table_P-1.pdf.

CDC, 2019a: CDC's Building Resilience Against Climate Effects (BRACE) Framework. Accessed 27 January 2021, https://www.cdc.gov/climateandhealth/BRACE.htm.

CDC, 2019b: Other Spotted Fever Group Rickettsioses. Accessed 27 January 2021, https://www.cdc.gov/otherspottedfever/index.html.

CDC, 2019c: Extreme Heat. Accessed 27 January 2021, https://www.cdc.gov/disasters/extremeheat/index.html.

CDC, 2019d: Dengue. Accessed 2 February 2021, https://www.cdc.gov/dengue/transmission/index.html.

CDC NCEH, 2020: Preparing for the Regional Health Impacts of Climate Change in the United States. 36 pp.

Cecchi, L., G. D'Amato, and I. Annesi-Maesano, 2018: External exposome and allergic respiratory and skin diseases. *J. Allergy Clin. Immunol.*, **141**, 846–857.

Clark, C.G., and Coauthors, 2003: Characterization of waterborne outbreak-associated *Campylobacter jejuni*, Walkerton, Ontario. *Emerg. Infect. Dis.*, **9**, 1232-1241.

Clark, L.P., D.B. Millet, and J.D. Marshall, 2017: Changes in transportation related air pollution exposures by race-ethnicity and socioeconomic status: outdoor nitrogen dioxide in the United States in 2000 and 2010. *Environ. Health Perspect.*, **125**, 9, 097012.

Clayton, S., 2020: Climate anxiety: Psychological responses to climate change. *J. Anxiety Disord.*, **74**, 102263.

Clayton, S., C.M. Manning, K. Krygsman, and M. Speiser, 2017: Mental Health and Our Changing Climate: Impacts, Implications, and Guidance. Washington, D.C., American Psychological Association and ecoAmerica.

Cohen-Shacham, E., G. Walters, C. Janzen, and S. Maginnis (eds.), 2016: Nature-Based Solutions to Address Global Societal Challenges. IUCN, xiii + 97 pp.

Crimmins, A., and Coauthors Eds., 2016: The Impacts of Climate Change on Human Health in the United States: A Scientific Assessment. U.S. Global Change Research Program, Washington, D.C., 312 pp.

Curriero, F.C., J.A. Patz, J.B. Rose, and S. Lele, 2001: The association between extreme precipitation and waterborne disease outbreaks in the United States, 1948–1994. *Amer. J. Public Health*, **91**, 1194–1199.

D'Amato, G., C. Vitale, M. Lanza, A. Molino, and M. D'Amato, 2016: Climate change, air pollution, and allergic respiratory diseases: an update. *Curr. Opin. Allergy Clin. Immunol.*, **16**, 434–440.

D'Amato, G., and Coauthors, 2015: Meteorological conditions, climate change, new emerging factors, and asthma and related allergic disorders. A statement of the World Allergy Organization. *World Allergy Organ. J.*, **8**, 25.

Daley, W.R., L. Shireley, and R. Gilmore, 2001: A flood-related outbreak of carbon monoxide poisoning—Grand Forks, North Dakota. *J. Emerg. Med.*, **21**, 249–253.

Dodgen, L.K., W.R. Kelly, S.V. Panno, S.J. Taylor, D.L. Armstrong, K.N. Wiles, Y. Zhang, and W. Zheng, 2017: Characterizing pharmaceutical, personal care product, and hormone contamination in a karst aquifer of southwestern Illinois, USA, using water quality and stream flow parameters. *Sci. Total Environ.*, **578**, 281–289.

Dorevitch, S., A. Shrestha, S. DeFlorio-Barker, C. Breitenbach, and I. Heimler, 2017: Monitoring urban beaches with qPCR vs. culture measures of fecal indicator bacteria: Implications for public notification. *Environ. Health*, **16**, 45.

Dosa, D.M., N. Grossman, T. Wetle, and V. Mor, 2007: To evacuate or not to evacuate: lessons learned from Louisiana nursing home administrators following Hurricanes Katrina and Rita. *J. Amer. Med. Dir. Assoc.*, **8**, 142–149.

Du, W., G.J. FitzGerald, M. Clark, and X.Y. Hou, 2010: Health impacts of floods. *Prehosp. Disaster Med.*, **25**, 265–272.

Dura, G., T. Pandics, M. Kadar, K. Krisztalovics, Z. Kiss, J. Bodnar, A. Asztalos, and E. Papp, 2010: Environmental health aspects of drinking water-borne outbreak due to karst flooding: case study. *J. Water Health*, **8**, 513–520.

Ebi, K.L., T.J. Teisberg, L.S. Kalkstein, L. Robinson, and R. F. Weiher, 2004: Heat watch/warning systems save lives: estimated costs and benefits for Philadelphia 1995–98. *Bull. Amer. Meteor. Soc.*, **85**, 1067–1074.

Ebi, K.L., and Coauthors, 2018: Human Health. In *Impacts, Risks, and Adaptation in the United States: Fourth National Climate Assessment, Volume II* [Reidmiller, D.R. C.W. Avery, D.R. Easterling, K.E. Kunkel, K.L.M. Lewis, T.K. Maycock, and B.C. Stewart, Eds.]. U.S. Global Change Research Program, Washington, D.C., USA, 572–603, doi: 10.7930/NCA4.2018.CH14.

Emerson, J. B., P.B. Keady, T.E. Brewer, N. Clements, E.E. Morgan, J. Awerbuch, S.L. Miller, and N. Fierer, 2015: Impacts of flood damage on airborne bacteria and fungi in homes after the 2013 Colorado Front Range flood. *Environ. Sci. Technol.*, **49**, 2675–2684.

Evans, L., T.L. Milfont, and J. Lawrence, 2014: Considering local adaptation increases willingness to mitigate. *Global Environ. Change*, **25**, 69–75.

Flanagan, B.E., E.J. Hallisey, E. Adams, and A. Lavery, 2018: Measuring community vulnerability to natural and anthropogenic hazards: The Centers for Disease Control and Prevention's Social Vulnerability Index. *J. Environ. Health*, **80**, 34–36.

Flanagan, B.E., E.W. Gregory, E.J. Hallisey, J.L. Heitgerd, and B. Lewis, 2011: A Social Vulnerability Index for Disaster Management. *J. Homeland Secur. Emerg. Manage.*, **8**, 1.

Fong, T.T., L.S. Mansfield, D.L. Wilson, D.J. Schwab, S.L. Molloy, and J.B. Rose, 2007: Massive microbiological groundwater contamination associated with a waterborne outbreak in Lake Erie, South Bass Island, Ohio. *Environ. Health Perspect.*, **115**, 856–864.

Fritze, J.G., G.A. Blashki, S. Burke, and J. Wiseman, 2008: Hope, despair and transformation: Climate change and the promotion of mental health and wellbeing. *Int. J. Ment. Health Syst.*, **2**, 13.

Frumkin, H., J. Hess, G. Luber, J. Malilay, and M. McGeehin, 2008: Climate change: the public health response. *Amer. J. Public Health*, **98**, 435–445.

Gallup News Service, 2020: Nurses Continue to Rate Highest in Honesty, Ethics. Accessed 27 January 2021, https://news.gallup.com/poll/274673/nurses-continue-rate-highest-honesty-ethics.aspx.

Gasparrini, A., and Coauthors, 2015: Mortality risk attributable to high and low ambient temperature: a multicountry observational study. *Lancet*, **386**, 369–375.

Grossman, E., M. Hathaway, A. Khan, A. Sambanis, and S. Dorevitch, 2021: A web-based interactive map to promote health care facility flood preparedness. *J. Disaster Med. Public Health Preparedness*, 1–4, doi:10.1017/dmp.2020.482.

Guzman Herrador, B., and Coauthors, 2016: Association between heavy precipitation events and waterborne outbreaks in four Nordic countries, 1992–2012. *J. Water Health*, **14**, 1019–1027.

Hahn, M.B., A.J. Monaghan, M.H. Hayden, R.J. Eisen, M.J. Delorey, N.P. Lindsey, R.S. Nasci, and M. Fischer, 2015: Meteorological conditions associated with increased incidence of West Nile virus disease in the United States, 2004–2012. *Amer. J. Trop. Med. Hyg.*, **92**, 1013–1022.

Hayhoe, K., S.S. Sheridan, L.K. Kalkstein, and S. Greene, 2010: Climate change, heat waves, and mortality projections for Chicago. *J. Great Lakes Res.*, **36**, 65–73.

Hogan, A., A. Bode, and H. Berry, 2011: Farmer health and adaptive capacity in the face of climate change and variability. Part 2: Contexts, personal attributes and behaviors. *Int. J. Environ. Res. Public Health*, **8**, 4055–4068.

Howard, M., S. Ahmed, P. Lachapelle, and M. Schure, 2020: Farmer and rancher perceptions of climate change and their relationships with mental health. *J. Rural Mental Health*, **44**, 87–95.

Hughes, D.D., C.B.A. Mampage, L.M. Jones, Z. Liu, and E.A. Stone, 2020: Characterization of atmospheric pollen fragments during springtime thunderstorms. *Environ. Sci. Technol. Lett.*, **7**, 409–414.

Illinois Department of Public Health (IDPH), 2016: Healthy Illinois 2021: State Health Assessment. Accessed 27 January 2021, http://www.idph.state.il.us/ship/icc/documents/State-Health-Assessment-Final-091316.pdf.

Illinois Department of Public Health (IDPH), 2018a: Asthma Trends BRFSS 2011-2017. Accessed 27 January 2021, https://www.dph.illinois.gov/sites/default/files/publications/122018ohpmbrfsstrendscombined.pdf.

Illinois Department of Public Health (IDPH), 2018b: Rocky Mountain Spotted Fever Data. Accessed 27 January 2021, http://www.dph.illinois.gov/topics-services/diseases-and-conditions/diseases-a-z-list/rocky-mountain-spotted-fever/rocky-mountain-spotted-fever-data.

Illinois Department of Public Health (IDPH), 2018c: Lyme Disease Data. Accessed 27 January 2021, http://dph.illinois.gov/topics-services/diseases-and-conditions/diseases-a-z-list/lyme-disease/lyme-disease-data.

Iqbal, S., J.H. Clower, S.A. Hernandez, S.A. Damon, and F.Y. Yip, 2012: A review of disaster-related carbon monoxide poisoning: surveillance, epidemiology, and opportunities for prevention. *Amer. J. Public Health*, **102**, 1957–1963.

Issel, L.M., 2009: Health Program Planning and Evaluation: a Practical and Systematic Approach for Community Health. 2nd ed. Jones and Bartlett Publishers, 594 pp.

Jagai, J.S., E. Grossman, L. Navon, A. Sambanis, and S. Dorevitch, 2017: Hospitalizations for heat-stress illness varies between rural and urban areas: an analysis of Illinois data, 1987–2014. *Environ. Health*, **16**, 38.

Jagai, J.S., Q. Li, S. Wang, K.P. Messier, T.J. Wade, and E.D. Hilborn, 2015: Extreme Precipitation and Emergency Room Visits for Gastrointestinal Illness in Areas with and without Combined Sewer Systems: An Analysis of Massachusetts Data, 2003–2007. *Environ. Health Perspect.*, **123**, 873–879.

Kaizer, A.M., S.A. Fore, H.J. Kim, and E.C. York, 2015: Modeling the biotic and abiotic factors that describe the number of active off-host *Amblyomma americanum larvae*. *J. Vector Ecol.*, **40**, 1–10.

Kelman, J., K. Finne, A. Bogdanov, C. Worrall, G. Margolis, K. Rising, T.E. MaCurdy, and N. Lurie, 2015: Dialysis care and death following Hurricane Sandy. *Amer. J. Kidney Dis.*, **65**, 109–115.

Kenword, A., and U. Raja, 2014: Blackout: Extreme weather, climate change, and power outages. Climate Central, Accessed 27 January 2021, https://www.eenews.net/assets/2014/04/14/document_ew_01.pdf.

Kessler, R.C., S. Galea, M.J. Gruber, N.A. Sampson, R.J. Ursano, and S. Wessely, 2008: Trends in mental illness and suicidality after Hurricane Katrina. *Mol. Psychiatry*, **13**, 374–384.

Keyel, A.C., and Coauthors, 2019: Seasonal temperatures and hydrological conditions improve the prediction of West Nile virus infection rates in Culex mosquitoes and human case counts in New York and Connecticut. *PLoS One*, **14**, e0217854.

Kiwanuka-Tondo, J., and K. Pettiway, 2017: Localizing complex scientific communication: A SWOT and multi-sectoral analysis of communicating climate change. *Commun. Des. Q.*, **4**, 74–85.

Klinenberg, E., 2002: Heat Wave: A Social Autopsy of Disaster in Chicago. University of Chicago Press, 305 pp.

Knowlton, K., M. Rotkin-Ellman, L. Geballe, W. Max, and G.M. Solomon, 2011: Six climate change-related events in the United States accounted for about $14 billion in lost lives and health costs. *Health Aff.*, **30**, 11, 2167–2176.

Koval, W.T., and G.M. Vazquez-Prokopec, 2018: Environmental stochasticity and intraspecific competition influence the population dynamics of Culex quinquefasciatus (Diptera: Culicidae). *Parasit. Vectors*, **11**, 114.

Kraemer, M.U.G., and Coauthors, 2019: Past and future spread of the arbovirus vectors *Aedes aegypti* and *Aedes albopictus*. *Nat. Microbiol.*, **4**, 854–863.

Langer, J., A. Dufoe, and J. Brady, 2018: U.S. Faces a Rise in Mosquito 'Disease Danger Days'. Climate Central, Accessed 27 January 2021, http://assets.climatecentral.org/pdfs/August2018_CMN_Mosquitoes.pdf?pdf=Mosquitoes-Report.

Lauritsen, J.L., and N. White, 2014: Seasonal Patterns in Criminal Victimization Trends. U.S. Department of Justice, Bureau of Justice Statistics, Accessed 27 January 2021, https://www.bjs.gov/content/pub/pdf/spcvt.pdf.

Lay, C., and Coauthors, 2018: Emergency department visits and ambient temperature: Evaluating the conection and projecting future outcomes. *GeoHealth*, **2**, 182–194.

Lehnert, E.A., G. Wilt, B. Flanagan, and E. Haillisey, 2020: Spatial exploration of the CDC's Social Vulnerability Index and heat-related health outcomes in Georgia. *Int. J. Disaster Risk Reduct.*, **46**, 101517.

Limaye, V.S., W. Max, J. Constible, and K. Knowlton, 2019: Estimating the Health-Related Costs of 10 Climate-Sensitive U.S. Events During 2012. *Geohealth*, **3**, 245–265.

Liu, Y., S. Saha, B.O. Hoppe, and M. Convertino, 2019: Degrees and dollars - Health costs associated with suboptimal ambient temperature exposure. *Sci. Total Environ.*, **678**, 702–711.

MacKenzie, W.R., W.L. Schell, K.A. Blair, D.G. Addiss, D.E. Peterson, N.J. Hoxie, J.J. Kazmierczak, and J.P. Davis, 1995: Massive outbreak of waterborne cryptosporidium infection in Milwaukee, Wisconsin: recurrence of illness and risk of secondary transmission. *Clin. Infect. Dis.*, **21**, 57–62.

Marshall, K.A., and M.A. Gonzalez-Meler, 2016: Can ecosystem services be part of the solution to environmental justice? *Ecosyst. Serv.*, **22**, 202–203.

Martin-Latry, K., M.P. Goumy, P. Latry, C. Gabinski, B. Begaud, I. Faure, and H. Verdoux, 2007: Psychotropic drugs use and risk of heat-related hospitalisation. *Eur. Psychiatry*, **22**, 335–338.

McDonald, E., S.W. Martin, K. Landry, C.V. Gould, J. Lehman, M. Fischer, and N.P. Lindsey, 2019: West Nile virus and other domestic nationally notifiable arboviral diseases - United States, 2018. *Morb. Mortal. Wkly. Rep.*, **68**, 673–678.

Metzger, K.B., K. Ito, and T.D. Matte, 2010: Summer heat and mortality in New York City: how hot is too hot? *Environ. Health Perspect.*, **118**, 80–86.

Mohajerani, A., J. Bakaric, and T. Jeffrey-Bailey, 2017: The urban heat island effect, its causes, and mitigation, with reference to the thermal properties of asphalt concrete. *J. Environ. Manage.*, **197**, 522–538.

Mordecai, E.A., and Coauthors, 2013: Optimal temperature for malaria transmission is dramatically lower than previously predicted. *Ecol. Lett.*, **16**, 22–30.

Mordecai, E.A., and Coauthors, 2017: Detecting the impact of temperature on transmission of Zika, dengue, and chikungunya using mechanistic models. *PLoS Negl. Trop. Dis.*, **11**, e0005568.

Mudarri, D., and W.J. Fisk, 2007: Public health and economic impact of dampness and mold. *Indoor Air*, **17**, 226–235.

Murakami, N., H.B. Siktel, D. Lucido, J.F. Winchester, and N.B. Harbord, 2015: Disaster preparedness and awareness of patients on hemodialysis after Hurricane Sandy. *Clin. J. Amer. Soc. Nephrol.*, **10**, 1389–1396.

National Agricultural Statistics Service (NASS), 2019: Crop Progress. United States Department of Agriculture, Washington, D.C., Accessed 2 December 2020, https://www.nass.usda.gov/Publications/Todays_Reports/reports/prog2219.pdf.

National Alliance on Mental Illness (NAMI) Chicago, 2015: Making the Case for Funding and Supporting Comprehensive, Evidence-Based Mental Health Services in Illinois. Accessed 1 February 2021, https://www.namichicago.org/policy-reports.

Nawrocki, S.J., and W.A. Hawley, 1987: Estimation of the northern limits of distribution of *Aedes albopictus* in North America. *J. Amer. Mosq. Control Assoc.*, **3**, 314–317.

Neumann, J.E., and Coauthors, 2019: Estimates of present and future asthma emergency department visits associated with exposure to oak, birch, and grass pollen in the United States. *Geohealth*, **3**, 11–27.

NOAA National Centers for Environmental Information, 2020a: 1980–2020 Billion-Dollar Weather and Climate Disasters (CPI-Adjusted), Accessed 27 January 2021, https://www.ncdc.noaa.gov/billions/mapping.

NOAA National Centers for Environmental Information, 2020b: Billion-Dollar Weather and Climate Disasters: Time Series Illinois, Accessed 27 January 2021, https://www.ncdc.noaa.gov/billions/time-series/IL.

NOAA National Centers for Environmental Information, 2020c: Billion-Dollar Weather and Climate Disasters: Overview. Accessed 27 January 2021, https://www.ncdc.noaa.gov/billions/overview.

Ogden, N.H., R. Milka, C. Caminade, and P. Gachon, 2014: Recent and projected future climatic suitability of North America for the Asian tiger mosquito *Aedes albopictus*. *Parasit. Vectors*, **7**, 532.

Ogden, N.H., and Coauthors, 2006: Climate change and the potential for range expansion of the Lyme disease vector *Ixodes scapularis* in Canada. *Int. J. Parasitol.*, **36**, 63–70.

Paaijmans, K.P., A.F. Read, and M.B. Thomas, 2009: Understanding the link between malaria risk and climate. *PNAS*, **106**, 13844–13849.

Panno, S.V., W.R. Kelly, J. Scott, W. Zheng, R.E. McNeish, N. Holm, T.J. Hoellein, and E.L. Baranski, 2019: Microplastic contamination in karst groundwater systems. *Ground Water*, **57**, 189–196.

Parker, K., J.M. Horowitz, A. Brown, R. Fry, D. Cohn, and R. Igielnik, 2018: What Unites and Divides Urban, Suburban and Rural Communities. Pew Research Center, Accessed 1 February 2021, https://www.pewsocialtrends.org/2018/05/22/what-unites-and-divides-urban-suburban-and-rural-communities/.

Perdue, W.C., L.A. Stone, and L.O. Gostin, 2003: The built environment and its relationship to the public's health: the legal framework. *Amer. J. Public Health*, **93**, 1390–1394.

Peterson, C., A. Sussell, J. Li, P.K. Schumacher, K. Yeoman, and D.M. Stone, 2020: Suicide rates by industry and occupation - National Violent Death Reporting System, 32 states, 2016. *Morb. Mortal. Wkly. Rep*., **69**, 57–62.

Phillips, V.C., E.A. Zieman, C.H. Kim, C.M. Stone, H.C. Tuten, and F.A. Jimenez, 2020: Documentation of the expansion of the Gulf Coast tick (*Amblyomma maculatum*) and Rickettsia parkeri: first report in Illinois. *J. Parasitol*., **106**, 9-13.

Polivka, B.J., R.V. Chaudry, and J.M. Crawford, 2012: Public health nurses' knowledge and attitudes regarding climate change. *Environ. Health Perspect*., **120**, 321–325.

Poole, J.A., and Coauthors, 2019: Impact of weather and climate change with indoor and outdoor air quality in asthma: a work group report of the AAAAI Environmental Exposure and Respiratory Health Committee. *J. Allergy Clin. Immunol*., **143**, 1702-1710.

Ragettli, M.S., A.M. Vicedo-Cabrera, C. Schindler, and M. Roosli, 2017: Exploring the association between heat and mortality in Switzerland between 1995 and 2013. *Environ. Res*., **158**, 703–709.

Raker, E.J., S.R. Lowe, M.C. Arcaya, S.T. Johnson, J. Rhodes, and M.C. Waters, 2019: Twelve years later: The long-term mental health consequences of Hurricane Katrina. *Soc. Sci. Med.*, **242**, 112610.

Rando, R.J., C.W. Kwon, and J.J. Lefante, 2014: Exposures to thoracic particulate matter, endotoxin, and glucan during post-Hurricane Katrina restoration work, New Orleans 2005–2012. *J. Occup. Environ. Hyg.*, **11**, 9–18.

Rando, R.J., J.J. Lefante, L.M. Freyder, and R.N. Jones, 2012: Respiratory health effects associated with restoration work in post-Hurricane Katrina New Orleans. *J. Environ. Public Health*, **2012**, 462478.

Rudolph, L., C. Harrison, L. Buckley, and S. North, 2018: Climate Change, Health, and Equity: A Guide for Local Health Departments. Public Health Institute, Accessed 1 February 2021 https://www.apha.org/topics-and-issues/climate-change/guide.

Salvadori, M.I., J.M. Sontrop, A.X. Garg, L.M. Moist, R.S. Suri, and W.F. Clark, 2009: Factors that led to the Walkerton tragedy. *Kidney Int. Suppl*., S33–34.

Schinasi, L.H., and G.B. Hamra, 2017: A time series analysis of associations between daily temperature and crime events in Philadelphia, Pennsylvania. *J. Urban Health*, **94**, 892–900.

Schroth, O., J. Angel, S. Sheppard, and A. Dulic, 2014: Visual climate change communication: From iconography to locally framed 3D visualization. *Environ. Commun*., **8**, 413–432.

Schwartz, A.M., M.B. Shankar, K.J. Kugeler, R.J. Max, A.F. Hinckley, M.I. Meltzer, and C.A. Nelson, 2020: Epidemiology and cost of Lyme disease-related hospitalizations among patients with employer-sponsored health insurance—United States, 2005–2014. *Zoonoses Public Health*, **67**, 407–415.

Shand, L., and Coauthors, 2016: Predicting West Nile virus infection risk from the synergistic effects of rainfall and temperature. *J. Med. Entomol*., **53**, 935–944.

Sheppard, S., A. Shaw, D. Flanders, S. Burch, A. Wiek, J. Carmichael, J. Robinson, and S. Cohen, 2011: Future visioning of local climate change: A framework for community engagement and planning with scenarios and visualisation. *Futures*, **43**, 400–412.

Shonkoff, S.B., R. Morello-Frosch, M. Pastor, and J. Sadd, 2011: Environmental health and equity impacts from climate change and mitigation policies in California: a review of the literature. *Clim. Change*, **109**, 485–503.

Shrestha, A., C.A. Kelty, M. Sivaganesan, O.C. Shanks, and S. Dorevitch, 2020: Fecal pollution source characterization at non-point source impacted beaches under dry and wet weather conditions. *Water Res.*, **182**, 116014.

Smith, A.B., and R.W. Katz, 2013: US billion-dollar weather and climate disasters: data sources, trends, accuracy and biases. *Natural Hazards*, **67**, 387–410.

Smith, K.R., and Coauthors, 2014: Human health: impacts, adaptation, and co-benefits. In *Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part A: Global and Sectoral Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*, [Field, C.B., V.R. Barros, D.J. Dokken, K.J. Mach, M.D. Mastrandrea, T.E. Bilir, M. Chatterjee, K.L. Ebi, Y.O. Estrada, R.C. Genova, B. Girma, E.S. Kissel, A.N. Levy, S. MacCracken, P.R. Mastrandrea, and L.L. White, Eds.]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 709–754.

Sonenshine, D.E., 2018: Range expansion of tick disease vectors in North America: implications for spread of tick-borne disease. *Int. J. Environ. Res. Public Health*, **15**, 3, 478.

Stone, C.M., Z. Zuo, B. Li, M. Ruiz, J. Swanson, J. Hunt, C.H. Kim., and R.L. Smith, 2020: Spatial, temporal, and genetic invasion dynamics of *Aedes albopictus* (Diptera: Culicidae) in Illinois. *J. Med. Entomol.*, **57**, 1488–1500.

Teperman, S., 2013: Hurricane Sandy and the greater New York health care system. *J. Trauma Acute Care Surg.*, **74**, 1401–1410.

Texas Hospital Association, 2017: Texas Hospital Association Hurricane Harvey Analysis: Texas Hospital's Preparation Strategies and Priorities for Future Disaster Response. Accessed 2 February 2021, https://www.tha.org/harvey.

Thomas, K.M., D.F. Charron, D. Waltner-Toews, C. Schuster, A.R. Maarouf, and J.D. Holt, 2006: A role of high impact weather events in waterborne disease outbreaks in Canada, 1975–2001. *Int. J. Environ. Health Res.*, **16**, 167–180.

Tuten, H.C., and Coauthors, 2020: Heartland virus in humans and ticks, Illinois, USA, 2018–2019. *Emerg. Infect. Dis.*, **26**, 1548–1552.

U.S. Department of Agriculture Economic Research Service (USDA ERS), 2018: Rural America at a Glance 2018 Edition. Economic Information Bulletin 200.

U.S. Environmental Protection Agency (EPA), 2017: Multi-Model Framework for Quantitative Sectoral Impacts Analysis: A Technical Report for the Fourth National Climate Assessment. Accessed 27 January 2021, https://cfpub.epa.gov/si/si_public_record_Report.cfm?Lab=OAP&dirEntryId=335095.

U.S. Environmental Protection Agency (EPA), 2020a: Heat Island Effect. Accessed 27 Janaury 2021, https://www.epa.gov/heatislands.

U.S. Environmental Protection Agency (EPA), 2020b: Ground-level Ozone Pollution. Accessed 27 Janaury 2021, https://www.epa.gov/ground-level-ozone-pollution/ground-level-ozone-basics#formation.

USGCRP, 2018: Impacts, Risks, and Adaptation in the United States: Fourth National Climate Assessment, Volume II [Reidmiller, D.R., C.W. Avery, D.R. Easterling, K.E. Kunkel, K.L.M. Lewis, T.K. Maycock, and B.C. Stewart, Eds.]. U.S. Global Change Research Program, Washington, D.C., USA, 1515 pp., doi:10.7930/NCA4.2018.

Vaidyanathan, A., J. Malilay, P. Schramm, and S. Saha, 2020: Heat-related deaths—United States, 2004–2018. *Morb. Mortal. Wkly. Rep.*, 729–734.

Vaithyanathan, V.K., S. Ravi, R. Leduc, V.K. Vaidyanathan, and H. Cabana, 2020: Utilization of biosolids for glucose oxidase production: A potential bio-fenton reagent for advanced oxidation process for removal of pharmaceutically active compounds. *J. Environ. Manage.*, **271**, 110995.

Valdez, L.D., G.J. Sibona, L.A. Diaz, M.S. Contigiani, and C.A. Condat, 2017: Effects of rainfall on *Culex* mosquito population dynamics. *J. Theor. Biol.*, **421**, 28–38.

Villella, C., 2011: Climate change: what do doctors think? What can doctors do?: An international survey of general practitioners, Medicine, Dentistry & Health Sciences, General Practice. The University of Melbourne.

Watts, N., and Coauthors, 2019: The 2019 report of *The Lancet* Countdown on health and climate change: ensuring that the health of a child born today is not defined by a changing climate. *Lancet*, **394**, 1836–1878.

Wellenius, G.A., M.N. Eliot, K.F. Bush, D. Holt, R.A. Lincoln, A.E. Smith, and J. Gold, 2017: Heat-related morbidity and mortality in New England: evidence for local policy. *Environ. Res. Lett.*, **156**, 845–853.

Whitman, S., G. Good, E.R. Donoghue, N. Benbow, W. Shou, and S. Mou, 1997: Mortality in Chicago attributed to the July 1995 heat wave. *Amer. J. Public Health*, **87**, 1515–1518.

Wolkin, A., J.R. Patterson, S. Harris, E. Soler, S. Burrer, M. McGeehin, and S. Greene, 2015: Reducing public health risk during disasters: identifying social vulnerabilities. *J. Homeland Secur. Emerg. Manag.*, **12**, 809–822.

Yale, J.D., T.B. Cole, H.G. Garrison, C.W. Runyan, and J.K. Ruback, 2003: Motor vehicle–related drowning deaths associated with inland flooding after hurricane Floyd: a field investigation. *Traffic Inj. Prev.*, **4**, 279–284.

Yale Program on Climate Change Communication, 2020: Yale Climate Opinion Maps 2020. Accessed 27 January 2021, https://climatecommunication.yale.edu/visualizations-data/ycom-us/.

Younger, M., H.R. Morrow-Almeida, S.M. Vindigni, and A.L. Dannenberg, 2008: The built environment, climate change, and health: opportunities for co-benefits. *Amer. J. Prev. Med.*, **35**, 517–526.

Zhang, H., Y.J. Jiang, Y.Z. Zhang, Y.F. Duan, X.F. Lü, and Q.F. He, 2016: Tracing the fecal contamination sources based on Bacteroides 16S rRNA PCR-DGGE in karst groundwater: taking Laolongdong underground river system, Nanshan, Chongqing as an example. *Huan Jing Ke Xue*, **37**, 1805–1813.

Zhang, J.J., Y. Wei, and Z. Fang, 2019: Ozone pollution: a major health hazard worldwide. *Front. Immunol.*, **10**, 2518.

Ziska, L., and Coauthors, 2011: Recent warming by latitude associated with increased length of ragweed pollen season in central North America. *PNAS*, **108**, 4248–4251.

Chapter 6

Alsip, P.J., H. Zhang, M.D. Rowe, E. Rutherford, D.M. Mason, C. Riseng, and Z. Su, 2020: Modeling the interactive effects of nutrient loads, meteorology, and invasive mussels on suitable habitat for Bighead and Silver Carp in Lake Michigan. *Biol. Invasions*, **22**, 2769–2785, https://doi.org/10.1007/s10530-020-02296-4.

Anderson, R.C., 1970: Prairies in the Prairie State. *Trans. Ill. State Acad. Sci.*, **63**, 214–221.

Anderson, R.C., 1991: Illinois Prairies: A Historical Perspective. *Our Living Heritage: The Biological Resources of Illinois*, L.M. Page and M.R. Jeffords, Eds., Illinois Natural History Survey Bulletin, **34**, 4, 384–391.

Bailey, R.G., 1980: Description of the Ecoregions of the United States. USDA Forest Service, Miscellaneous Publication 1391, Washington, D.C., 77 pp.

Beletsky, D., and D. Schwab, 2001: Modeling circulation and thermal structure in Lake Michigan: annual cycle and interannual variability. *J. Geophys. Res.*, **106**, 19,745–19,771, https://doi.org/10.1029/2000JC000691.

Breeggemann, J.J., and Coauthors, 2016: Potential direct and indirect effects of climate change on a shallow natural lake fish assemblage. *Ecol. Freshwater Fish*, **25**, 3, 487–499, https://doi.org/10.1111/eff.12248.

Breshears, D.D., and Coauthors, 2005: Regional vegetation die-off in response to global-change-type drought. *PNAS*, **102**, 15144–48, https://doi.org/10.1073/pnas.0505734102.

Bunn, S.E., and A.H. Arthington, 2002: Basic principles and ecological consequences of altered flow regimes for aquatic biodiversity. *Environ. Manage.*, **30**, 4, 492–507.

Burr, B.M., and L.M. Page, 2009: Illinois Fish Communities: More Than a Century of Change. *Canaries in the Catbird Seat: The Past, Present, and Future of Biological Resources in a Changing Environment*, C.A. Taylor, J.B. Taft, and C.E. Warwick, Eds., Illinois Natural History Survey Special Publication, **30**, 147–162.

Collingsworth, P.D., and Coauthors, 2017: Climate change as a long-term stressor for the fisheries of the Laurentian Great Lakes of North America. *Rev. Fish Biol. Fish.*, **27**, 363–391, https://doi.org/10.1007/s11160-017-9480-3.

Dahl, T.E., 1990: Wetland losses in the United States 1780's to 1980's. United States Department of the Interior, Fish and Wildlife Service, Washington, D.C., USA, 13 pp.

DeWalt, R.E., C.A. Taylor, J.S. Tiemann, and K.S. Cummings, 2009: Aquatic macroinvertebrate assemblages in Illinois: Diversity, changes, and prospectus for the future. *Canaries in the Catbird Seat: The Past, Present, and Future of Biological Resources in a Changing Environment*, C.A. Taylor, J.B. Taft, and C.E. Warwick, Eds., Illinois Natural History Survey Special Publication, **30**, 163–175.

DuFour, M.R. and Coauthors, 2015: Portfolio theory as a management tool to guide conservation and restoration of multi-stock fish populations. *Ecosphere*, **6**, 296, https://doi.org/10.1890/ES15-00237.1.

Dukes, J.S., and H.A. Mooney, 1999: Does global change increase the success of biological invaders? *Trends Ecol. Evol*., **14**, 135–39, https://doi.org/10.1016/S0169-5347(98)01554-7.

Fichot, C.G., K. Matsumoto, B. Holt, M.M. Gierach, K.S. Tokos, 2019: Assessing change in the overturning behavior of the Laurentian Great Lakes using remotely sensed lake surface water temperatures. *Remote Sens. Environ.*, **235**, 111427, https://doi.org/10.1016/j.rse.2019.111427.

Garris, H.W., R.J. Mitchell, L.H. Fraser, and L.R. Barrett, 2015: Forecasting climate change impacts of the distribution of wetland habitat in the Midwestern United States. *Global Change Biol.*, **21**, 766–776.

Gebauer, R.L.E., and J.R. Ehleringer, 2000: Water and nitrogen uptake patterns following moisture pulses in a cold desert community. *Ecol.*, **81**, 1415–24, https://doi.org/10.1890/0012-9658(2000)081[1415:WANUPF]2.0.CO;2.

Gieisztowt, J., A.T. Classen, and J.R. Deslippe, 2020: Climate change and invasion may synergistically affect native plant reproduction. *Ecol.*, **101**, 15–19, http://doi.org/10.1002/ecy.2913.

Hansen, G.J.A., J.S. Read, J.F. Hansen, and L.A. Winslow, 2017: Projected shifts in fish species dominance in Wisconsin lakes under climate change. *Global Change Biol.*, **23**, 4, 1463–1476, https://doi.org/10.1111/gcb.13462.

Hey, D.L., and N.S. Philippi, 1995: Flood reduction through wetland restoration: The Upper Mississippi River Basin as a case history. *Restor. Ecol*., **3**, 4–17.

Höök T.O, P. Collingsworth, L. Dorworth, B. Fisher, C. Foley, J.F. Hoverman, E. LaRue, M. Pyron, and J. Tank, 2020: An assessment of the potential impacts of climate change on the freshwater habitats and biota of Indiana, USA. *Clim. Change*, **163**, 1897–1916, https://doi.org/10.1007/s10584-019-02502-w.

Hoover, J.P., and W.M. Schelsky, 2020: Warmer April temperatures on breeding grounds promote earlier nesting in a long-distance migratory bird, the Prothonotary Warbler. *Front. Ecol. Evol*., **8**, 427.

Illinois Department of Natural Resources (IDNR), 2008: Illinois Natural Heritage Database, Accessed 15 August 2008, https://www2.illinois.gov/dnr/conservation/NaturalHeritage/Pages/NaturalHeritageDatabase.aspx.

Iverson, L.R., 1988: Land-use changes in Illinois, USA: The influence of landscape attributes on current and historic land use. *Landscape Ecol*., **2**, 45–61.

Iverson, L.R., M.P. Peters, A.M. Prasad, and S.N. Matthews, 2019a: Analysis of climate change impacts on tree species of the Eastern US: Results of DISTRIB-II modeling. *Forests*, **10**, 4, 302, https://doi.org/10.3390/f10040302.

Iverson, L.R., A.M. Prasad, M.P. Peters, and S.N. Matthews, 2019b: Facilitating adaptive forest management under climate change: a spatially specific synthesis of 125 species for habitat changes and assisted migration over the Eastern United States. *Forests*, **10**, 11, 989, doi.org/10.3390/f10110989.

Jacobs, G.R., C.P. Madenjian, D.B. Bunnell, D.M. Warner, and R.M. Claramunt, 2013: Chinook salmon foraging patterns in a changing Lake Michigan. *Trans. Amer. Fish. Soc.*, **142**, 362–372, https://doi.org/10.1080/00028487.2012.739981.

Johnson, W.C., B.V. Millett, T. Gilmanov, R. A. Voldseth, G.R. Guntenspergen, and D.E. Naugle, 2005: Vulnerability of northern prairie wetlands to climate change. *BioSci*., **55**, 863–872.

Junk, W.J., S. An, C.M. Finlayson, B. Gopal, J. Květ, S.A. Mitchell, W.J. Mitsch, and R.D. Roberts, 2013: Current state of knowledge regarding the world's wetlands and their future under global climate change: a synthesis. *Aquat. Sci*., **75**, 151–167.

Kao, Y., C.P. Madenjian, D.B. Bunnell, B.M. Lofgren, and M. Perroud, 2015: Potential effects of climate change on the growth of fishes from different thermal guilds in Lakes Michigan and Huron. *J. Great Lakes Res*., **41**, 423–435, https://doi.org/10.1016/j.jglr.2015.03.012.

Kaur, M., F. Atif, M. Ali, H. Rehman, and S. Raisuddin, 2005: Heat stress-induced alterations of antioxidants in the freshwater fish *Channa punctata* Bloch. *J. Fish Biol*., **67**, 6, 1653–1665, https://doi.org/10.1111/j.1095-8649.2005.00872.x.

King, J.E., 1981: Late-quaternary vegetational history of Illinois. *Ecol. Monogr.*, **51**, 43–62, https://doi.org/10.2307/2937306.

Knapp, A.K., and Coauthors, 2008: Consequences of more extreme precipitation regimes for terrestrial ecosystems. *BioSci*., **58**, 811–21, https://doi.org/10.1641/B580908.

Larson, G., and R. Schaetzl, 2001: Origin and evolution of the Great Lakes. *J. Great Lakes Res*., 27, 518–546, https://doi.org/10.1016/S0380-1330(01)70665-X.

Lin, D., J. Xia, and S. Wan, 2010: Climate warming and biomass accumulation of terrestrial plants: a meta-analysis. *New Phytol*., **188**, 187–98, https://doi.org/10.1111/j.1469-8137.2010.03347.x.

Lyons, J., A.L. Rypel, P.W. Rasmussen, T.E. Burzynski, B.T. Eggold, J.T. Myers, T.J. Paoli, and P.B. McIntyre, 2015: Trends in the reproductive phenology of two Great Lakes fishes. *Trans. Amer. Fish. Soc.*, **144**, 1263–1274, https://doi.org/10.1080/00028487.2015.1082502.

Madenjian, C.P., and Coauthors, 2002: Dynamics of the Lake Michigan food web, 1970–2000. *Can. J. Fish. Aquat. Sci.*, **59**, 736–753, https://doi.org/10.1139/f02-044.

Mitsch, W.J., J.W. Day, J.W. Gilliam, P.M. Groffman, D.L. Hey, G.W. Randall, and N. Wang, 2001: Reducing nitrogen loading to the Gulf of Mexico from the Mississippi River Basin: strategies to counter a persistent ecological problem. *BioSci*., **51**, 373-388.

Mohseni, O., H.G. Stefan, and J.G. Eaton, 2003: Global warming and potential changes in fish habitat in US streams. *Clim. Change*, **59**, 3, 389–409.

Morgan, J.A., D.G. Milchunas, D.R. LeCain, M. West, and A.R. Mosier, 2007: carbon dioxide enrichment alters plant community structure and accelerates shrub growth in the shortgrass steppe. *PNAS*, **104**, 14724–29, https://doi.org/10.1073/pnas.0703427104.

Moore, M.V., and Coauthors, 1997: Potential effects of climate change on freshwater ecosystems of the New England/Mid-Atlantic region. *Hydrol. Processes*, **11**, 925–947.

National Agricultural Statistics Service (NASS), 2019: Cropland Data Layer 2019. United States Department of Agriculture, Washington, D.C., Accessed 2 January 2021, https://nassgeodata.gmu.edu/CropScape/.

NOAA Great Lakes Environmental Research Laboratory (NOAA-GLERL), 2020: Great Lakes Ice Cover Database, Accessed 1 February 2021, https://www.glerl.noaa.gov/data/ice/#historical.

Noss, R., and E.T. Laroe, 1996: Endangered ecosystems of the United States: a preliminary assessment of loss and degradation. *Ecol. Restor*., **14**, https://doi.org/10.3368/er.14.1.95.

Parker, J., J. Epifanio, A. Casper, and Y. Cao, 2015: The effects of improved water quality on fish assemblages in a heavily modified large river system. *River Res. Appl*., **32**, 992–1007.

Pechony, O., and D.T. Shindell, 2010: Driving forces of global wildfires over the past millennium and the forthcoming century. *PNAS*, **107**, 19167–70, https://doi.org/10.1073/pnas.1003669107.

Peters, M.P., L.R. Iverson, A.M. Prasad, and S.N. Matthews, 2019: Utilizing the density of inventory samples to define a hybrid lattice for species distribution models: DISTRIB-II for 135 eastern U.S. trees. *Ecol. Evol*., **9**, 15, 8876–8899, https://doi.org/10.1002/ece3.5445.

Peterson, B.C., and B.C. Small, 2005: Effects of exogenous cortisol on the GH/IGF-I/IGFBP network in channel catfish. *Domest. Anim. Endocrinol*., **28**, 4, 391–404, https://doi.org/10.1016/j.domaniend.2005.01.003.

Plumb, J.M. and C.M. Moffitt, 2015: Re-estimating temperature-dependent consumption parameters in bioenergetics models for juvenile Chinook salmon. *Trans. Amer. Fish. Soc*., **144**, 323–330, https://doi.org/10.1080/00028487.2014.986336.

Poff, N.L., and J.D. Allan, 1995: Functional organization of stream fish assemblages in relation to hydrological variability. *Ecol*., **76**, 2, 606–627.

Potter, B.A., R.J. Gates, G.J. Soulliere, R.P. Russel, D.A. Granfors, and D.N. Ewert, 2007: Upper Mississippi River and Great Lakes region joint venture shorebird habitat conservation strategy. United States Fish and Wildlife Service, Fort Snelling, MN, 101 pp.

Prasad, A.M., L.R. Iverson, S.N. Matthews, and M.P. Peters, 2016: A multistage decision support framework to guide tree species management under climate change via habitat suitability and colonization models, and a knowledge-based scoring system. *Landscape Ecol*., **31**, 2187–2204, doi:10.1007/s10980-016-0369-7.

Ratajczak, Z., J.B. Nippert, and S.L. Collins, 2012: Woody encroachment decreases diversity across North American grasslands and savannas. *Ecol*., **93**, 697–703, https://doi.org/10.1890/11-1199.1.

Rogers, M.W., D.B. Bunnell, C.P. Madenjian, and D.M. Warner, 2014: Lake Michigan offshore ecosystem structure and food web changes from 1987 to 2008. *Can. J. Fish. Aquat. Sci.*, **71**, 1–15, https://doi.org/10.1139/cjfas-2013-0514.

Rowe, M.D., E.J. Anderson, H.A. Vanderploeg, S.A. Pothoven, A.K. Elgin, J.Wang, and F. Yousef, 2017: Influence of invasive quagga mussels, phosphorus loads, and climate on spatial and temporal patterns of productivity in Lake Michigan: A biophysical modeling study. *Limnol. Oceanogr.*, **62**, 2629–2649, https://doi.org/10.1002/lno.10595.

Sherry, R.A., E. Weng, J.A. Arnone III, D.W. Johnson, D.S. Schimel, P.S. Verburg, L.L. Wallace, and Y. Luo, 2008: Lagged effects of experimental warming and doubled precipitation on annual and seasonal aboveground biomass production in a tallgrass prairie. *Glob. Change Biol.*, **14**, 2923–36, https://doi.org/10.1111/j.1365-2486.2008.01703.x.

Smith, S.D.P., and Coauthors, 2019: Evidence for interactions among environmental stressors in the Laurentian Great Lakes. *Ecol. Indic.*, **101**, 203–211, https://doi.org/10.1016/j.ecolind.2019.01.010.

Soons, M.B., A.L. Brochet, E. Kleyheeg, and A.J. Green, 2016: Seed dispersal by dabbling ducks: an overlooked dispersal pathway for a broad spectrum of plant species. *J. Ecol*., **104**, 443–455.

Spyreas, G., J. Ellis, C. Carroll, and B. Molano-Flores, 2004. Non-native plant commonness and dominance in the forests, wetlands and grasslands of Illinois, USA. *Nat. Areas J.*, **24**, 4, 290–299.

Taft, J.B., R.C. Anderson, and L.R. Iverson, 2009: Vegetation ecology and change in terrestrial ecosystems. *Canaries in the Catbird Seat: The Past, Present, and Future of Biological Resources in a Changing Environment*, C.A. Taylor, J.B. Taft, and C. Warwick, Eds., Illinois Natural History Survey Special Publication, **30**, 35–72.

U.S. Forest Service (USFS), 2019: Forest Inventory and Analysis Database: Illinois. Accessed 20 October 2020, https://apps.fs.usda.gov/fia/datamart/datamart_excel.html.

U.S. Environmental Protection Agency (EPA), 2016: National Wetland Condition Assessment: Technical report. United States Environmental Protection Agency, Washington, D.C., EPA-843-R-15-006.

Vadeboncoeur, Y., P.B. McIntyre, and M.J. Vander Zanden, 2011: Borders of biodiversity: life at the edge of the world's large lakes. *Biosci*., **61**, 526–537, https://doi.org/10.1525/bio.2011.61.7.7.

Walk, J.W., and R.E. Warner, 2000: Grassland management for the conservation of songbirds in the Midwestern USA. *Biol. Conserv*. **94**, 165–172.

Walk, J.W., M.P. Ward, T.J. Benson, J.L. Deppe, S.A. Lischka, S.D. Bailey, and J.D. Brawn, 2010: Illinois Birds: A Century of Change. Illinois Natural History Survey Special Publication, **31**.

Wells, L., and A.L. McLain, 1973: Lake Michigan: Man's effects on native fish stocks and other biota. Great Lakes Fishery Commission, Technical Report No. 20, 55 pp.

Wuebbles, D. and Coauthors, 2019: An Assessment of the Impacts of Climate Change on the Great Lakes. Environmental Law and Policy Center, 71 pp.

Yin, Y., Y. Wu, S.M. Bartell, and R. Cosgriff, 2009: Patterns of forest succession and impacts of flood in the Upper Mississippi River floodplain ecosystem. *Ecol. Complexity*., **6**, 4, 463–472.

Zedler, J.B., 2010: How frequent storms affect wetland vegetation: a preview of climate-change impacts. *Front. Ecol. Environ*., **8**, 540–547.

Supplemental Tables

The supplemental materials for this report can be accessed at the following links.

Supplemental materials for Chapter 4 (Agriculture):

- To access the supplemental materials for this chapter, please visit:
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