15 BIOGEOCHEMICAL CYCLES

KEY MESSAGES

1. **Human activities have increased atmospheric carbon dioxide by about 40% over pre-industrial levels and more than doubled the amount of nitrogen available to ecosystems. Similar trends have been observed for phosphorus and other elements, and these changes have major consequences for biogeochemical cycles and climate change.**
2. **In total, land in the United States absorbs and stores an amount of carbon equivalent to about 17% of annual U.S. fossil fuel emissions. U.S. forests and associated wood products account for most of this land sink. The effect of this carbon storage is to partially offset warming from emissions of CO_2 and other greenhouse gases.**
3. **Altered biogeochemical cycles together with climate change increase the vulnerability of biodiversity, food security, human health, and water quality to changing climate. However, natural and managed shifts in major biogeochemical cycles can help limit rates of climate change.**

Biogeochemical cycles involve the fluxes of chemical elements among different parts of the Earth: from living to non-living, from atmosphere to land to sea, and from soils to plants. They are called "cycles" because matter is always conserved and because elements move to and from major pools via a variety of two-way fluxes, although some elements are stored in locations or in forms that are differentially accessible to living things. Human activities have mobilized Earth elements and accelerated their cycles – for example, more than doubling the amount of reactive nitrogen that has been added to the biosphere since pre-industrial times.[1,2] Reactive nitrogen is any nitrogen compound that is biologically, chemically, or radiatively active, like nitrous oxide and ammonia, but not nitrogen gas (N_2). Global-scale alterations of biogeochemical cycles are occurring, from human activities both in the U.S. and elsewhere, with impacts and implications now and into the future. Global carbon dioxide emissions are the most significant driver of human-caused climate change. But human-accelerated cycles of other elements, especially nitrogen, phosphorus, and sulfur, also influence climate. These elements can affect climate directly or act as indirect factors that alter the carbon cycle, amplifying or reducing the impacts of climate change.

Climate change is having, and will continue to have, impacts on biogeochemical cycles, which will alter future impacts on climate and affect our capacity to cope with coupled changes in climate, biogeochemistry, and other factors.

Key Message 1: Human-Induced Changes

Human activities have increased atmospheric carbon dioxide by about 40% over pre-industrial levels and more than doubled the amount of nitrogen available to ecosystems. Similar trends have been observed for phosphorus and other elements, and these changes have major consequences for biogeochemical cycles and climate change.

The human mobilization of carbon, nitrogen, and phosphorus from the Earth's crust and atmosphere into the environment has increased 36, 9, and 13 times, respectively, compared to geological sources over pre-industrial times.[3] Fossil fuel burning, land-cover change, cement production, and the extraction and production of fertilizer to support agriculture are major causes of these increases.[4] Carbon dioxide (CO_2) is the most abundant of the heat-trapping greenhouse gases that are increasing due to human activities, and its production dominates atmospheric forcing of global climate change.[5] However, methane (CH_4) and nitrous oxide (N_2O) have higher greenhouse-warming potential per molecule than CO_2, and both are also increasing in the atmosphere. In the U.S. and Europe, sulfur emissions have declined over the past three decades, especially since the mid-1990s, because of efforts to reduce air pollution.[6] Changes in biogeochemical cycles of carbon, nitrogen, phosphorus, and other elements – and the coupling of those cycles – can influence climate. In turn, this can change atmospheric composition in other ways that affect how the planet absorbs and reflects sunlight (for example, by creating small particles known as aerosols that can reflect sunlight).

State of the Carbon Cycle

The U.S. was the world's largest producer of human-caused CO_2 emissions from 1950 until 2007, when it was surpassed by China. U.S. emissions account for approximately 85% of North American emissions of CO_2[7] and 18% of global emissions.[8,9] Ecosystems represent potential "sinks" for CO_2, which are places where carbon can be stored over the short or long term (see "Estimating the U.S. Carbon Sink"). At the continental scale, there has been a large and relatively consistent increase in forest carbon stocks over the last two decades,[10] due to recovery from past forest harvest, net increases in forest area, improved forest management regimes, and faster growth driven by climate or fertilization by CO_2 and nitrogen.[7,11] The largest rates of disturbance and "regrowth sinks" are in southeastern, south central, and Pacific northwestern regions.[11] However, emissions of CO_2 from human activities in the U.S. continue to increase and exceed ecosystem CO_2 uptake by more than three times. As a result, North America remains a net source of CO_2 into the atmosphere[7] by a substantial margin.

Major North American Carbon Dioxide Sources and Sinks

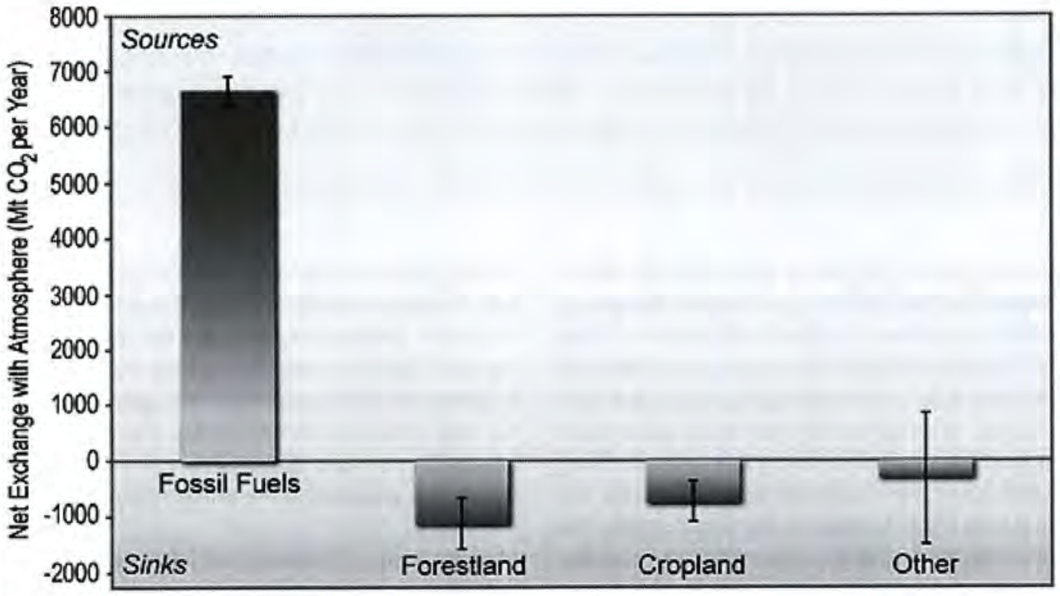

Figure 15.1. The release of carbon dioxide from fossil fuel burning in North America (shown here for 2010) vastly exceeds the amount that is taken up and temporarily stored in forests, crops, and other ecosystems (shown here is the annual average for 2000-2006). (Figure source: King et al. 2012[7]).

Sources and Fates of Reactive Nitrogen

The nitrogen cycle has been dramatically altered by human activity, especially by the use of nitrogen fertilizers, which have increased agricultural production over the past half century.[1,2] Although fertilizer nitrogen inputs have begun to level off in the U.S. since 1980,[12] human-caused reactive nitrogen inputs are now at least five times greater than those from natural sources.[13,14,15,16] At least some of the added nitrogen is converted to nitrous oxide (N_2O), which adds to the greenhouse effect in Earth's atmosphere.

An important characteristic of reactive nitrogen is its legacy. Once created, it can, in sequence, travel throughout the environment (for example, from land to rivers to coasts, sometimes via the atmosphere), contributing to environmental problems such as the formation of coastal low-oxygen "dead zones" in marine ecosystems in summer. These problems persist until the reactive nitrogen is either captured and stored in a long-term pool, like the mineral layers of soil or deep ocean sediments, or converted back to nitrogen gas.[17,18] The nitrogen cycle affects atmospheric concentrations of the three most important human-caused greenhouse gases: carbon dioxide, methane, and nitrous oxide. Increased available nitrogen stimulates the uptake of carbon dioxide by plants, the release of methane from wetland soils, and the production of nitrous oxide by soil microbes.

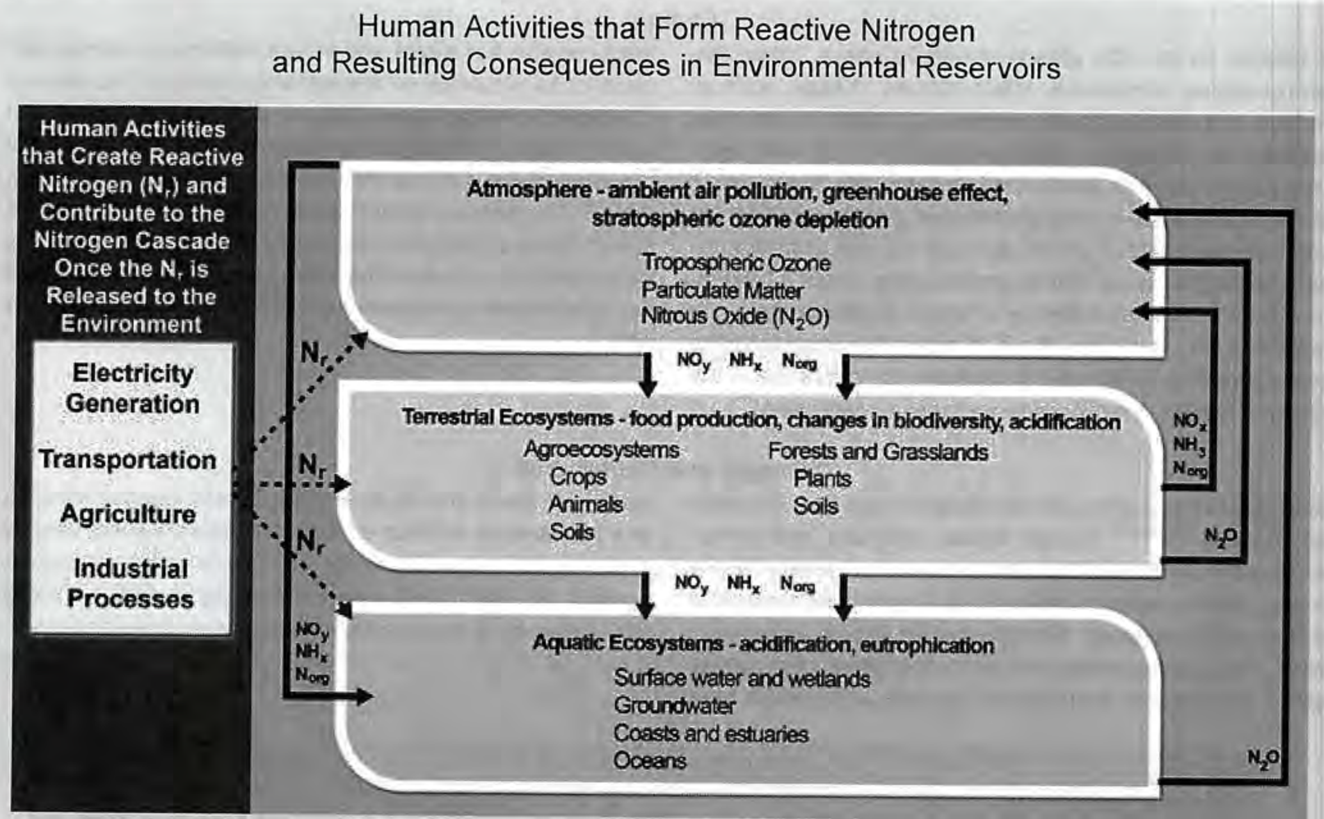

Figure 15.2. Once created, a molecule of reactive nitrogen has a cascading impact on people and ecosystems as it contributes to a number of environmental issues. Molecular terms represent oxidized forms of nitrogen primarily from fossil fuel combustion (such as nitrogen oxides, NO_x), reduced forms of nitrogen primarily from agriculture (such as ammonia, NH_3), and organic forms of nitrogen (N_{org}) from various processes. NO_y is all nitrogen-containing atmospheric gases that have both nitrogen and oxygen, other than nitrous oxide (N_2O). NH_x is the sum of ammonia (NH_3) and ammonium (NH_4). (Figure source: adapted from EPA 2011;[13] Galloway et al. 2003;[17] with input from USDA. USDA contributors were Adam Chambers and Margaret Walsh).

Phosphorus and other elements

The phosphorus cycle has been greatly transformed in the United States,[19] primarily from the use of phosphorus fertilizers in agriculture. Phosphorus has no direct effects on climate, but does have indirect effects, such as increasing carbon sinks by fertilizing plants. Emissions of sulfur, as sulfur dioxide, can reduce the growth of plants and stimulate the leaching of soil nutrients needed by plants.[20]

Key Message 2: Sinks and Cycles

In total, land in the United States absorbs and stores an amount of carbon equivalent to about 17% of annual U.S. fossil fuel emissions. U.S. forests and associated wood products account for most of this land sink. The effect of this carbon storage is to partially offset warming from emissions of CO_2 and other greenhouse gases.

Considering the entire atmospheric CO_2 budget, the temporary net storage on land is small compared to the sources: more CO_2 is emitted than can be taken up (see "Estimating the U.S. Carbon Sink").[7,21,22,23] Other elements and compounds affect that balance by direct and indirect means (for example, nitrogen stimulates carbon uptake [direct] and nitrogen decreases the soil methane sink [indirect]). The net effect on Earth's energy balance from changes in major biogeochemical cycles (carbon, nitrogen, sulfur, and phosphorus) depends upon processes that directly affect how the planet absorbs or reflects sunlight, as well as those that indirectly affect concentrations of greenhouse gases in the atmosphere.

Carbon

In addition to the CO_2 effects described above, other carbon-containing compounds affect climate change, such as methane and volatile organic compounds (VOCs). As the most abundant non-CO_2 greenhouse gas, methane is 20 to 30 times more potent than CO_2 over a century timescale. It accounted for 9% of all human-caused greenhouse gas emissions in the United States in 2011,[8] and its atmospheric concentration today is more than twice that of pre-industrial times.[24,25] Methane has an atmospheric lifetime of about 10 years before it is oxidized to CO_2, but it has about 25 times the global warming potential of CO_2. An increase in methane concentration in the industrial era has contributed to warming in many ways.[26] Methane also has direct and indirect effects on climate because of its influences on atmospheric chemistry. Increases in atmospheric methane and VOCs are expected to deplete concentrations of hydroxyl radicals, causing methane to persist in the atmosphere and exert its warming effect for longer periods.[25,27] The hydroxyl radical is the most important "cleaning agent" of the troposphere (the active weather layer extending up to about 5 to 10 miles above the ground), where it is formed by a complex series of reactions involving ozone and ultraviolet light.[3]

Nitrogen and Phosphorus

The climate effects of an altered nitrogen cycle are substantial and complex.[4,28,29,30,31] Carbon dioxide, methane, and nitrous oxide contribute most of the human-caused increase in climate forcing, and the nitrogen cycle affects atmospheric concentrations of all three gases. Nitrogen cycling processes regulate ozone (O_3) concentrations in the troposphere and stratosphere, and produce atmospheric aerosols, all of which have additional direct effects on climate. Excess reactive nitrogen also has multiple indirect effects that simultaneously amplify and mitigate changes in climate. Changes in ozone and organic aerosols are short-lived, whereas changes in carbon dioxide and nitrous oxide have persistent impacts on the atmosphere.

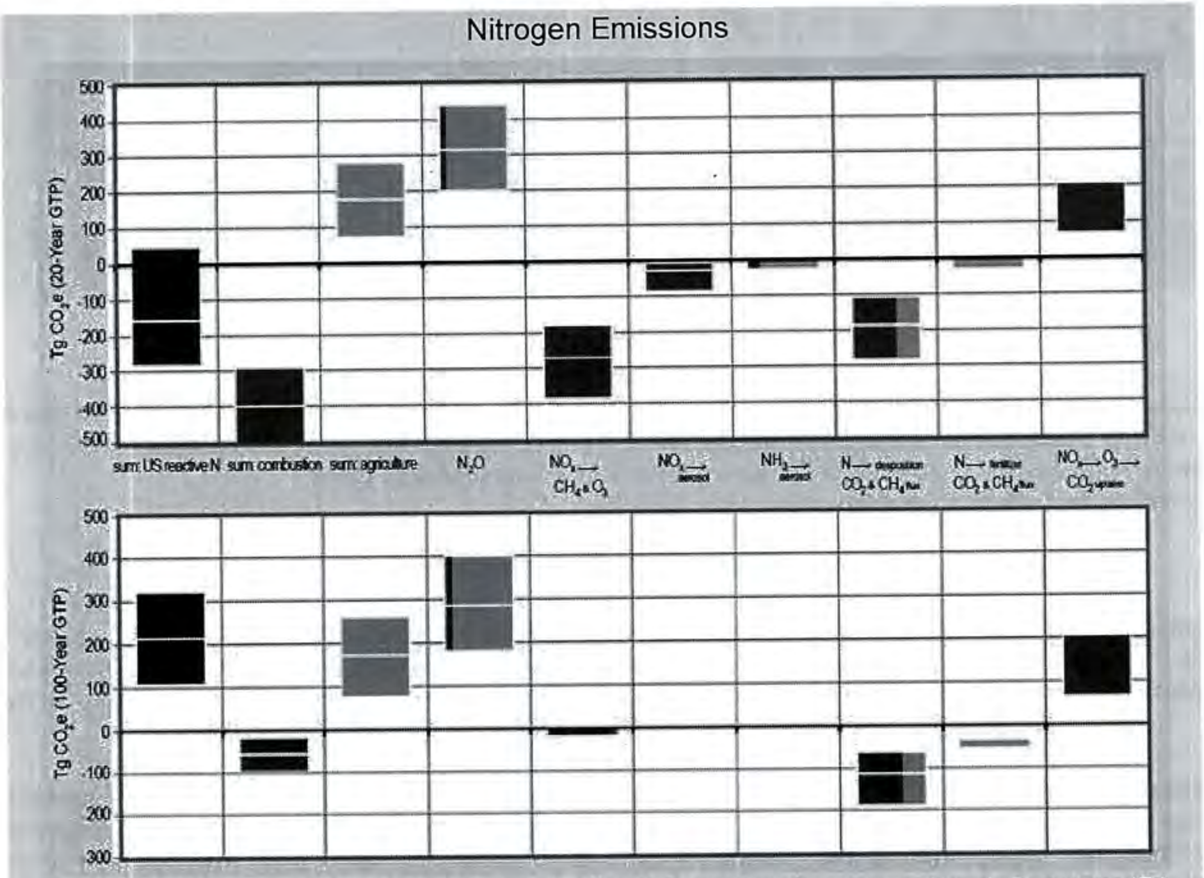

Figure 15.3. Figure shows how climate change will affect U.S. reactive nitrogen emissions, in Teragrams (Tg) CO_2 equivalent, on a 20-year (top) and 100-year (bottom) global temperature potential basis. Positive values on the vertical axis depict warming; negative values reflect cooling. The height of the bar denotes the range of uncertainty, and the white line denotes the best estimate. The relative contribution of combustion (dark brown) and agriculture (green) is denoted by the color shading. (Figure source: adapted from Pinder et al. 2012[28]).

The strongest direct effect of an altered nitrogen cycle is through emissions of nitrous oxide (N_2O), a long-lived and potent greenhouse gas that is increasing steadily in the atmosphere.[25,26] Globally, agriculture has accounted for most of the atmospheric rise in N_2O.[32,33] Roughly 60% of agricultural N_2O derives from elevated soil emissions resulting from the use of nitrogen fertilizer. Animal waste treatment accounts for about 30%, and the remaining 10% comes from crop-residue burning.[34] The U.S. reflects this global trend: around 75% to 80% of U.S. human-caused N_2O emissions are due to agricultural activities, with the majority being emissions from fertilized soil. The remaining 20% is derived from a variety of industrial and energy sectors.[35,36] While N_2O currently accounts for about 6% of human-caused warming,[26] its long lifetime in the atmosphere and rising concentrations will increase N_2O-based climate forcing over a 100-year time scale.[33,37,38]


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Excess reactive nitrogen indirectly exacerbates changes in climate by several mechanisms. Emissions of nitrogen oxides (NO_x) increase the production of tropospheric ozone, which is a greenhouse gas.[39] Elevated tropospheric ozone may reduce CO_2 uptake by plants and thereby reduce the terrestrial CO_2 sink.[40] Nitrogen deposition to ecosystems can also stimulate the release of nitrous oxide and methane and decrease methane uptake by soil microbes.[41]

However, excess reactive nitrogen also mitigates changes in greenhouse gas concentrations and climate through several intersecting pathways. Over short time scales, NO_x and ammonia emissions lead to the formation of atmospheric aerosols, which cool the climate by scattering or absorbing incoming radiation and by affecting cloud cover.[26,42] In addition, the presence of NO_x in the lower atmosphere increases the formation of sulfate and organic aerosols.[43] At longer time scales, NO_x can increase rates of methane oxidation, thereby reducing the lifetime of this important greenhouse gas.

One of the dominant effects of reactive nitrogen on climate stems from how it interacts with ecosystem carbon capture and storage, and thus, the carbon sink. As mentioned previously, addition of reactive nitrogen to natural ecosystems can increase carbon storage as long as other factors are not limiting plant growth, such as water and nutrient availability.[44] Nitrogen deposition from human sources is estimated to contribute to a global net carbon sink in land ecosystems of 917 to 1,830 million metric tons (1,010 to 2,020 million tons) of CO_2 per year. These are model-based estimates, as comprehensive, observationally-based estimates at large spatial scales are hindered by the limited number of field experiments. This net land sink represents two components: 1) an increase in vegetation growth as nitrogen limitation is alleviated by human-caused nitrogen deposition, and 2) a contribution from the influence of increased reactive nitrogen availability on decomposition. While the former generally increases with increased reactive nitrogen, the net effect on decomposition in soils is not clear. The net effect on total ecosystem carbon storage was an average of 37 metric tons (41 tons) of carbon stored per metric ton of nitrogen added in forests in the U.S. and Europe.[45]

When all direct and indirect links between reactive nitrogen and climate in the U.S. are added up, a recent estimate suggests a modest reduction in the rate of warming in the near term (next several decades), but a progressive switch to greater net warming over a 100-year timescale.[28,29] That switch is due to a reduction in nitrogen oxide (NO_x) emissions, which provide modest cooling effects, a reduction in the nitrogen-stimulated CO_2 storage in forests, and a rising importance of agricultural nitrous oxide emissions. Current policies tend to reinforce this switch. For example, policies that reduce nitrogen oxide and sulfur oxide emissions have large public health benefits, but also reduce the indirect climate mitigation co-benefits by reducing carbon storage and aerosol formation.

Changes in the phosphorus cycle have no direct effects on climate, but phosphorus availability constrains plant and microbial activity in a wide variety of land- and water-based ecosystems.[46,47] Changes in phosphorus availability due to human activity can therefore have indirect impacts on climate and the emissions of greenhouse gases in a variety of ways. For example, in land-based ecosystems, phosphorus availability can limit both CO_2 storage and decomposition[46,48] as well as the rate of nitrogen accumulation.[49] In turn, higher nitrogen inputs can alter phosphorus cycling via changes in the production and activity of enzymes that release phosphorus from decaying organic matter,[50] creating another mechanism by which rising nitrogen inputs can stimulate carbon uptake.

Other Effects: Sulfate Aerosols

In addition to the aerosol effects from nitrogen mentioned above, there are both direct and indirect effects on climate from other aerosol sources. Components of the sulfur cycle exert a cooling effect through the formation of sulfate aerosols created from the oxidation of sulfur dioxide (SO_2) emissions.[26] In the United States, the dominant source of sulfur dioxide is coal combustion. Sulfur dioxide emissions rose until 1980, but have since decreased by more than 50% following a series of air-quality regulations and incentives focused on improving human health and the environment, as well as reductions in the delivered price of low-sulfur coal.[51] That decrease in emissions has had a marked effect on U.S. climate forcing: between 1970 and 1990, sulfate aerosols caused cooling, primarily over the eastern U.S., but since 1990, further reductions in sulfur dioxide emissions have reduced the cooling effect of sulfate aerosols by half or more.[42] Continued declines in sulfate aerosol cooling are projected for the future,[42] particularly if coal continues to be replaced by natural gas (which contains far fewer sulfur impurities) for electricity generation. Here, as with nitrogen oxide emissions, the environmental and socioeconomic tradeoffs are important to recognize: lower sulfur dioxide and nitrogen oxide emissions remove some climate cooling agents, but improve ecosystem health and save lives.[16,31,52]

Three low-concentration industrial gases are particularly potent for trapping heat: nitrogen trifluoride (NF_3), sulfur hexafluoride (SF_6), and trifluoromethyl sulfur pentafluoride (SF_5CF_3). None currently makes a major contribution to climate forcing, but since their emissions are increasing and their effects last for millennia, continued monitoring is important.

Key Message 3: Impacts and Options

Altered biogeochemical cycles together with climate change increase the vulnerability of biodiversity, food security, human health, and water quality to changing climate. However, natural and managed shifts in major biogeochemical cycles can help limit rates of climate change.

Climate change alters key aspects of biogeochemical cycling, creating the potential for feedbacks that alter both warming and cooling processes into the future. For example, as soils warm, the rate of decomposition will increase, adding more CO_2 to the atmosphere. In addition, both climate and biogeochemistry interact strongly with environmental and ecological concerns, such as biodiversity loss, freshwater and marine eutrophication (unintended fertilization of aquatic ecosystems that leads to water quality problems), air pollution, human health, food security, and water resources. Many of the latter connections are addressed in other sections of this assessment, but we summarize some of them here because consideration of mitigation and adaptation options for changes in climate and biogeochemistry often requires this broader context.

Climate-Biogeochemistry Feedbacks

Both rising temperatures and changes in water availability can alter climate-relevant biogeochemical processes. For example, as summarized above, nitrogen deposition drives temperate forest carbon storage, both by increasing plant growth and by slowing organic-matter decomposition.[53] Higher temperatures will counteract soil carbon storage by increasing decomposition rates and subsequent emission of CO_2 via microbial respiration. However, that same increase in decomposition accelerates the release of reactive nitrogen (and phosphorus) from organic matter, which in turn can fuel additional plant growth.[44] Temperature also has direct effects on net primary productivity (the total amount of CO_2 stored by a plant through photosynthesis minus the amount released through respiration). The combined effects on ecosystem carbon storage will depend on the extent to which nutrients constrain both net primary productivity and decomposition, on the extent of warming, and on whether any simultaneous changes in water availability occur.[54]

Similarly, natural methane sources are sensitive to variations in climate; ice core records show a strong correlation between methane concentrations and warmer, wetter conditions.[55] Thawing permafrost in polar regions is of particular concern because it stores large amounts of methane that could potentially be released to the atmosphere.

Biogeochemistry, Climate, and Interactions with Other Factors

Societal options for addressing links between climate and biogeochemical cycles must often be informed by connections to a broader context of global environmental changes. For example, both climate change and nitrogen deposition can reduce biodiversity in water- and land-based ecosystems. The greatest combined risks are expected to occur where critical loads are exceeded.[56,57] A critical load is defined as the input rate of a pollutant below which no detrimental ecological effects occur over the long-term according to present knowledge.[57] Although biodiversity is often shown to decline when nitrogen deposition is high due to fossil fuel combustion and agricultural emissions,[57,58] the compounding effects of multiple stressors are difficult to predict. Warming and changes in water availability have been shown to interact with nitrogen in additive or synergistic ways to exacerbate biodiversity loss.[59] Unfortunately, very few multi-factorial studies have been done to address this gap.

Human induced acceleration of the nitrogen and phosphorus cycles already causes widespread freshwater and marine eutrophication,[60,61] a problem that is expected to worsen under a warming climate.[61,62] Without efforts to reduce future climate change and to slow the acceleration of biogeochemical cycles, existing climate changes will combine with increasing inputs of nitrogen and phosphorus into freshwater and estuarine ecosystems. This combination of changes is projected to have substantial negative effects on water quality, human health, inland and coastal fisheries, and greenhouse gas emissions.[18,61]

Similar concerns – and opportunities for the simultaneous reduction of multiple environmental problems (known as "co-benefits") – exist in the realms of air pollution, human health, and food security. For example, methane, volatile organic compounds, and nitrogen oxide emissions all contribute to the formation of tropospheric ozone, which is a greenhouse gas and has negative consequences for human health and crop and forest productivity.[37,63,64] Rates of ozone formation are accelerated by higher temperatures, creating a reinforcing cycle between rising temperatures and continued human alteration of the nitrogen and carbon cycles.[65] Rising temperatures also work against some of the benefits of air pollution control.[64] Some changes will trade gains in one arena for declines in others. For example, lowered NO_x, NH_x, and SO_x emissions remove cooling agents from the atmosphere, but improve air quality.[16,31] Recent analyses suggest that targeting reductions in compounds like methane and black carbon aerosols that have both climate and air-pollution consequences can achieve significant improvements in not only the rate of climate change, but also in human health.[31] Finally, reductions in excess nitrogen and phosphorus from agricultural and industrial activities can potentially reduce the rate and impacts of climate change, while simultaneously addressing concerns in biodiversity, water quality, food security, and human health.[66]

Many Factors Combine to Affect Biogeochemical Cycles

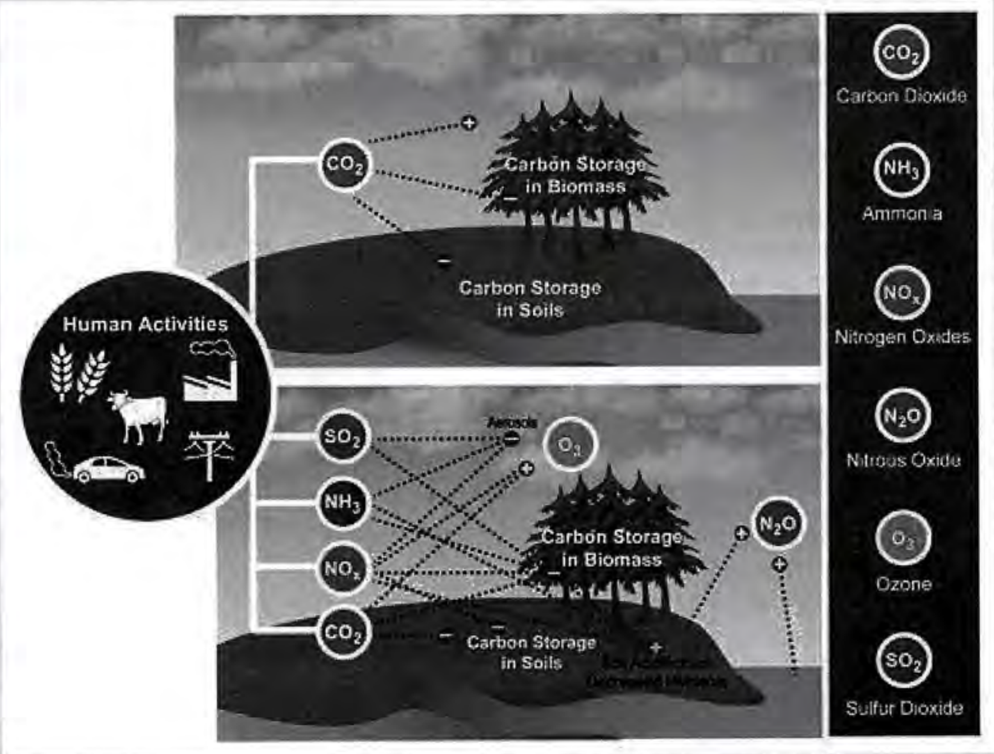

Figure 15.4. Top panel shows the impact of the alteration of the carbon cycle alone on radiative forcing. The bottom panel shows the impacts of the alteration of carbon, nitrogen, and sulfur cycles on radiative forcing. SO_2 and NH_3 increase aerosols and decrease radiative forcing. NH_3 is likely to increase plant biomass, and consequently decrease forcing. NO_x is likely to increase the formation of tropospheric ozone (O_3) and increase radiative forcing. Ozone has a negative effect on plant growth/biomass, which might increase radiative forcing. CO_2 and NH_3 act synergistically to increase plant growth, and therefore decrease radiative forcing. SO_2 is likely to reduce plant growth, perhaps through the leaching of soil nutrients, and consequently increase radiative forcing. NO_x is likely to reduce plant growth directly and through the leaching of soil nutrients, therefore increasing radiative forcing. However, it could act as a fertilizer that would have the opposite effect.

ESTIMATING THE U.S. CARBON SINK

Any natural or engineered process that temporarily or permanently removes and stores carbon dioxide (CO_2) from the atmosphere is considered a carbon "sink." Temporary (10 to 100 years) CO_2 sinks at the global scale include absorption by plants as they photosynthesize, as well as CO_2 dissolution into the ocean. Forest biomass and soils in North America offer large temporary carbon sinks in the global carbon budget; however, the spatial distribution, longevity, and mechanisms controlling these sinks are less certain.[67] Understanding these processes is critical for predicting how ecosystem carbon sinks will change in the future, and potentially for managing the carbon sink as a mitigation strategy for climate change.

Table 15.1. Carbon (C) sinks and uncertainty estimated by Pacala et al. for the first State of the Carbon Cycle Report.[23] Forests take up the highest percentage of carbon of all land-based carbon sinks. Due to a number of factors, there are high degrees of uncertainty in carbon sink estimates.

Land Area	C sink (Tg C/y) (95% CI)	Method
Forest	-256 (+/- 50%)	inventory, modeled
Wood products	-57 (+/- 50%)	inventory
Woody encroachment	-120 (+/- >100%)	inventory
Agricultural soils	-8 (+/- 50%)	modeled
Wetlands	-23 (+/- >100%)	inventory
Rivers and reservoirs	-25 (+/- 100%)	inventory
Net Land Sink	**-489 (+/- 50%)**	**inventory**

Both inventory (measurement) and modeling techniques have been used to estimate land-based carbon sinks at a range of scales in both time and space. For inventory methods, carbon stocks are measured at a location at two points in time, and the amount of carbon stored or lost can be estimated over the intervening time period. This method is widely used to estimate the amount of carbon stored in forests in the United States over timescales of years to decades. Terrestrial biosphere models estimate carbon sinks by modeling a suite of processes that control carbon cycling dynamics, such as photosynthesis (CO_2 uptake by plants) and respiration (CO_2 release by plants, animals, and microorganisms in soil and water). Field-based data and/or remotely sensed data are used as inputs and also to validate these models. Estimates of the land-based carbon sink can vary depending on the data inputs and how different processes are modeled.[22] Atmospheric inverse models use information about atmospheric CO_2 concentrations and atmospheric transport (like air currents) to estimate the terrestrial carbon sink.[68] This approach can provide detailed information about carbon sinks over time. However, because atmospheric CO_2 is well-mixed and monitoring sites are widely dispersed, these models estimate fluxes over large areas and it is difficult to identify processes responsible for the sink from these data.[22] Recent estimates using atmospheric inverse models show that global land and ocean carbon sinks are stable or even increasing globally.[69]

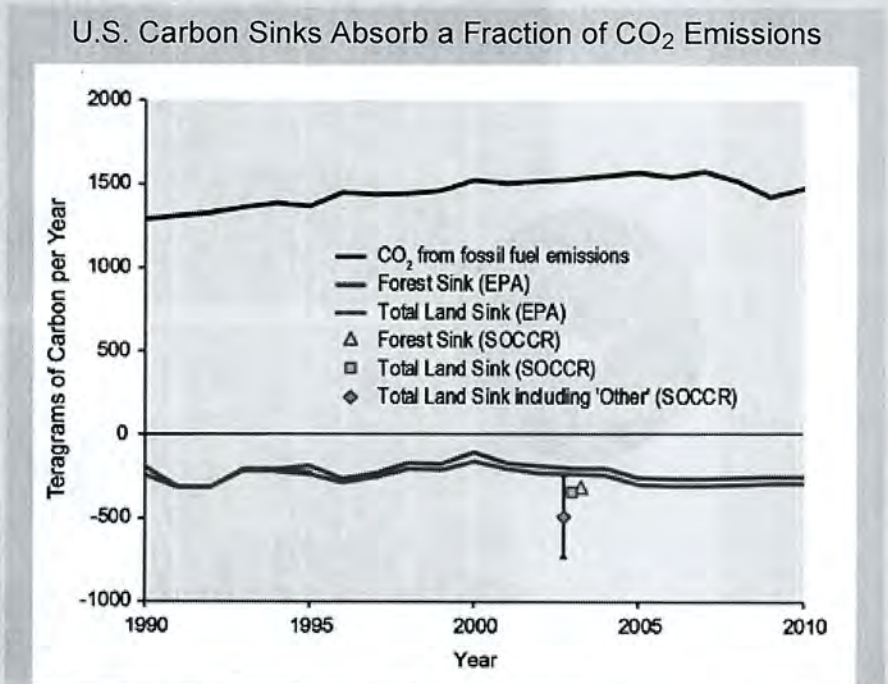

Figure 15.5. Figure shows growth in fossil fuel CO_2 emissions (black line) and forest and total land carbon sinks in the U.S. for 1990–2010 (green and orange lines; from EPA 2012[21]) and for 2003 (symbols; from the first State of the Carbon Cycle Report[67]). Carbon emissions are significantly higher than the total land sink's capacity to absorb and store them. (Data from EPA 2012 and CCSP 2007[21,67]).

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ESTIMATING THE U.S. CARBON SINK (CONTINUED)

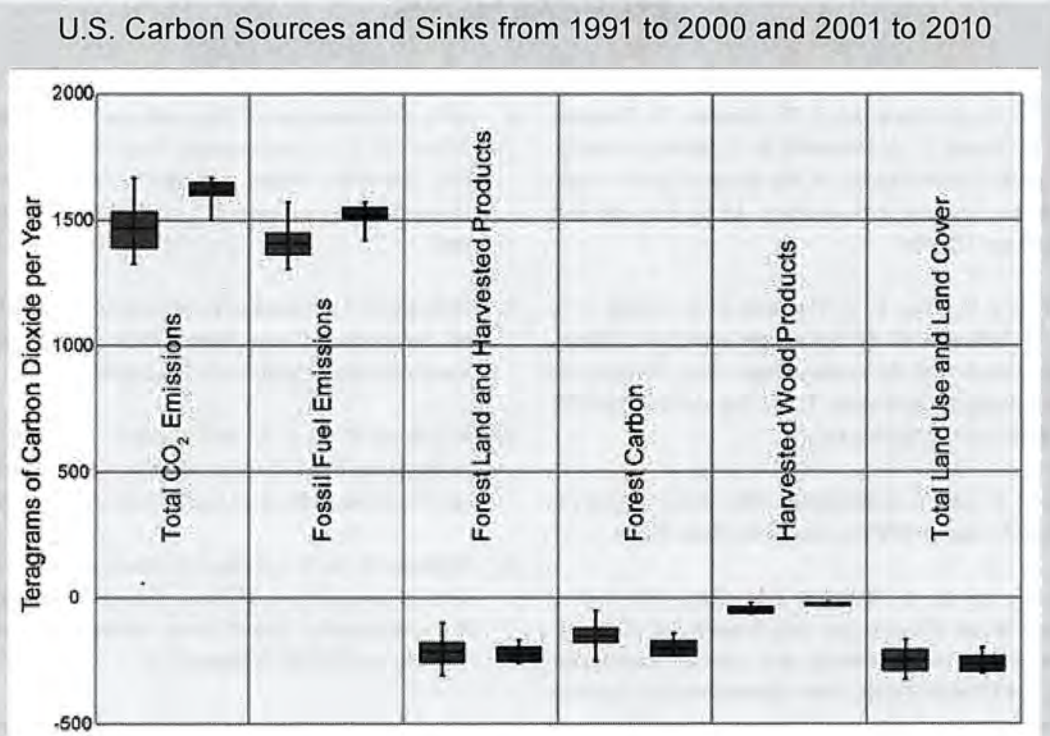

Figure 15.6. Changes in CO_2 emissions and land-based sinks in two recent decades, showing among-year variation (vertical lines: minimum and maximum estimates among years; boxes: 25th and 75th quartiles; horizontal line: median). Total CO_2 emissions, as well as total CO_2 emissions from fossil fuels, have risen; land-based carbon sinks have increased slightly, but at a much slower pace. (Data from EPA 2012 and CCSP 2007[21,67]).

The U.S. Environmental Protection Agency (EPA) conducts an annual inventory of U.S. greenhouse gas emissions and sinks as part of the nation's commitments under the Framework Convention on Climate Change. Estimates are based on inventory studies and models validated with field-based data (such as the CENTURY model) in accordance with the Intergovernmental Panel on Climate Change (IPCC) best practices.[70] An additional comprehensive assessment, The First State of the Carbon Cycle Report (SOCCR), provides estimates for carbon sources and sinks in the U.S. and North America around 2003.[67] This assessment also utilized inventory and field-based terrestrial biosphere models, and incorporated additional land sinks not explicitly included in EPA assessments.

Data from these assessments suggest that the U.S. carbon sink has been variable over the last two decades, but still absorbs and stores a small fraction of CO_2 emissions. The forest sink comprises the largest fraction of the total land sink in the United States, annually absorbing 7% to 24% (with a best estimate of 16%) of fossil fuel CO_2 emissions during the last two decades. Because the U.S. Forest Service has conducted detailed forest carbon inventory studies, the uncertainty surrounding the estimate for the forest sink is lower than for most other components (see Pacala et al. 2007, Table 2[23]). The role of lakes, reservoirs, and rivers in the carbon budget, in particular, has been difficult to quantify and is rarely included in national budgets.[71] The IPCC guidelines for estimating greenhouse gas sources or sinks from lakes, reservoirs, or rivers are included in the "wetlands" category, but only for lands converted to wetlands. These ecosystems are not included in the EPA's estimates of the total land sink. Rivers and reservoirs were estimated to be a sink in the State of the Carbon Cycle analysis,[23] but recent studies suggest that inland waters may actually be an important source of CO_2 to the atmosphere.[72] It is important to note that these two methods use different datasets, different models, and different methodologies to estimate land-based carbon sinks in the United States. In particular, we note that the EPA Inventory, consistent with IPCC Guidelines for national inventories, includes only carbon sinks designated as human-caused, while the SOCCR analysis does not make this distinction.

15: BIOGEOCHEMICAL CYCLES

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15: BIOGEOCHEMICAL CYCLES

SUPPLEMENTAL MATERIAL

TRACEABLE ACCOUNTS

Process for Developing Key Messages

The key messages and supporting text summarize extensive evidence documented in two technical input reports submitted to the NCA: 1) a foundational report supported by the Departments of Energy and Agriculture: *Biogeochemical Cycles and Biogenic Greenhouse Gases from North American Terrestrial Ecosystems: A Technical Input Report for the National Climate Assessment,*[30] and 2) an external report: *The Role of Nitrogen in Climate Change and the Impacts of Nitrogen-Climate Interactions on Terrestrial and Aquatic Ecosystems, Agriculture, and Human Health in the United States: A Technical Report Submitted to the U.S. National Climate Assessment.*[4] The latter report was supported by the International Nitrogen Initiative, a National Science Foundation grant, and the David and Lucille Packard Foundation.

Author meetings and workshops were held regularly for the foundational report,[30] including a workshop at the 2011 Soil Science Society of America meeting. A workshop held in July 2011 at the USGS John Wesley Powell Center for Analysis and Synthesis in Fort Collins, CO, focused on climate-nitrogen actions and was summarized in the second primary source.[4] An additional 15 technical input reports on various topics were also received and reviewed as part of the Federal Register Notice solicitation for public input.

The entire author team for this chapter conducted its deliberations by teleconference from April to June 2012, with three major meetings resulting in an outline and a set of key messages. The team came to expert consensus on all of the key messages based on their reading of the technical inputs, other published literature, and professional judgment. Several original key messages were later combined into a broader set of statements while retaining most of the original content of the chapter. Major revisions to the key messages, chapter, and traceable accounts were approved by authors; further minor revisions were consistent with the messages intended by the authors.

KEY MESSAGE #1 TRACEABLE ACCOUNT

Human activities have increased atmospheric carbon dioxide by about 40% over pre-industrial levels and more than doubled the amount of nitrogen available to ecosystems. Similar trends have been observed for phosphorus and other elements, and these changes have major consequences for biogeochemical cycles and climate change.

Description of evidence base

The author team evaluated technical input reports (17) on biogeochemical cycles, including the two primary sources.[4,31] In particular, one report[4] focused on changes in the nitrogen cycle and was comprehensive. Original literature was consulted for changes in other biogeochemical cycles. The foundational report[30] updated several aspects of our understanding of the carbon balance in the United States.

Publications have shown that human activities have altered biogeochemical cycles. A seminal paper comparing increases in the global fluxes of carbon (C), nitrogen (N), sulfur (S), and phosphorous (P) was published in 2000[73] and was recently updated.[3] Changes observed in the nitrogen cycle[1,17,18] show anthropogenic sources to be far greater than natural ones.[14,36,47] For phosphorus, the effect of added phosphorus on plants and microbes is well understood.[19,46,47] Extensive research shows that increases in CO_2 are the strongest human impact forcing climate change, mainly because the concentration of CO_2 is so much greater than that of other greenhouse gases.[5,7,73]

New information and remaining uncertainties

The sources of C, N, and P are from well-documented processes, such as fossil fuel burning and fertilizer production and application. The flux from some processes is well known, while others have significant remaining uncertainties.

Some new work has synthesized the assessment of global and national CO_2 emissions[7] and categorized the major CO_2 sources and sinks.[4,30] Annual updates of CO_2 emissions and sink inventories are done by EPA (for example, EPA 2013[8]).

Advances in the knowledge of the nitrogen cycle have quantified that human-caused reactive nitrogen inputs are now at least five times greater than natural inputs.[4,13,14]

Assessment of confidence based on evidence

High confidence. Evidence for human inputs of C, N, and P come from academic, government, and industry sources. The data show substantial agreement.

Confidence Level

Very High

Strong evidence (established theory, multiple sources, consistent results, well documented and accepted methods, etc.), high consensus

High

Moderate evidence (several sources, some consistency, methods vary and/or documentation limited, etc.), medium consensus

Medium

Suggestive evidence (a few sources, limited consistency, models incomplete, methods emerging, etc.), competing schools of thought

Low

Inconclusive evidence (limited sources, extrapolations, inconsistent findings, poor documentation and/or methods not tested, etc.), disagreement or lack of opinions among experts

The likelihood of continued dominance of CO_2 over other greenhouse gases as a driver of global climate change is also judged to be **high**, because its concentration is an order of magnitude higher and its rate of change is well known.

KEY MESSAGE #2 TRACEABLE ACCOUNT

In total, land in the United States absorbs and stores an amount of carbon equivalent to about 17% of annual U.S. fossil fuel emissions. U.S. forests and associated wood products account for most of this land sink. The effect of this carbon storage is to partially offset warming from emissions of CO2 and other greenhouse gases.

Description of evidence base

The author team evaluated technical input reports (17) on biogeochemical cycles, including the two primary sources.[4,30] The "Estimating the U.S. Carbon Sink" section relies on multiple sources of data that are described therein.

Numerous studies of the North American and U.S. carbon sink have been published in reports and the scientific literature. Estimates of the percentage of fossil fuel CO_2 emissions that are captured by forest, cropland, and other lands vary from a low of 7% to a high of about 24%, when the carbon storage is estimated from carbon inventories.[7,22,36] The forest sink has persisted in the U.S. as forests that were previously cut have regrown. Further studies show that carbon uptake can be increased to some extent by a fertilization effect with reactive nitrogen[44,45] and phosphorus,[46,47,48] both nutrients that can limit the rate of photosynthesis. The carbon sink due to nitrogen fertilization is projected to lessen in the future as controls on nitrogen emissions come into play.[28]

While carbon uptake by ecosystems has a net cooling effect, trace gases emitted by ecosystems have a warming effect that can offset the cooling effect of the carbon sink.[26] The most important of these gases are methane and nitrous oxide (N_2O), the concentrations of which are projected to rise.[25,26,33,37,38]

New information and remaining uncertainties

The carbon sink estimates have very wide margins of error. The percent of U.S. CO_2 emissions that are stored in ecosystems depends on which years are used for emissions and whether inventories, ecosystem process models, atmospheric inverse models, or some combination of these techniques are used to estimate the sink size (see "Estimating the U.S. Carbon Sink"). The inventories are continually updated (for example, EPA 2013[8]), but there is a lack of congruence on which of the three techniques is most reliable. A recent paper that uses atmospheric inverse modeling suggests that the global land and ocean carbon sinks are stable or increasing.[69]

While known to be significant, continental-scale fluxes and sources of the greenhouse gases N_2O and CH_4 are based on limited data and are potentially subject to revision. Recent syntheses[28] evaluate the dynamics of these two important gases and project future changes. Uncertainties remain high.

Assessment of confidence based on evidence

We have **very high** confidence that the value of the forest carbon sink lies within the range given, 7% to 24% (with a best estimate of 16%) of annual U.S. greenhouse gas emissions. There is wide acceptance that forests and soils store carbon in North America, and that they will continue to do so into the near future. The exact value of the sink strength is very poorly constrained, however, and knowledge of the projected future sink is low. As forests age, their capacity to store carbon in living biomass will necessarily decrease,[10] but if other, unknown sinks are dominant, ecosystems may continue to be a carbon sink.

We have **high** confidence that the combination of ecosystem carbon storage of human-caused greenhouse gas emissions and potential warming from other trace gases emitted by ecosystems will ultimately result in a net warming effect. This is based primarily on one recent synthesis,[28] which provides ranges for multiple factors and describes the effects of propagating uncertainties. However, the exact amount of warming or cooling produced by various gases is not yet well known, because of the interactions of multiple factors.

KEY MESSAGE #3 TRACEABLE ACCOUNT

Altered biogeochemical cycles together with climate change increase the vulnerability of biodiversity, food security, human health, and water quality to changing climate. However, natural and managed shifts in major biogeochemical cycles can help limit rates of climate change.

Description of evidence base

The author team evaluated technical input reports (17) on biogeochemical cycles, including the two primary sources.[4,30]

The climate–biogeochemical cycle link has been demonstrated through numerous studies on the effects of reactive nitrogen and phosphorus on forest carbon uptake and storage, and decomposition of organic matter;[44,53] temperature effects on ecosystem productivity;[54] and sensitivity of natural methane emissions to climate variation.[55]

Where the nitrogen and phosphorus cycles are concerned, a number of publications have reported effects of excess loading on ecosystem processes[60,61] and have projected these effects to worsen.[61,62] Additionally, studies have reported the potential for future climate change and increasing nitrogen and phosphorus loadings to have an additive effect and the need for remediation.[18,61] The literature suggests that co-benefits are possible from addressing the environmental concerns of both nutrient loading and climate change.[4,31,64,65,66]

New information and remaining uncertainties

Scientists are still investigating the impact of nitrogen deposition on carbon uptake and of sulfur and nitrogen aerosols on radiative forcing.

Recent work has shown that more than just climate change aspects can benefit from addressing multiple environmental concerns (air/water quality, biodiversity, food security, human health, and so on)

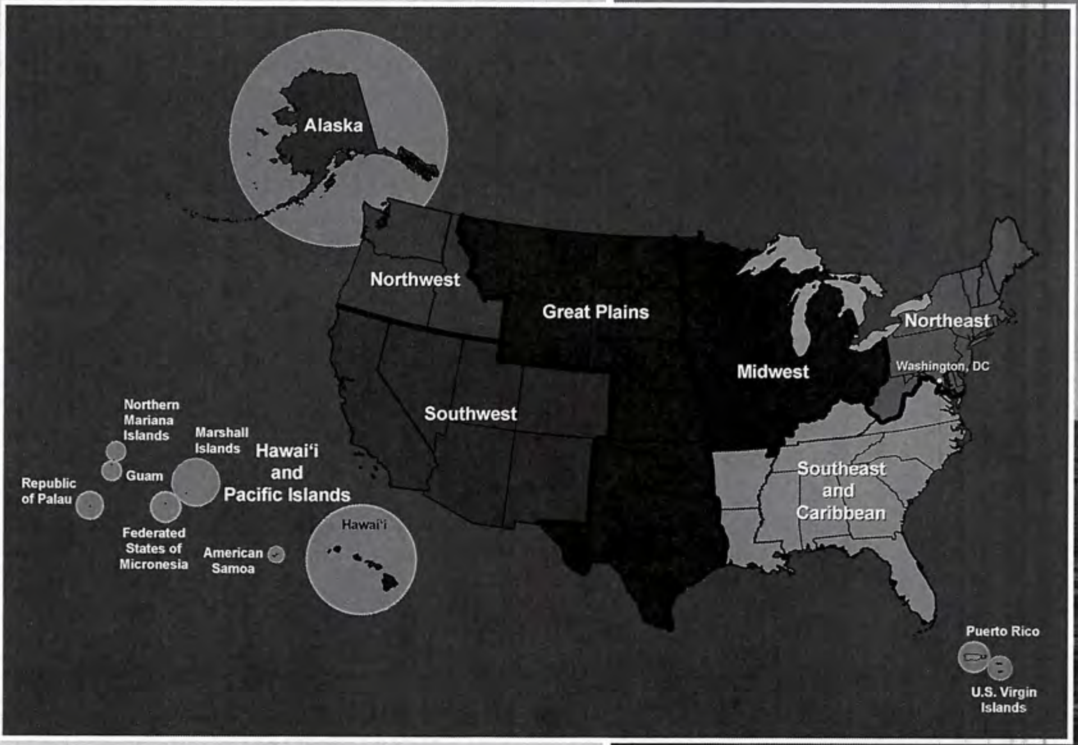
Assessment of confidence based on evidence

High. We have a **high** degree of confidence that climate change will affect biogeochemical cycles through its effects on ecosystem structure and function (species composition and productivity). Similarly, there is **high** confidence that altered biogeochemical cycles will affect climate change, as for example in the increased rates of carbon storage in forests and soils that often accompany excess nitrogen deposition.

REGIONS

From the Rocky Mountains to the Shenandoah Valley, the Great Lakes to the Gulf of Mexico, our country's landscapes and communities vary dramatically. But amidst our geographical and economic diversity, we share many common attributes and challenges. One common challenge facing every U.S. region is a new and dynamic set of realities resulting from our changing climate.

The evidence can be found in every region, and impacts are visible in every state. Some of the most dramatic changes are in Alaska, where average temperatures have increased more than twice as fast as the rest of the country. The rapid decline of Arctic sea ice cover in the last decade is reshaping that region. In the Southwest, a combination of increased temperatures and reductions in annual precipitation are already affecting forests and diminishing water supplies. Meanwhile, that region's population continues to grow at double-digit rates, increasing the stress on water supplies. In various regions, evidence of climate change is apparent in ecosystem changes, such as species moving northward, increases in invasive species and insect outbreaks, and changes in the length of the growing season. In many cities, impacts to the urban environment are closely linked to the changing climate, with increased flooding, greater incidence of heat waves, and diminished air quality. Along most of our coastlines, increasing sea levels and associated threats to coastal areas and infrastructure are becoming a common experience.



For all U.S. regions, warming in the future is projected to be very large compared to historical variations. Precipitation patterns will be altered as well, with some regions becoming drier and some wetter. The exact location of some of these future changes is not easy to pinpoint, because the continental U.S. straddles a transition zone between projected drier conditions in the sub-tropics (south) and wetter conditions at higher latitudes (north). As a result, projected precipitation changes in the northernmost states (which will get wetter) and southernmost states (which will get drier) are more certain than those for the central areas of the country. The heaviest precipitation events are projected to increase everywhere, and by large amounts. Extended dry spells are also projected to increase in length.

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Regional differences in climate change impacts provide opportunities as well as challenges. A changing climate requires alterations in historical agricultural practices, which, if properly anticipated, can have some benefits. Warmer winters mean reductions in heating costs for those in the northern portions of the country. Well-designed adaptation and mitigation actions that take advantage of regional conditions can significantly enhance the nation's resilience in the face of multiple challenges, which include many factors in addition to climate change.

The regions defined in this report intentionally follow state lines (see Figure 1 and Table 1), but landscape features such as forests and mountain ranges do not follow these artificial boundaries. The array of distinct landscapes within each region required difficult choices of emphasis for the authors. The chapters that follow provide a summary of changes and impacts that are observed and anticipated in each of the eight regions of the United States, as well as on oceans and coasts.

For more information about the regional climate histories and projections[1] and sea level rise scenarios[2] developed for the National Climate Assessment, and used throughout this report, see Ch. 2: Our Changing Climate and Appendix 5: Scenarios and Model

Table 1: Composition of NCA Regions

Region	Composition
Northeast	Connecticut, Delaware, Maine, Maryland, Massachusetts, New Hampshire, New Jersey, New York, Pennsylvania, Rhode Island, Vermont, West Virginia, District of Columbia,
Southeast and Caribbean	Alabama, Arkansas, Florida, Georgia, Kentucky, Louisiana, Mississippi, North Carolina, South Carolina, Tennessee, Virginia, Puerto Rico, U.S. Virgin Islands
Midwest	Illinois, Indiana, Iowa, Michigan, Minnesota, Missouri, Ohio, Wisconsin
Great Plains	Kansas, Montana, Nebraska, North Dakota, Oklahoma, South Dakota, Texas, Wyoming
Northwest	Idaho, Oregon, Washington
Southwest	Arizona, California, Colorado, Nevada, New Mexico, Utah
Alaska	Alaska
Hawai'i and U.S. Pacific Islands	Hawai'i, Commonwealth of the Northern Mariana Islands, Federated States of Micronesia, Republic of the Marshall Islands, Republic of Palau, Territory of American Samoa, Territory of Guam

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Climate Change Impacts in the United States

CHAPTER 16
NORTHEAST

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INFORMATION DRAWN FROM THIS CHAPTER IS INCLUDED IN THE HIGHLIGHTS REPORT AND IS IDENTIFIED BY THIS ICON

16 NORTHEAST

KEY MESSAGES

1. **Heat waves, coastal flooding, and river flooding will pose a growing challenge to the region's environmental, social, and economic systems. This will increase the vulnerability of the region's residents, especially its most disadvantaged populations.**
2. **Infrastructure will be increasingly compromised by climate-related hazards, including sea level rise, coastal flooding, and intense precipitation events.**
3. **Agriculture, fisheries, and ecosystems will be increasingly compromised over the next century by climate change impacts. Farmers can explore new crop options, but these adaptations are not cost- or risk-free. Moreover, adaptive capacity, which varies throughout the region, could be overwhelmed by a changing climate.**
4. **While a majority of states and a rapidly growing number of municipalities have begun to incorporate the risk of climate change into their planning activities, implementation of adaptation measures is still at early stages.**

Sixty-four million people are concentrated in the Northeast. The high-density urban coastal corridor from Washington, D.C., north to Boston is one of the most developed environments in the world. It contains a massive, complex, and long-standing network of supporting infrastructure. The region is home to one of the world's leading financial centers, the nation's capital, and many defining cultural and historical landmarks.

The region has a vital rural component as well. The Northeast includes large expanses of sparsely populated but ecologically and agriculturally important areas. Much of the Northeast landscape is dominated by forest, but the region also has grasslands, coastal zones, beaches and dunes, and wetlands, and it is known for its rich marine and freshwater fisheries. These natural areas are essential to recreation and tourism sectors and support jobs through the sale of timber, maple syrup, and seafood. They also contribute important ecosystem services to broader populations – protecting water supplies, buffering shorelines, and sequestering carbon in soils and vegetation. The twelve Northeastern states have more than 180,000 farms, with $17 billion in annual sales.[1] The region's ecosystems and agricultural systems are tightly interwoven, and both are vulnerable to a changing climate.

Although urban and rural regions in the Northeast have profoundly different built and natural environments, both include populations that have been shown to be highly vulnerable to climate hazards and other stresses. Both also depend on aging infrastructure that has already been stressed by climate hazards including heat waves, as well as coastal and riverine flooding due to a combination of sea level rise, storm surge, and extreme precipitation events.

The Northeast is characterized by a diverse climate.[2] Average temperatures in the Northeast generally decrease to the north, with distance from the coast, and at higher elevations. Average annual precipitation varies by about 20 inches throughout the Northeast with the highest amounts observed in coastal and select mountainous regions. During winter, frequent storms bring bitter cold and frozen precipitation, especially to the north. Summers are warm and humid, especially to the south. The Northeast is often affected by extreme events such as ice storms, floods, droughts, heat waves, hurricanes, and major storms in the Atlantic Ocean off the northeast coast, referred to as nor'easters. However, variability is large in both space and


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time. For example, parts of southern New England that experienced heavy snows in the cold season of 2010-2011 experienced little snow during the cold season of 2011-2012. Of course, even a season with low totals can feature costly extreme events; snowfall during a 2011 pre-Halloween storm that hit most of the Northeast, when many trees were still in leaf, knocked out power for up to 10 days for thousands of households.


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Observed Climate Change

Between 1895 and 2011, temperatures in the Northeast increased by almost 2°F (0.16°F per decade), and precipitation increased by approximately five inches, or more than 10% (0.4 inches per decade).[3] Coastal flooding has increased due to a rise in sea level of approximately 1 foot since 1900. This rate of sea level rise exceeds the global average of approximately 8 inches (see Ch. 2: Our Changing Climate, Key Message 10; Ch. 25: Coasts), due primarily to land subsidence,[4] although recent research suggests that changes in ocean circulation in the North Atlantic – specifically, a weakening of the Gulf Stream – may also play a role.[5]

The Northeast has experienced a greater recent increase in extreme precipitation than any other region in the United States; between 1958 and 2010, the Northeast saw more than a 70% increase in the amount of precipitation falling in very heavy events (defined as the heaviest 1% of all daily events) (see Ch. 2: Our Changing Climate, Figure 2.18).[7]

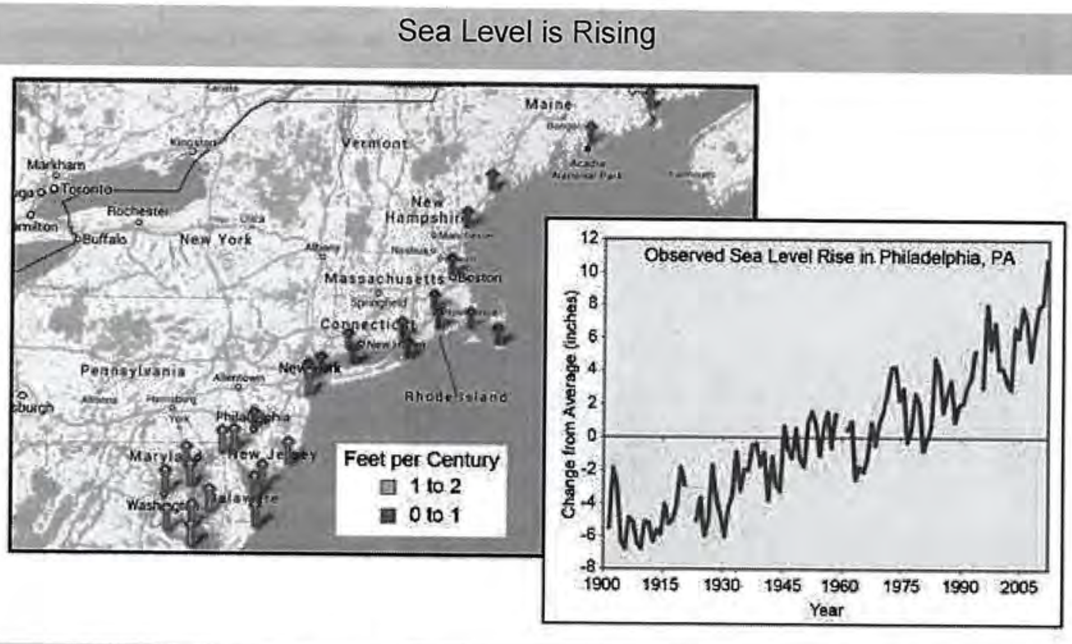
Sea Level is Rising

Figure 16.1. (Map) Local sea level trends in the Northeast region. Length of time series for each arrow varies by tide gauge location. (Figure source: NOAA[6]). (Graph) Observed sea level rise in Philadelphia, PA, has significantly exceeded the global average of 8 inches over the past century, increasing the risk of impacts to critical urban infrastructure in low-lying areas. Over 100 years (1901-2012), sea level increased 1.2 feet (Data from Permanent Service for Mean Sea Level).

Projected Climate Change

As in other areas, the amount of warming in the Northeast will be highly dependent on global emissions of heat-trapping gases. If emissions continue to increase (as in the A2 scenario), warming of 4.5F° to 10°F is projected by the 2080s; if global emissions were reduced substantially (as in the B1 scenario), projected warming ranges from about 3°F to 6°F by the 2080s.[3]

Under both emissions scenarios, the frequency, intensity, and duration of heat waves is expected to increase, with larger increases under higher emissions (Ch. 2: Our Changing Climate). Much of the southern portion of the region, including the majority of Maryland and Delaware, and southwestern West Virginia and New Jersey, are projected by mid-century to experience many more days per year above 90°F compared to the end of last century under continued increases in emissions (Figure 16.2, A2 scenario). This will affect the region's vulnerable populations, infrastructure, agriculture, and ecosystems.

The frequency, intensity, and duration of cold air outbreaks is expected to decrease as the century progresses, although some research suggests that loss of Arctic sea ice could indirectly reduce this trend by modifying the jet stream and mid-latitude weather patterns.[8,9]

Projections of precipitation changes are less certain than projections of temperature increases.[3] Winter and spring precipitation is projected to increase, especially but not exclusively in the northern part of the region (Ch. 2: Our Changing Climate, Key Messages 5 and 6).[3,10] A range of model projections for the end of this century under a higher emissions scenario (A2), averaged over the region, suggests about 5% to 20% (25th to 75th percentile of model projections) increases in winter precipitation. Projected changes in summer and fall, and for the entire year, are generally small at the end of the century compared to natural variations (Ch. 2: Our Changing Climate, Key Message 5).[3] The frequency of heavy downpours is projected to continue to increase as the century progresses (Ch. 2: Our Changing Climate, Key Message 6). Seasonal drought risk is also projected to increase in summer and fall as higher temperatures lead to greater evaporation and earlier winter and spring snowmelt.[11]

Global sea levels are projected to rise 1 to 4 feet by 2100 (Ch. 2: Our Changing Climate, Key Message 10),[12] depending in large part on the extent to which the Greenland and West Antarctic Ice Sheets experience significant melting. Sea level rise along most of the coastal Northeast is expected to exceed the global average rise due to local land subsidence, with the possibility of even greater regional sea level rise if the Gulf Stream weakens as some models suggest.[5,13] Sea level rise of two feet, without any changes in storms, would more than triple the frequency of dangerous coastal flooding throughout most of the Northeast.[14]

Although individual hurricanes cannot be directly attributed to climate change, Hurricanes Irene and Sandy nevertheless provided "teachable moments" by demonstrating the region's vulnerability to extreme weather events and the potential for adaptation to reduce impacts.

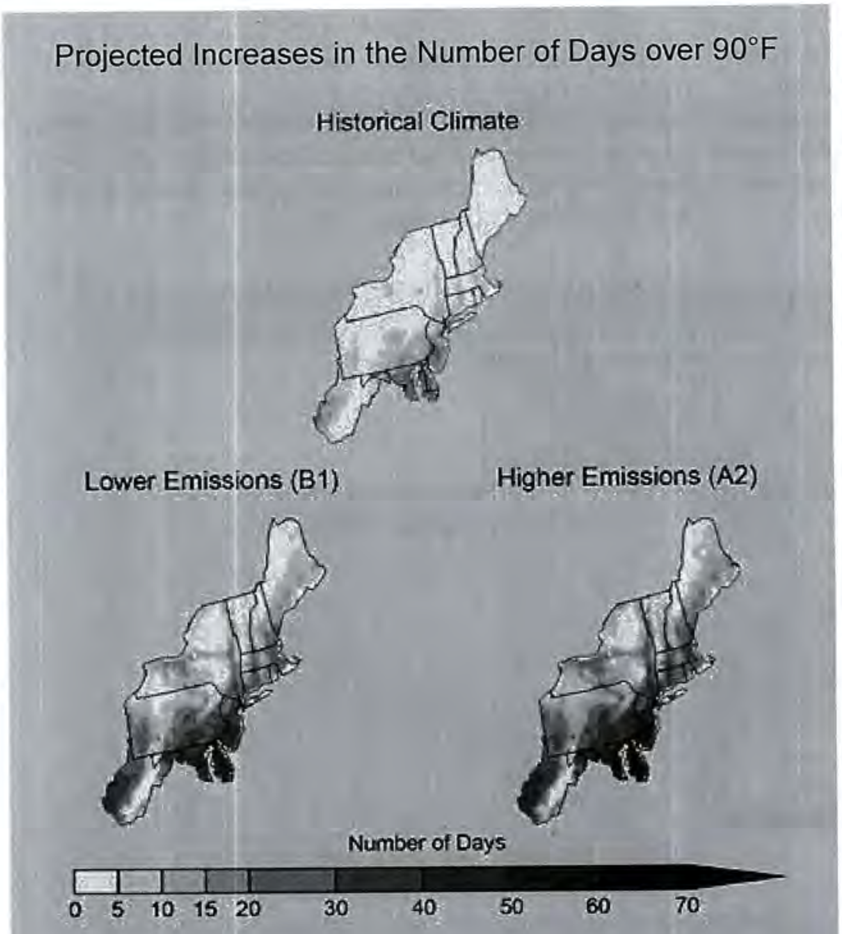

Figure 16.2. Projected number of days per year with a maximum temperature greater than 90°F averaged between 2041 and 2070, compared to 1971-2000 (Historical Climate), assuming continued increases in global emissions (A2) and substantial reductions in future emissions (B1). (Figure source: NOAA NCDC / CICS-NC).

HURRICANE VULNERABILITY

Two recent events contrast existing vulnerability to extreme events: Hurricane Irene, which produced a broad swath of very heavy rain (greater than five inches in total and sometimes two to three inches per hour in some locations) from southern Maryland to northern Vermont from August 27 to 29, 2011; and Hurricane Sandy, which caused massive coastal damage from storm surge and flooding along the Northeast coast from October 28 to 30, 2012.

Rainfall associated with Irene led to hydrological extremes in the region. These heavy rains were part of a broader pattern of wet weather preceding the storm (rainfall totals for August and September exceeded 25 inches across much of the Northeast) that left the region predisposed to extreme flooding from Irene; for example, the Schoharie Creek in New York experienced a 500-year flood.[15]

In anticipation of Irene, the New York City mass transit system was shut down, and 2.3 million coastal residents in Delaware, New Jersey, and New York faced mandatory evacuations. However, it was the inland impacts, especially in upstate New York and in central and southern Vermont, that were most severe. Ironically, many New York City residents fled to inland locations, which were harder hit. Flash flooding washed out roads and bridges, undermined railroads, brought down trees and power lines, flooded homes and businesses, and damaged floodplain forests. In Vermont, more than 500 miles of roadways and approximately 200 bridges were damaged, with estimated rebuilding costs of $175 to $250 million. Hazardous wastes were released in a number of areas, and 17 municipal wastewater treatment plants were breached by floodwaters. Agricultural losses included damage to barn structures and flooded fields of crops. Many towns and villages were isolated for days due to infrastructure impacts from river flooding (see also Ch. 5: Transportation, "Tropical Storm Irene Devastates Vermont Transportation in August 2011").[2] Affected residents suffered from increased allergen exposure due to mold growth in flooded homes and other structures and were exposed to potentially harmful chemicals and pathogens in their drinking water. In the state of Vermont, cleaning up spills from aboveground hazardous waste tanks cost an estimated $1.75 million. Septic systems were also damaged from high groundwater levels and river or stream erosion, including 17 septic system failures in the state of Vermont.[17]

Flooding and Hurricane Irene

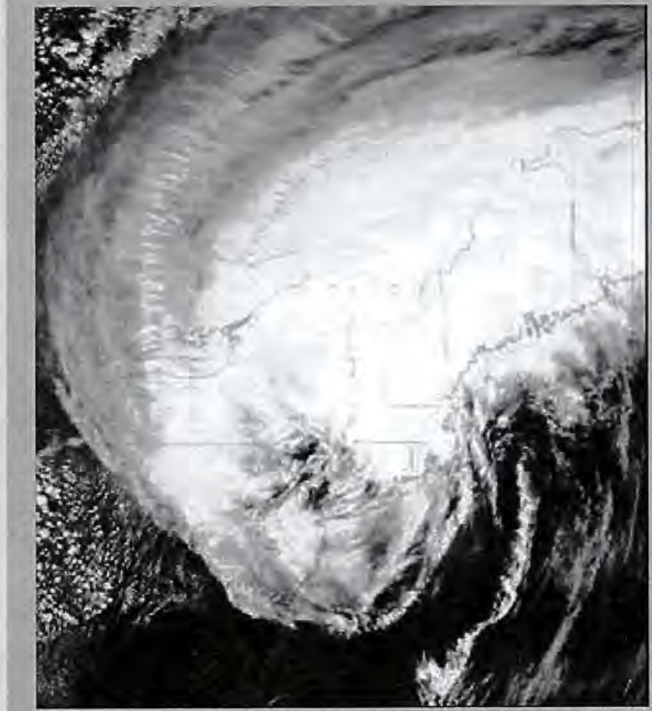

Figure 16.3. Hurricane Irene over the Northeast on August 28, 2011. The storm, which brought catastrophic flooding rains to parts of the Northeast, took 41 lives in the United States, and the economic cost was estimated at $16 billion.[16] (Figure source: MODIS instrument on NASA's Aqua satellite).

Sandy was responsible for about 150 deaths, approximately half of which occurred in the Northeast.[18] Damages, concentrated in New Jersey, New York, and Connecticut, were estimated at $60 to $80 billion, making Sandy the second most costly Atlantic Hurricane in history behind Katrina.[19] It is also estimated that 650,000 homes were damaged or destroyed, and that 8.5 million people were without power.[18] Floodwaters inundated subway tunnels in New York City (see also Ch. 5: Transportation, "Hurricane Sandy"). Sandy also caused significant damage to the electrical grid and overwhelmed sewage treatment plants.[18] In New Jersey, repairs to damaged power and gas lines are expected to cost about $1 billion, and repairs to waste, water, and sewer systems are expected to cost $3 billion.

Many of these vulnerabilities to coastal flooding and sea level rise (Ch. 2: Our Changing Climate, Key Message 10) and intensifying storms (Ch. 2: Our Changing Climate, Key Messages 8 and 9) – including the projected frequency of flooding of tunnels and airports – were documented as early as 2001 in a report developed in support of the 2000 National Climate Assessment.[20] Despite such reports, the observed vulnerability was a surprise to many coastal residents, which suggests improved communication is needed.

Continued

HURRICANE VULNERABILITY

Over the last decade, cities, states, and agencies in the New York metropolitan region took steps to reduce their vulnerability to coastal storms.[21] In 2008, New York City convened a scientific body of experts – the New York City Panel on Climate Change (NPCC) – and formed a Climate Adaptation Task Force comprised of approximately 40 agencies, private sector companies, and regional groups. A process, approach, and tools for climate change adaptation were developed and documented in New York City[11,22] and New York State.[23] In 2012, the NPCC and Climate Adaptation Task Force were codified into New York City law, a key step towards institutionalizing climate science, impact, and adaptation assessment into long-term planning.[24]

These initiatives led to adaptation efforts, including elevating infrastructure, restoring green spaces, and developing evacuation plans that helped reduce damage and save lives during Irene and Sandy (also see discussion of Hurricane Sandy in Ch. 11: Urban). As rebuilding and recovery advances,[24] decision-making based on current and projected risks from such events by a full set of stakeholders and participants in the entire Northeast could dramatically improve resilience across the region.

Coastal Flooding Along New Jersey's Shore

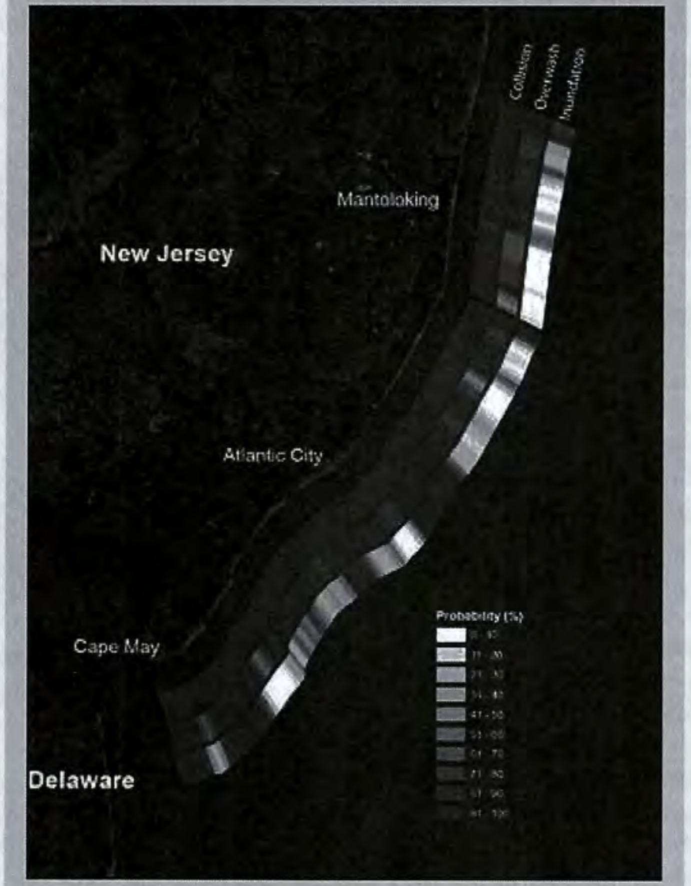

Figure 16.4. Predictions of coastal erosion prior to Sandy's arrival provided the region's residents and decision-makers with advance warning of potential vulnerability. The map shows three bands: collision of waves with beaches causing erosion on the front of the beach; overwash that occurs when water reaches over the highest point and erodes from the rear, which carries sand inland; and inundation, when the shore is severely eroded and new channels can form that lead to permanent flooding. The probabilities are based on the storm striking at high tide. For New Jersey, the model estimated that 21% of the shoreline had more than a 90% chance of experiencing inundation. These projections were realized, and made the New Jersey coastline even more vulnerable to the nor'easter that followed Hurricane Sandy by only 10 days. (Figure source: ESRI and USGS 2012[25]).

Key Message 1: Climate Risks to People

Heat waves, coastal flooding, and river flooding will pose a growing challenge to the region's environmental, social, and economic systems. This will increase the vulnerability of the region's residents, especially its most disadvantaged populations.

Urban residents have unique and multifaceted vulnerabilities to heat extremes. Northeastern cities, with their abundance of concrete and asphalt and relative lack of vegetation, tend to have higher temperatures than surrounding regions (the "urban heat island" effect). During extreme heat events, nighttime temperatures in the region's big cities are generally several degrees higher[26] than surrounding regions, leading to increased heat-related death among those less able to recover from the heat of the day.[27] Since the hottest days in the Northeast are often associated with high concentrations of ground-level ozone and other pollutants,[28] the combination of heat stress and poor air quality can pose a major health risk to vulnerable groups: young children, the elderly, and those with pre-existing health conditions including asthma.[29] Vulnerability is further increased as key infrastructure, including electricity for potentially life-saving air conditioning, is more likely to fail precisely when it is most needed – when demand exceeds available supply. Significant investments may be required to ensure that power generation keeps up with rising demand associated with rising temperatures.[30] Finally, vulnerability to heat waves is not evenly distributed throughout urban areas; outdoor versus indoor air temperatures, air quality, baseline health, and access to air conditioning are all dependent on socioeconomic factors.[29] Socioeconomic factors that tend to increase vulnerability to such hazards include race and ethnicity (being a minority), age (the elderly and children), gender (female), socioeconomic status (low income, status, or poverty), and education (low educational attainment). The condition of human settlements (type of housing and construction, infrastructure, and access to lifelines) and the built environment are also important determinants of socioeconomic vulnerability, especially given the fact that these characteristics influence potential economic losses, injuries, and mortality.[31]

Urban Heat Island

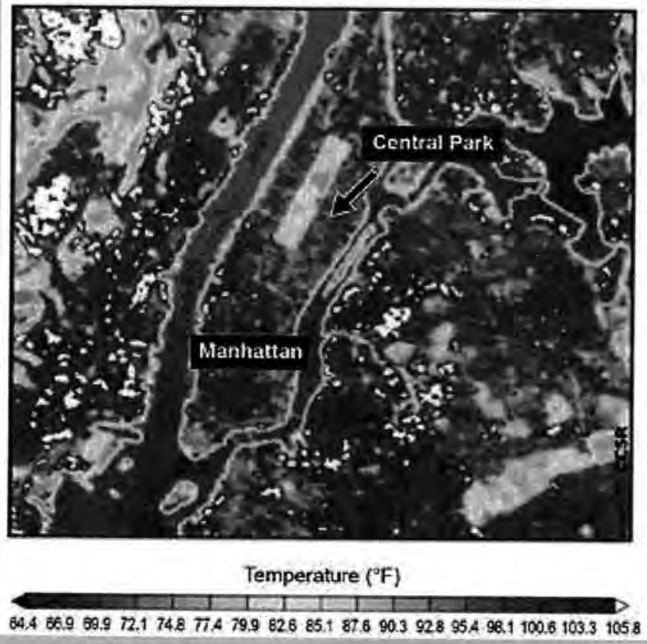

Figure 16.5. Surface temperatures in New York City on a summer's day show the "urban heat island," with temperatures in populous urban areas being approximately 10°F higher than the forested parts of Central Park. Dark blue reflects the colder waters of the Hudson and East Rivers. (Figure source: Center for Climate Systems Research, Columbia University).

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Increased health-related impacts and costs, such as premature death and hospitalization due to even modest increases in heat, are predicted in the Northeast's urban centers (Ch. 9: Human Health).[32] One recent study projected that temperature changes alone would lead to a 50% to 91% increase in heat-related deaths in Manhattan by the 2080s (relative to a 1980s baseline).[33] Increased ground-level ozone due to warming is projected to increase emergency department visits for ozone-related asthma in children (0 to 17 years of age) by 7.3% by the 2020s (given the A2 scenario) relative to a 1990 baseline of approximately 650 visits in the New York metropolitan area.[34]

Heat wave research has tended to focus on urban areas, but vulnerability to heat may also become a major issue in rural areas and small towns because air conditioning is currently not prevalent in parts of the rural Northeast where heat waves have historically been rare. Some areas of northern New England, near the Canadian border, are projected to shift from having less than five to more than 15 days per year over 90°F by the 2050s under the higher emissions scenario (A2) of heat-trapping gases.[3] It should be noted that winter heating needs, a significant expense for many Northeastern residents, are likely to decrease as the century progresses.[35]

The impacts of climate change on public health will extend beyond the direct effects of temperature on human physiology. Changing distributions of temperature, precipitation, and carbon dioxide could affect the potency of plant allergens,[36] and there has been an observed increase of 13 to 27 days in the ragweed pollen season at latitudes above 44°N.[36]

Vector-borne diseases are an additional concern. Most occurrences of Lyme disease in United States are in the Northeast, especially Connecticut.[37] While it is unclear how climate change will impact Lyme disease,[38] several studies in the Northeast have linked tick activity and Lyme disease incidence to climate, specifically abundant late spring and early summer moisture.[39] West Nile Virus (WNV) is another vector-borne disease that may be influenced by changes in climate. Suitable habitat for the Asian Tiger Mosquito, which can transmit West Nile and other vector-borne diseases, is expected to increase in the Northeast from the current 5% to 16% in the next two decades and from 43% to 49% by the end of the century, exposing more than 30 million people to the threat of dense infestations by this species.[40]

Many Northeast cities, including New York, Boston, and Philadelphia, are served by combined sewer systems that collect and treat both stormwater and municipal wastewater. During heavy rain events, combined systems can be overwhelmed and untreated water may be released into local water bodies. In Connecticut, the risk for contracting a stomach illness while swimming significantly increased after a one inch precipitation event,[41] and studies have found associations between diarrheal illness among children and sewage discharge in Milwaukee.[42] More frequent heavy rain events could therefore increase the incidence of waterborne disease.

Historical settlement patterns and ongoing investment in coastal areas and along major rivers combine to increase the vulnerabilities of people in the Northeast to sea level rise and coastal storms. Of the Northeast's population of 64 million,[43] approximately 1.6 million people live within the Federal Emergency Management Agency's (FEMA) 100-year coastal flood zone, with the majority – 63% of those at risk – residing in New York and New Jersey.[44] As sea levels rise, populations in the current 1-in-100-year coastal flood zone (defined as the area with at least a 1% chance of experiencing a coastal flood in a given year) will experience more frequent flooding, and populations that have historically fallen outside the 1-in-100-year flood zone will find themselves in that zone. People living in coastal flood zones are vulnerable to direct loss of life and injury associated with tropical storms and nor'easters. Flood damage to personal property, businesses, and public infrastructure can also result (see Key Message 2).

This risk is not limited to the 1-in-100-year flood zone; in the Mid-Atlantic part of the region alone, estimates suggest that between 450,000 and 2.3 million people are at risk from a three foot sea level rise,[45] which is in the range of projections for this century.

Throughout the Northeast, populations are also concentrated along rivers and their flood plains. In mountainous regions, including much of West Virginia and large parts of Pennsylvania, New York, Vermont, and New Hampshire, more intense precipitation events (Ch. 2: Our Changing Climate)[3] will mean greater flood risk, particularly in valleys, where people, infrastructure, and agriculture tend to be concentrated.

Key Message 2: Stressed Infrastructure

Infrastructure will be increasingly compromised by climate-related hazards, including sea level rise, coastal flooding, and intense precipitation events.

Disruptions to services provided by public and private infrastructure in the Northeast both interrupt commerce and threaten public health and safety (see also Ch. 11: Urban).[46] In New York State, two feet of sea level rise is estimated (absent adaptation investment) to flood or render unusable 212 miles of roads, 77 miles of rail, 3,647 acres of airport facilities, and 539 acres of runways.[47] Port facilities, such as in Maryland (primarily Baltimore), also have flooding impact estimates: 298 acres, or 32% of the overall port facilities in the state.[47] These impacts have potentially significant economic ramifications. For example, in 2006 alone the Port of Baltimore generated more than 50,200 jobs, $3.6 billion in personal income, $1.9 billion in business revenues, and $388 million in state, county, and municipal tax.[48] The New York City Panel on Climate Change highlighted a broader range of climate impacts on infrastructure sectors (see Table 16.1).[11] Although this study focused specifically on New York City, these impacts are applicable throughout the region. Predicted impacts of coastal flooding on infrastructure were largely borne out by Hurricane Sandy; sea level rise will only increase these vulnerabilities.

The more southern states within the region, including Delaware and Maryland, have a highly vulnerable land area because of a higher rate of sea level rise and relatively flat coastlines compared to the northern tier. The northern states, including Massachusetts, Rhode Island, and Connecticut, have less land area exposed to a high inundation risk because of a lower relative sea level rise and because of their relatively steep coastal terrain.[49] Still, low-lying coastal metropolitan areas in New England have considerable infrastructure at risk. In Boston alone, cumulative damage to buildings and building contents, as well as the associated emergency costs, could potentially be as high as $94 billion between 2000 and 2100, depending on the sea level rise scenario and which adaptive actions are taken.[50]

Table 16.1. Impacts of sea level rise and coastal floods on critical coastal infrastructure by sector. Sources: Horton and Rosenzweig 2010,[51] Zimmerman and Faris 2010,[52] and Ch. 25: Coasts.

Communications	Energy	Transportation	Water and Waste
Higher average sea level			
• Increased saltwater encroachment and damage to low-lying communications infrastructure not built to withstand saltwater exposure • Increased rates of coastal erosion and/or permanent inundation of low-lying areas, causing increased maintenance costs and shortened replacement cycles • Cellular tower destruction or loss of function	• Increased coastal erosion rates and/or permanent inundation of low-lying areas, threatening coastal power plants • Increased equipment damage from corrosive effects of saltwater encroachment, resulting in higher maintenance costs and shorter replacement cycles	• Increased saltwater encroachment and damage to infrastructure not built to withstand saltwater exposure • Increased coastal erosion rates and/or permanent inundation of low-lying areas, resulting in increased maintenance costs and shorter replacement cycles • Decreased clearance levels under bridges	• Increased saltwater encroachment and damage to water and waste infrastructure not built to withstand saltwater exposure • Increased release of pollution and contaminant runoff from sewer systems, treatment plants, brownfields, and waste storage facilities • Permanent inundation of low-lying areas, wetlands, piers, and marine transfer stations • Increased saltwater infiltration into freshwater distribution systems
More frequent and intense coastal flooding			
• Increased need for emergency management actions with high demand on communications infrastructure • Increased damage to communications equipment and infrastructure in low-lying areas	• Increased need for emergency management actions • Exacerbated flooding of low-lying power plants and equipment, as well as structural damage to infrastructure due to wave action • Increased use of energy to control floodwaters • Increased number and duration of local outages due to flooded and corroded equipment	• Increased need for emergency management actions • Exacerbated flooding of streets, subways, tunnel and bridge entrances, as well as structural damage to infrastructure due to wave action • Decreased levels of service from flooded roadways; increased hours of delay from congestion during street flooding episodes • Increased energy use for pumping	• Increased need for emergency management actions • Exacerbated street, basement, and sewer flooding, leading to structural damage to infrastructure • Episodic inundation of low-lying areas, wetlands, piers, and marine transfer stations

Coney Island after Hurricane Irene

Figure 16.6. Flooded subway tracks in Coney Island after Hurricane Irene. (Photo credit: Metropolitan Transportation Authority of the State of New York 2011).

In the transportation sector (see also Ch. 5: Transportation), many of the region's key highways (including I-95) and rail systems (including Amtrak and commuter rail networks) span areas that are prone to coastal flooding. In addition to temporary service disruptions, storm surge flooding can severely undermine or disable critical infrastructure along coasts, including subway systems, wastewater treatment plants, and electrical substations. Saltwater corrosion can damage sensitive and critical electrical equipment, such as electrical substations for energy distribution and signal equipment for rail systems; corrosion also accelerates rust damage on rail lines. Saltwater also threatens groundwater supplies and damages wastewater treatment plants.

Key Message 3: Agricultural and Ecosystem Impacts

Agriculture, fisheries, and ecosystems will be increasingly compromised over the next century by climate change impacts. Farmers can explore new crop options, but these adaptations are not cost- or risk-free. Moreover, adaptive capacity, which varies throughout the region, could be overwhelmed by a changing climate.

Farmers in the Northeast are already experiencing consequences of climate change. In addition to direct crop damage from increasingly intense precipitation events, wet springs can delay planting for grain and vegetables in New York, for example, and subsequently delay harvest dates and reduce yields.[53] This is an issue for agriculture nationally,[54] but is particularly acute for the Northeast, where heavy rainfall events have increased more than in any other region of the country (Ch. 2: Our Changing Climate, Key Message 6).[7] In the future, farmers may also face too little water in summer to meet increased crop water demand as summers become hotter and growing seasons lengthen.[55,56] Increased frequency of summer heat stress is also projected, which can negatively affect crop yields and milk production.[57]

Despite a trend toward warmer winters, the risk of frost and freeze damage continues, and has paradoxically increased over the past decade (see also Ch. 8: Ecosystems). These risks are exacerbated for perennial crops in years with variable winter temperatures. For example, midwinter-freeze damage cost wine grape growers in the Finger Lakes region of New York millions of dollars in losses in the winters of 2003 and 2004.[58] This was likely due to de-hardening of the vines during an unusually warm December, which increased susceptibility to cold damage just prior to a subsequent hard freeze. Another avenue for cold damage, even in a relatively warm winter, is when there is an extended warm period in late winter or early spring causing premature leaf-out or bloom, followed by a damaging frost event, as occurred throughout the Northeast in 2007[59] and again in 2012 when apple, grape, cherry, and other fruit crops were hard hit.[60]

Increased weed and pest pressure associated with longer growing seasons and warmer winters will be an increasingly important challenge; there are already examples of earlier arrival and increased populations of some insect pests such as corn earworm.[57] Furthermore, many of the most aggressive weeds, such as kudzu, benefit more than crop plants from higher atmospheric carbon dioxide, and become more resistant to herbicide control.[61] Many weeds respond better than most cash crops to increasing carbon dioxide concentrations, particularly "invasive" weeds with the so-called C_3 photosynthetic pathway, and with rapid and expansive growth patterns, including large allocations of below-ground biomass, such as roots.[62] Research also suggests that glyphosate (for example, Roundup), the most widely-used herbicide in the United States, loses its efficacy on weeds grown at the increased carbon dioxide levels likely to occur in the coming decades.[63] To date, all weed/crop competition studies where the photosynthetic pathway is the same for both species favor weed growth over crop growth as carbon dioxide is increased.[61]

Effects of rising temperatures on the Northeast's ecosystems have already been clearly observed (see also Ch. 8: Ecosystems). Further, changes in species distribution by elevation are occurring; a Vermont study found an upslope shift of 299 to 390 feet in the boundary between northern hardwoods and boreal forest on the western slopes of the Green Mountains between 1964 and 2004.[64] Wildflowers[65] and woody perennials are blooming earlier [66] and migratory birds are arriving sooner.[67] Because species differ in their ability to adjust, asynchronies (like a mismatch between key food source availability and migration patterns) can develop, increasing species and ecosystem vulnerability. Several bird species have expanded their ranges northward[68] as have some invasive insect species, such as the hemlock woolly adelgid,[69] which has devastated hemlock trees. Warmer winters and less snow cover in recent years have contributed to increased deer populations[70] that degrade forest understory vegetation.[71]

As ocean temperatures continue to rise, the range of suitable habitat for many commercially important fish and shellfish species is projected to shift northward. For example, cod and lobster fisheries south of Cape Cod are projected to have significant declines.[72] Although suitable habitats will be shrinking for some species (such as coldwater fish like brook trout) and expanding for others (such as warmwater fish like bass), it is difficult to predict what proportion of species will be able to move or adapt as their optimum climate zones shift.[73] As each species responds uniquely to climate change, disruptions of important species interactions (plants and pollinators; predators and prey) can be expected. For example, it is uncertain what forms of vegetation will move into the Adirondack Mountains when the suitable habitat for spruce-fir forests disappears.[74] Increased productivity of some northern hardwood trees in the Northeast is projected (due to longer growing seasons and assuming a significant benefit from higher atmospheric carbon dioxide), but summer drought and other extreme events may offset potential productivity increases.[75] Range shifts in traditional foods gathered from the forests by Native American communities, such as Wabanaki berries in the Northeast, can have negative health and cultural impacts (Ch. 12: Indigenous Peoples).[76]

In contrast, many insect pests, pathogens, and invasive plants like kudzu appear to be highly and positively responsive to recent and projected climate change.[77] Their expansion will lead to an overall loss of biodiversity, function, and resilience of some ecosystems.

The Northeast's coastal ecosystems and the species that inhabit them are highly vulnerable to rising seas (see also Ch. 25: Coasts, Key Message 4). Beach and dune erosion, both a cause and effect of coastal flooding, is also a major issue in the Northeast.[78,79] Since the early 1800s, there has been an estimated 39% decrease in marsh coverage in coastal New England; in the metropolitan Boston area, marsh coverage is estimated to be less than 20% of its late 1700s value.[80] Impervious urban surfaces and coastal barriers such as seawalls limit the ability of marshes to expand inland as sea levels rise.[81]

THE CHESAPEAKE BAY

The Chesapeake Bay is the largest U.S. estuary, with a drainage basin that extends over six states. It is a critical and highly integrated natural and economic system threatened by changing land-use patterns and a changing climate – including sea level rise, higher temperatures, and more intense precipitation events. The ecosystem has a central role in the economy, including providing sources of food for people and the region's other inhabitants, and cooling water for the energy sector. It also provides critical ecosystem services.

As sea levels rise, the Chesapeake Bay region is expected to experience an increase in coastal flooding and drowning of estuarine wetlands. The lower Chesapeake Bay is especially at risk due to high rates of sinking land (known as subsidence).[82] Climate change and sea level rise are also likely to cause a number of ecological impacts, including declining water quality and clarity, increases in harmful algae and low oxygen (hypoxia) events, decreases in a number of species including eelgrass and seagrass beds, and changing interactions among trophic levels (positions in the food chain) leading to an increase in subtropical fish and shellfish species in the bay.[83]

Key Message 4: Planning and Adaptation

While a majority of states and a rapidly growing number of municipalities have begun to incorporate the risk of climate change into their planning activities, implementation of adaptation measures is still at early stages.

Of the 12 states in the Northeast, 11 have developed adaptation plans for several sectors and 10 have released, or plan to release, statewide adaptation plans.[84] Given the interconnectedness of climate change impacts and adaptation, multi-state coordination could help to ensure that information is shared efficiently and that emissions reduction and adaptation strategies do not operate at cross-purposes.

Figure 16.7. The Nature Conservancy's adaptation decision-support tool (www.coastalresilience.org)[88] depicts building-level impacts due to inundation (developed land cover, yellow areas) and potential marsh advancement zones (undeveloped land cover – currently forest, grass, and agriculture – blue areas) using downscaled sea level rise projections (52 inches by 2080s depicted) along the Connecticut and New York coasts. (Figure source: Ferdaña et al. 2010,[90] Beck et al. 2013[89]).

Local and state governments in the Northeast have been leaders and incubators in utilizing legal and regulatory opportunities to foster climate change policies.[85] The Regional Greenhouse Gas Initiative (RGGI) was the first market-based regulatory program in the U.S. aimed at reducing greenhouse gas emissions; it is a cooperative effort among nine northeastern states.[86] Massachusetts became the first state to officially incorporate climate change impacts into its environmental review procedures by adopting legislation that directs agencies to "consider reasonably foreseeable climate change impacts, including additional greenhouse gas emissions, and effects, such as predicted sea level rise."[87] In addition, Maine, Massachusetts, and Rhode Island have each adopted some form of "rolling easement" to ensure that wetlands or dunes migrate inland as sea level rises and reduce the risk of loss of life and property.[45]

Northeast cities have employed a variety of mechanisms to respond to climate change, including land-use planning, provisions to protect infrastructure, regulations related to the design and construction of buildings, and emergency preparation, response, and recovery.[91] While significant progress has been made, local governments still face limitations of legal authority, geographic jurisdiction, and resource constraints that could be addressed through effective engagement and support from higher levels of government.

Keene, New Hampshire, has been a pilot community for ICLEI's Climate Resilient Communities program for adaptation planning[92] – a process implemented through innovative community engagement methods.[93] The Cape Cod Commission is another example in New England; the Commission has drafted model ordinances to help communities incorporate climate into zoning decision-making. Farther south, New York City has taken numerous steps to implement PlaNYC, a far-reaching sustainability plan for the city, including amending the construction code and the zoning laws and the implementation of measures focused on developing adaptation strategies to protect the City's public and private infrastructure from the effects of climate change;[24] some major investments in protection have even been conceptualized.

Storm Surge Barrier

Figure 16.8. Conceptual design of a storm surge barrier in New York City. (Figure source: Jansen and Dircke 2009).

One widely used adaptation-planning template is the eight-step iterative approach developed by the New York City Panel on Climate Change; it was highlighted in the contribution of the National Academy of Science's Adaptation Panel to America's Climate Choices and adopted by the Committee on America's Climate Choices. It describes a procedure that decision-makers at all levels can use to design a flexible adaptation pathway to address infrastructure and other response issues through inventory and assessment of risk. The key, with respect to infrastructure, is to link adaptation strategies with capital improvement cycles and adjustment of plans to incorporate emerging climate projections[11,94] – but the insights are far more general than that (see the Adaptation Panel Report[95]).

In most cases, adaptation requires information and tools coupled to a decision-support process steered by strong leadership, and there are a growing number of examples in the Northeast. At the smaller, municipal scale, coastal pilot projects in Maryland,[96] Delaware,[97] New York, and Connecticut[90] are underway.

Research and outreach efforts are underway in the region to help farmers find ways to cope with a rapidly changing climate, take advantage of a longer growing season, and reduce greenhouse gas emissions,[56,98] but unequal access to capital and information for strategic adaptation and mitigation remain a challenge. Financial barriers can constrain farmer adaptation.[99] Even relatively straightforward adaptations such as changing varieties are not always a low-cost option. Seed for new stress-tolerant varieties is sometimes expensive or regionally unavailable, and new varieties often require investments in new planting equipment or require adjustment in a wide range of farming practices. Investment in irrigation and drainage systems are relatively expensive options, and a challenge for farmers will be determining when the frequency of yield losses due to summer water deficits or flooding has or will become frequent enough to warrant such capital investments.

Regional activities in the Northeast are also being linked to federal efforts. For example, NASA's Agency-wide Climate Adaptation Science Investigator Workgroup (CASI) brings together NASA facilities managers with NASA climate scientists in local Climate Resilience Workshops. This approach was in evidence at the Goddard Space Flight Center in Maryland, where scientists helped institutional managers address energy and stormwater management vulnerabilities.

MAINE'S CULVERTS: AN ADAPTATION CASE STUDY

Culverts and the structures they protect are receiving increasing attention, since they are vulnerable to damage during the types of extreme precipitation events that are occurring with increasing frequency in the Northeast (Ch. 2: Our Changing Climate, Key Message 6; Ch. 5: Transportation). For instance, severe storms in the Northeast that were projected in the 1950s to occur only once in 100 years, now are projected to occur once every 60 years.[100]

The Maine Department of Transportation manages more than 97,000 culverts, but individual property owners or small towns manage even more; Scarborough, Maine, for example, has 2,127 culverts. When 71 town managers and officials in coastal Maine were surveyed as part of the statewide Sustainability Solutions Initiative, culverts, with their 50 to 65 year expected lifespan, emerged atop a wish list for help in adapting to climate change.[101]

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A research initiative that mapped decisions by town managers in Maine to sources of climate information, engineering design, mandated requirements, and calendars identified the complex, multi-jurisdictional challenges of widespread adaptation for even such seemingly simple actions as using larger culverts to carry water from major storms.[101] To help towns adapt culverts to expected climate change over their lifetimes, the Sustainability Solutions Initiative is creating decision tools to map culvert locations, schedule maintenance, estimate needed culvert size, and analyze replacement needs and costs.

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SUPPLEMENTAL MATERIAL
TRACEABLE ACCOUNTS

Process for Developing Key Messages:
Results of the Northeast Regional Climate assessment workshop that was held on November 17-18, 2011, at Columbia University, with approximately 60 attendees, were critically important in our assessment. The workshop was the beginning of the process that led to the foundational Technical Input Report (TIR).[2] That 313-page report consisted of seven chapters by 13 lead authors and more than 60 authors in total. Public and private citizens or institutions who service and anticipate a role in maintaining support for vulnerable populations in Northeast cities and communities indicated that they are making plans to judge the demand for adaptation services. These stakeholder interactions were surveyed and engaged in the preparation of this chapter. We are confident that the TIR authors made a vigorous attempt to engage various agencies at the state level and non-governmental organizations (NGOs) that have broader perspectives.

The author team engaged in multiple technical discussions via teleconferences, which included careful review of the foundational TIR[2] and approximately 50 additional technical inputs provided by the public, as well as the other published literature and professional judgment. Discussions were followed by expert deliberation of draft key messages by the authors and targeted consultation with additional experts by the lead author of each key message.

KEY MESSAGE #1 TRACEABLE ACCOUNT

Heat waves, coastal flooding, and river flooding will pose a growing challenge to the region's environmental, social, and economic systems. This will increase the vulnerability of the region's residents, especially its most disadvantaged populations.

Description of evidence base
The key message and supporting text summarizes extensive evidence documented in the Northeast Technical Input Report.[2] Nearly 50 Technical Input reports, on a wide range of topics, were also received and reviewed as part of the Federal Register Notice solicitation for public input.

Numerous peer-reviewed publications (including many that are not cited) describe increasing hazards associated with sea level rise and storm surge, heat waves, and intense precipitation and river flooding for the Northeast. For sea level rise (SLR), the authors relied on the NCA SLR scenario[12] and research by the authors on the topic (for example, Horton et al. 2010[51]). Recent work[26] summarizes the literature on heat islands and extreme events. For a recent study on climate in the Northeast,[3] the authors worked closely with the region's state climatologists on both the climatology and projections.

The authors also considered many recent peer-reviewed publications[29,32,34,44] that describe how human vulnerabilities to climate hazards in the region can be increased by socioeconomic and other factors. Evaluating coupled multi-system vulnerabilities is an emerging field; as a result, additional sources including white papers[3] have informed this key message as well.

To capture key issues, concerns, and opportunities in the region, various regional assessments were also consulted, such as PlaNYC (http://www.nyc.gov/html/planyc2030) and Boston's Climate Plan (http://www.cityofboston.gov/Images_Documents/A%20Climate%20of%20Progress%20-%20CAP%20Update%202011_tcm3-25020.pdf).

New information and remaining uncertainties
Important new evidence (cited above) confirmed many of the findings from a prior Northeast assessment[10] (see http://nca2009.globalchange.gov/northeast).

The evidence included results from improved models and updated observational data (for example, Liu et al. 2012; Parris et al. 2012; Sallenger et al. 2012[5,9,12]). The current assessment included insights from stakeholders collected in a series of distributed engagement meetings that confirm its relevance and significance for local decision-makers; examples include a Northeast Listening Session in West Virginia, a kickoff meeting in New York City, and New York City Panel on Climate Change meetings.

There is wide diversity of impacts across the region driven by both exposure and sensitivity that are location and socioeconomic context specific. Future vulnerability will be influenced by changes in demography, economics, and policies (development and climate driven) that are difficult to predict and dependent on international and national considerations. Another uncertainty is the potential for adaptation strategies (and to a lesser extent mitigation) to reduce these vulnerabilities.

There are also uncertainties associated with the character of the interconnections among systems, and the positive and negative synergies. For example, a key uncertainty is how systems will respond during extreme events and how people will adjust their short- to long-term planning to take account of a dynamic climate. Such events are, by definition, manifestations of historically rare and therefore relatively undocumented climatology which represent uncertainty in the exposure to climate risk. Nonetheless, these events are correlated, when considered holistically, with climate change driven to some degree by human interference with the climate system. There are uncertainties in exposure.

There are also uncertainties associated with sensitivity to future changes driven to some (potentially significant) degree by non-climate stressors, including background health of the human population and development decisions. Other uncertainties include how much effort will be put into making systems more resilient and the success of these efforts. Another critical uncertainty is associated with the climate system itself.

Assessment of confidence based on evidence

Given the evidence base and remaining uncertainties, confidence is:

Very high for sea level rise and coastal flooding as well as heat waves.

High for intense precipitation events and riverine flooding.

Very high for both added stresses on environmental, social, and economic systems and for increased vulnerability, especially for populations that are already most disadvantaged.

Confidence Level
Very High
Strong evidence (established theory, multiple sources, consistent results, well documented and accepted methods, etc.), high consensus
High
Moderate evidence (several sources, some consistency, methods vary and/or documentation limited, etc.), medium consensus
Medium
Suggestive evidence (a few sources, limited consistency, models incomplete, methods emerging, etc.), competing schools of thought
Low
Inconclusive evidence (limited sources, extrapolations, inconsistent findings, poor documentation and/or methods not tested, etc.), disagreement or lack of opinions among experts

KEY MESSAGE #2 TRACEABLE ACCOUNT

Infrastructure will be increasingly compromised by climate-related hazards, including sea level rise, coastal flooding, and intense precipitation events.

Description of evidence base

The key message summarizes extensive evidence documented in the Northeast Technical Input Report (TIR).[2] Technical Input reports (48) on a wide range of topics were also received and reviewed as part of the Federal Register Notice solicitation for public input.

To capture key issues, concerns and opportunities in the region, various regional assessments were also consulted, such as PlaNYC (http://www.nyc.gov/html/planyc2030) and Boston's Climate Plan (http://www.cityofboston.gov/Images_Documents/A%20Climate%20of%20Progress%20-%20CAP%20Update%202011_tcm3-25020.pdf).

In addition, a report by the U.S. Department of Transportation[47] provided extensive documentation that augmented an NGO report.[102] Other sources that support this key message include Horton and Rosenzweig, 2010, Rosenzweig et al. 2011, and Zimmerman and Faris, 2010.[23,51,52]

New information and remaining uncertainties

Important new evidence (cited above) confirmed many of the findings from the prior Northeast assessment: (http://nca2009.globalchange.gov/northeast) which informed the prior NCA.[10]

The new sources above relied on improved models that have been calibrated to new observational data across the region.

It is important to note, of course, that there is wide diversity across the region because both exposure and sensitivity are location- and socioeconomic-context-specific. The wisdom derived from many previous assessments by the National Academy of Sciences, the New York Panel on Climate Change, and the 2009 National Climate Assessment[10,11,95] indicates that future vulnerability at any specific location will be influenced by changes in demography, economics, and policy. These changes are difficult to predict at local scales even as they also depend on international and national considerations. The potential for adaptation strategies (and to a lesser extent mitigation) to reduce these vulnerabilities is yet another source of uncertainty that expands as the future moves into the middle of this century.

Assessment of confidence based on evidence

We have **very high** confidence in projected sea level rise and increased coastal flooding, and **high** confidence for increased intense precipitation events. This assessment of confidence is based on our review of the literature and submitted input and has been defended internally and externally in conversation with local decision-makers and representatives of interested NGOs, as well as the extensive interactions with stakeholders across the region reported in the Northeast TIR.[2]

Very high confidence that infrastructure will be increasingly compromised, based on the clear evidence of impacts on current infrastructure from hazards such as Hurricane Irene, and from the huge deficit of needed renewal identified by a diverse engineering community.[46]

KEY MESSAGE #3 TRACEABLE ACCOUNT

Agriculture, fisheries, and ecosystems will be increasingly compromised over the next century by climate change impacts. Farmers can explore new crop options, but these adaptations are not cost- or risk-free. Moreover, adaptive capacity, which varies throughout the region, could be overwhelmed by a changing climate.

Description of evidence base

The key message summarizes extensive evidence documented in the Northeast Technical Input Report.[2] Technical Input reports (48) on a wide range of topics were also received and reviewed as part of the Federal Register Notice solicitation for public input. The Traceable Account for Key Message 1 provides the evidence base on sea level rise, flooding, and precipitation.

Various regional assessments were also consulted to capture key issues, concerns and opportunities in the region with particular focus on managed (agriculture and fisheries) and unmanaged (ecosystems) systems (for example, Buonaiuto et al. 2011; Wolfe et al. 2011[56,70,78]).

Species and ecosystem vulnerability have been well documented historically in numerous peer-reviewed papers in addition to the ones cited in the TIR.[2] There have also been many examples of impacts on agriculture of climate variability and change in the Northeast (for example, Wolfe et al. 2008[57]). Most note that there is potential for significant benefits associated with climate changes to partially offset expected negative outcomes for these managed systems (for example, Hatfield et al. 2011[54])

New information and remaining uncertainties

Important new evidence (cited above, plus Najjar et. al. 2010,[83] for example) confirmed many of the findings from the prior Northeast assessment (http://nca2009.globalchange.gov/northeast) which informed the 2009 NCA.[10] These new sources also relied on improved models that have been calibrated to new observational data across the region.

Agriculture, fisheries, and ecosystems in the Northeast are strongly linked to climate change and to other changes occurring outside the region and beyond the boundaries of the United States. These changes can influence the price of crops and agricultural inputs such as fertilizer, for example, as well as the abundance of ecosystem and agricultural pests and the abundance and range of fish stocks. Other uncertainties include imprecise understandings of how complex ecosystems will respond to climate- and non-climate-induced changes and the extent to which organisms may be able to adapt to a changing climate.

Assessment of confidence based on evidence

Based on our assessment, we have **very high** confidence for climate impacts (especially sea level rise and storm surge) on ecosystems; and we have **high** confidence for climate impacts on agriculture (reduced to some degree, compared to our level of confidence about ecosystems, by uncertainty about the efficacy and implementation of adaptation options). Confidence in fisheries changes is **high** since confidence in both ocean warming and fish sensitivity to temperature is **high**.

KEY MESSAGE #4 TRACEABLE ACCOUNT

While a majority of states and a rapidly growing number of municipalities have begun to incorporate the risk of climate change into their planning activities, implementation of adaptation measures is still at early stages.

Description of evidence base

The key message relies heavily on extensive evidence documented in the Northeast Technical Input Report (TIR).[2] Technical Input reports (48) on a wide range of topics were also received and reviewed as part of the Federal Register Notice solicitation for public input. Many of the key references cited in the TIR reflected experiences and processes developed in iterative stakeholder engagement concerning risk management[94,103] that have been heavily cited and employed in new venues – local communities like Keane (NH) and New York City, for example.

Various regional assessments were also consulted to capture key issues, concerns and opportunities in the region (for example, for Delaware, Maine, Maryland, and Long Island, NY). In addition, there have been agency and government white paper reports describing proposed adaptation strategies based on climate impact assessments.[11,90] We discovered that 10 of the 12 states in the Northeast have statewide adaptation plans in place or under development (many plans can be found at: http://georgetownclimate.org/node/3324).

New information and remaining uncertainties

That most Northeast states have begun to plan for adaptation is a matter of record. That few adaptation plans have been implemented is confirmed in Technical Inputs submitted to the National Climate Assessment process as well as prior assessments (http://nca2009.globalchange.gov/northeast), which informed the 2009 NCA.[10]

Key uncertainties looking forward include: 1) the extent to which proposed adaptation strategies will be implemented given a range of factors including competing demands and limited funding; 2) the role of the private sector and individual action in adaptation, roles which can be difficult to document; 3) the extent of the federal role in adaptation planning and implementation; and 4) how changes in technology and the world economy may change the feasibility of specific adaptation strategies.[11]

Assessment of confidence based on evidence

This Key Message is simply a statement of observed fact, so confidence language is not applicable.

Climate Change Impacts in the United States

CHAPTER 17
SOUTHEAST AND THE CARIBBEAN

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INFORMATION DRAWN FROM THIS CHAPTER IS INCLUDED IN THE HIGHLIGHTS REPORT AND IS IDENTIFIED BY THIS ICON

17 SOUTHEAST
AND THE CARIBBEAN

KEY MESSAGES

1. **Sea level rise poses widespread and continuing threats to both natural and built environments and to the regional economy.**
2. **Increasing temperatures and the associated increase in frequency, intensity, and duration of extreme heat events will affect public health, natural and built environments, energy, agriculture, and forestry.**
3. **Decreased water availability, exacerbated by population growth and land-use change, will continue to increase competition for water and affect the region's economy and unique ecosystems.**

The Southeast and Caribbean are exceptionally vulnerable to sea level rise, extreme heat events, hurricanes, and decreased water availability. The geographic distribution of these impacts and vulnerabilities is uneven, since the region encompasses a wide range of natural system types, from the Appalachian Mountains to the coastal plains. It is also home to more than 80 million people[1] and draws millions of visitors every year. In 2009, Puerto Rico hosted 3.5 million tourists who spent $3.5 billion.[2] In 2012, Louisiana and Florida alone hosted more than 115 million visitors.[3]

The region has two of the most populous metropolitan areas in the country (Miami and Atlanta) and four of the ten fastest-growing metropolitan areas.[1] Three of these (Palm Coast, FL, Cape Coral-Fort Myers, FL, and Myrtle Beach area, SC) are along the coast and are vulnerable to sea level rise and storm surge. Puerto Rico has one of the highest population densities in the world, with 56% of the population living in coastal municipalities.[4]

The Gulf and Atlantic coasts are major producers of seafood and home to seven major ports[5] that are also vulnerable. The Southeast is a major energy producer of coal, crude oil, and natural gas, and is the highest energy user of any of the National Climate Assessment regions.[5]

The Southeast's climate is influenced by many factors, including latitude, topography, and proximity to the Atlantic Ocean

Figure 17.1. This map summarizes the number of times each state has been affected by weather and climate events over the past 30 years that have resulted in more than a billion dollars in damages. The Southeast has been affected by more billion-dollar disasters than any other region. The primary disaster type for coastal states such as Florida is hurricanes, while interior and northern states in the region also experience sizeable numbers of tornadoes and winter storms. For a list of events and the affected states, see: http://www.ncdc.noaa.gov/billions/events.[6] (Figure source: NOAA NCDC).


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STORIES OF CHANGE: COASTAL LOUISIANA TRIBAL COMMUNITIES

Climate change impacts, especially sea level rise and related increases in storm surges pulsing farther inland, will continue to exacerbate ongoing land loss already affecting Louisiana tribes. Four Native communities in Southeast Louisiana (Grand Bayou Village, Grand Caillou/Dulac, Isle de Jean Charles, and Pointe-au-Chien) have already experienced significant land loss. Management of river flow has deprived the coastal wetlands of the freshwater and sediment that they need to replenish and persist. Dredging of canals through marshes for oil and gas exploration and pipelines has led to erosion and intense saltwater intrusion, resulting in additional land loss. Due to these and other natural and man-made problems, Louisiana has lost 1,880 square miles of land in the last 80 years.[8] This combination of changes has resulted in a cascade of losses of sacred places, healing plants, habitat for important wildlife, food security,[9] and in some cases connectivity with the mainland. Additional impacts include increased inundation of native lands, further travel to reach traditional fishing grounds, reduced connections among family members as their lands have become more flood-prone and some have had to move, and declining community cohesiveness as heat requires more indoor time.[10] (For more specifics, see Ch. 12: Indigenous Peoples). Numerous other impacts from increases in temperature, sea level rise, land loss, erosion, subsidence, and saltwater intrusion amplify these existing problems.

Figure 17.2. Aerial photos of Isle de Jean Charles in Louisiana taken 45 years apart shows evidence of the effects of rising seas, sinking land, and human development. The wetlands adjacent to the Isle de Jean Charles community (about 60 miles south of New Orleans) have been disappearing rapidly since the photo on the left was taken in 1963. By 2008, after four major hurricanes, significant erosion, and alteration of the surrounding marsh for oil and gas extraction, open water surrounds the greatly reduced dry land. See Ch. 25: Coasts for more information. (Photo credit: USGS).

and the Gulf of Mexico. Temperatures generally decrease northward and into mountain areas, while precipitation decreases with distance from the Gulf and Atlantic coasts. The region's climate also varies considerably over seasons, years, and decades, largely due to natural cycles such as the El Niño-Southern Oscillation (ENSO – periodic changes in ocean surface temperatures in the Tropical Pacific Ocean), the semi-permanent high pressure system over Bermuda, differences in atmospheric pressure over key areas of the globe, and land-falling tropical weather systems.[7] These cycles alter the occurrences of hurricanes, tornadoes, droughts, flooding, freezing winters, and ice storms, contributing to climate and weather disasters in the region that have exceeded the total number of billion dollar disasters experienced in all other regions of the country combined (see Figure 17.1).

Observed and Projected Climate Change

Average annual temperature during the last century across the Southeast cycled between warm and cool periods (see Figure 17.3, black line). A warm peak occurred during the 1930s and 1940s followed by a cool period in the 1960s and 1970s. Temperatures increased again from 1970 to the present by an average of 2°F, with higher average temperatures during summer months. There have been increasing numbers of days above 95°F and nights above 75°F, and decreasing numbers of extremely cold days since 1970.[11] The Caribbean also exhibits a trend since the 1950s, with increasing numbers of very warm days and nights, and with daytime maximum temperatures above 90°F and nights above 75°F.[4] Daily and five-day rainfall intensities have also increased.[5] Also, summers have been either increasingly dry or extremely wet.[11] For the Caribbean, precipitation trends are unclear, with some regions experiencing smaller annual amounts of rainfall and some increasing amounts.[4] Although the number of major tornadoes has increased over the last 50 years, there is no statistically significant trend (Ch 2: Our Changing Climate, Key Message 9).[11,12] This increase may be attributable to better reporting of tornadoes. The number of Category 4 and 5 hurricanes in the Atlantic basin has increased substantially since the early 1980s compared to the historical record that dates back to the mid-1880s (Ch. 2: Our Changing Climate, Key Message 8). This can be attributed to both natural variability and climate change.

Southeast Temperature: Observed and Projected

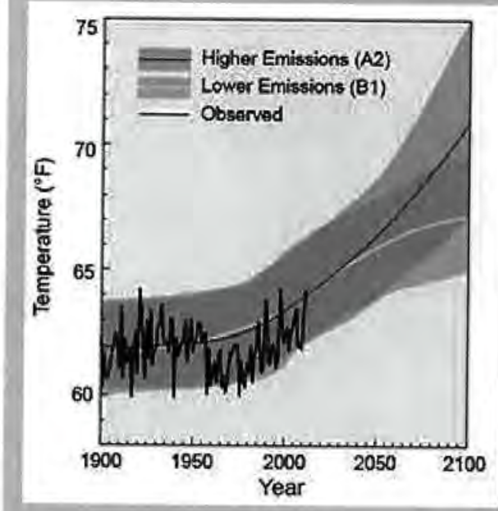
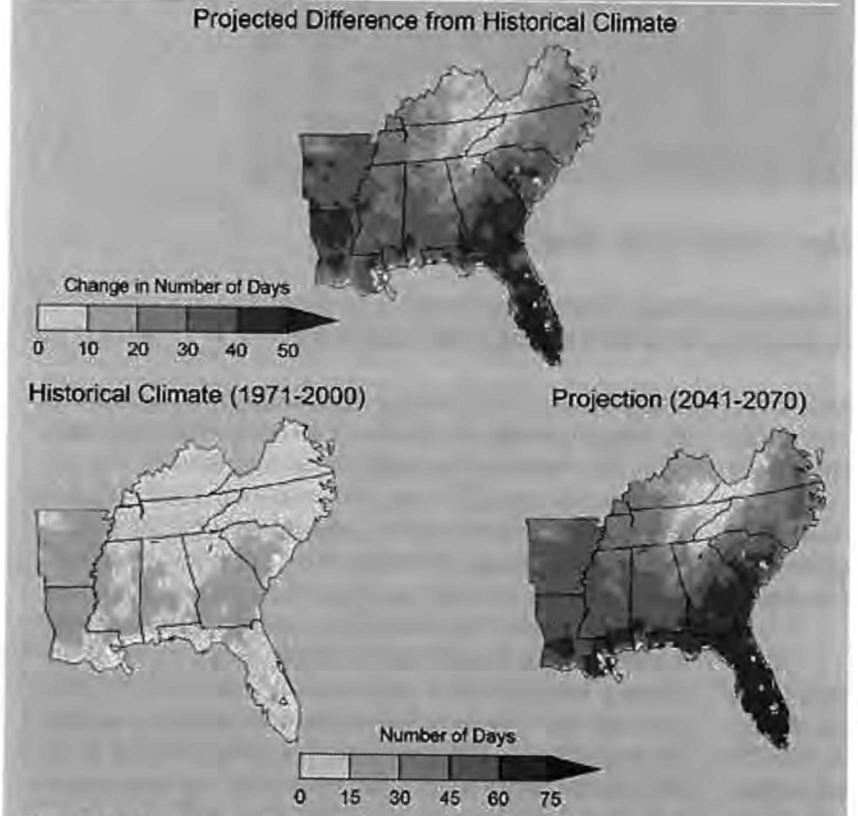


Figure 17.3. Observed annual average temperature for the Southeast and projected temperatures assuming substantial emissions reductions (lower emissions, B1) and assuming continued growth in emissions (higher emissions, A2).[11] For each emissions scenario, shading shows the range of projections and the line shows a central estimate. The projections were referenced to observed temperatures for the period 1901-1960. The region warmed during the early part of last century, cooled for a few decades, and is now warming again. The lack of an overall upward trend over the entire period of 1900-2012 is unusual compared to the rest of the U.S. and the globe. This feature has been dubbed the "warming hole" and has been the subject of considerable research, although a conclusive cause has not been identified. (Figure source: adapted from Kunkel et al. 2013[11]).

Temperatures across the Southeast and Caribbean are expected to increase during this century, with shorter-term (year-to-year and decade-to-decade) fluctuations over time due to natural climate variability (Ch. 2: Our Changing Climate, Key Message 3).[4] Major consequences of warming include significant increases in the number of hot days (95°F or above) and decreases in freezing events. Although projected increases for some parts of the region by the year 2100 are generally smaller than for other regions of the United States, projected increases for interior states of the region are larger than coastal regions by 1°F to 2°F. Regional average increases are in the range of 4°F to 8°F (combined 25th to 75th percentile range for A2 and B1 emissions scenarios) and 2°F to 5°F for Puerto Rico.[11]

Projected Change in Number of Days Over 95°F


Projected Difference from Historical Climate

Historical Climate (1971-2000)

Projection (2041-2070)

Figure 17.4. Projected average number of days per year with maximum temperatures above 95°F for 2041-2070 compared to 1971-2000, assuming emissions continue to grow (A2 scenario). Patterns are similar, but less pronounced, assuming a reduced emissions scenario (B1). (Figure source: NOAA NCDC / CICS-NC).

Projections of future precipitation patterns are less certain than projections for temperature increases.[11] Because the Southeast is located in the transition zone between projected wetter conditions to the north and drier conditions to the southwest, many of the model projections show only small changes relative to natural variations. However, many models do project drier conditions in the far southwest of the region and wetter conditions in the far northeast of the region, consistent with the larger continental-scale pattern of wetness and dryness (Ch. 2: Our Changing Climate, Key Message 5).[11] For the Caribbean, it is equally difficult to project the magnitude of precipitation changes, although the majority of models show future decreases in precipitation are likely, with a few areas showing increases. In general, annual average decreases are likely to be spread across the entire region.[4] Projections further suggest that warming will cause tropical storms to be fewer in number globally, but stronger in force, with more Category 4 and 5 storms (Ch. 2: Our Changing Climate, Key Message 8).[13] On top of the large increases in extreme precipitation observed during last century and early this century (Ch. 2: Our Changing Climate, Figures 2.16, 2.17, and 2.18), substantial further increases are projected as this century progresses (Ch. 2: Our Changing Climate, Figure 2.19).

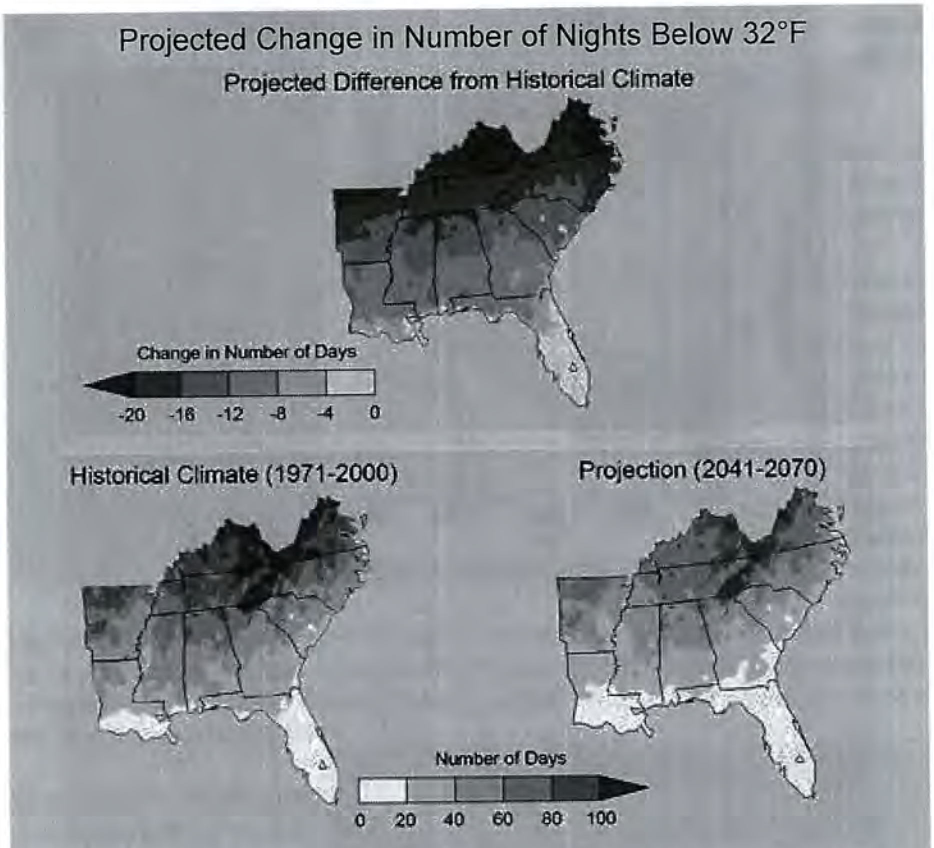


Figure 17.5. Projected average number of days per year with temperatures less than 32°F for 2041-2070 compared to 1971-2000, assuming emissions continue to grow (A2 scenario). Patterns are similar, but less pronounced, assuming a reduced emissions scenario (B1). (Figure source: NOAA NCDC / CICS-NC).

Key Message 1: Sea Level Rise Threats

Sea level rise poses widespread and continuing threats to both natural and built environments and to the regional economy.

Global sea level rise over the past century averaged approximately eight inches (Ch. 2: Our Changing Climate, Key Message 10),[14,15] and that rate is expected to accelerate through the end of this century.[16] Portions of the Southeast and Caribbean are highly vulnerable to sea level rise.[4,5] How much sea level rise is experienced in any particular place depends on whether and how much the local land is sinking (also called subsidence) or rising, and changes in offshore currents.[16,17]

Large numbers of cities, roads, railways, ports, airports, oil and gas facilities, and water supplies are at low elevations and potentially vulnerable to the impacts of sea level rise. New Orleans (with roughly half of its population living below sea level[19]), Miami, Tampa, Charleston, and Virginia Beach are among those most at risk.[20] As a result of current sea level rise, the coastline of Puerto Rico around Rincón is being eroded at a rate of 3.3 feet per year.[4]

According to a recent study co-sponsored by a regional utility, coastal counties and parishes in Alabama, Mississippi, Louisiana, and Texas, with a population of approximately 12 million, assets of about $2 trillion, and producers of $634 billion in annual gross domestic product, already face significant losses that annually average $14 billion from hurricane winds, land subsidence, and sea level rise. Future losses for the 2030 timeframe could reach $18 billion (with no sea level rise or change in hurricane wind speed) to $23 billion (with a nearly 3% increase in hurricane wind speed and just under 6 inches of sea level rise). Approximately 50% of the increase in the estimated losses is related to climate change. The study identified $7 billion in cost-effective adaptation investments that could reduce estimated annual losses by about 30% in the 2030 timeframe.[21]

The North Carolina Department of Transportation is raising the roadbed of U.S. Highway 64 across the Albemarle-Pamlico Peninsula by four feet, which includes 18 inches to allow for high-

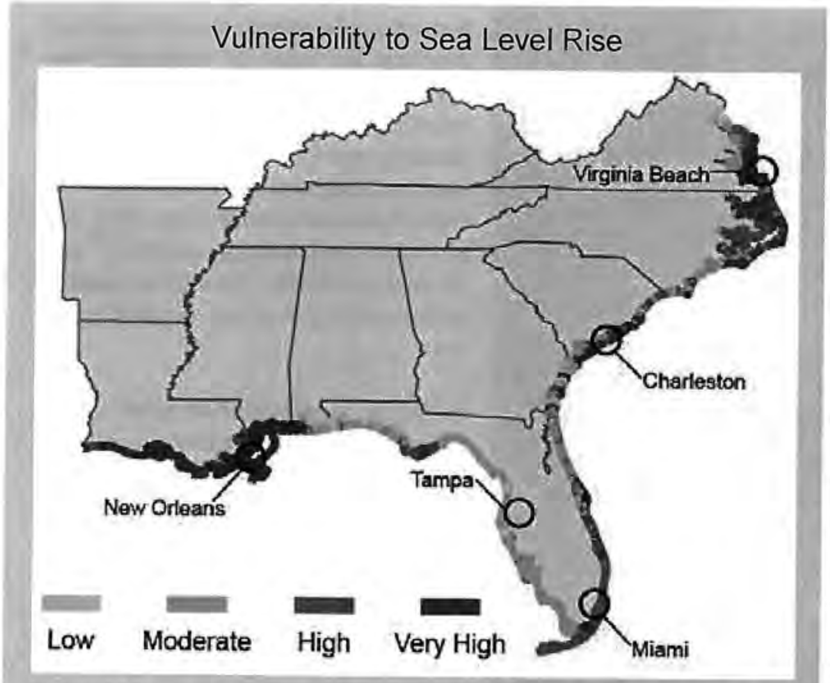


Figure 17.6. The map shows the relative risk that physical changes will occur as sea level rises. The Coastal Vulnerability Index used here is calculated based on tidal range, wave height, coastal slope, shoreline change, landform and processes, and historical rate of relative sea level rise. The approach combines a coastal system's susceptibility to change with its natural ability to adapt to changing environmental conditions, and yields a relative measure of the system's natural vulnerability to the effects of sea level rise. (Data from Hammar-Klose and Thieler 2001[18]).

er future sea levels.[22] Louisiana State Highway 1, heavily used for delivering critical oil and gas resources from Port Fourchon, is literally sinking, resulting in more frequent and more severe flooding during high tides and storms.[8] The Department of Homeland Security estimated that a 90-day shutdown of this road would cost the nation $7.8 billion.[23]

Sea level rise increases pressure on utilities – such as water and energy – by contaminating potential freshwater supplies with saltwater. Such problems are amplified during extreme dry periods with little runoff. Uncertainties in the scale, timing, and location of climate change impacts can make decision-making difficult, but response strategies, especially those that try to anticipate possible unintended consequences, can be more effective with early planning. Some utilities in the region are already taking sea level rise into account in the construction of new facilities and are seeking to diversify their water sources.[24]

There is an imminent threat of increased inland flooding during heavy rain events in low-lying coastal areas such as southeast Florida, where just inches of sea level rise will impair the capacity of stormwater drainage systems to empty into the ocean.[24] Drainage problems are already being experienced in many locations during seasonal high tides, heavy rains, and storm surge events. Adaptation options that are being assessed in this region include the redesign and improvement of storm drainage canals, flood control structures, and stormwater pumps.

As temperatures and sea levels increase, changes in marine and coastal systems are expected to affect the potential for energy resource development in coastal zones and the outer continental shelf. Oil and gas production infrastructure in bays and coves that are protected by barrier islands, for example, are likely to become increasingly vulnerable to storm surge as sea level rises and barrier islands deteriorate along the central Gulf Coast. The capacity for expanding and maintaining onshore and offshore support facilities and transportation networks is also apt to be affected.[25]

Sea level rise and storm surge can have impacts far beyond the area directly affected. Homes and infrastructure in low areas are increasingly prone to flooding during tropical storms. As a result, insurance costs may increase or coverage may become unavailable[26] and people may move from vulnerable areas, stressing the social and infrastructural capacity of surrounding areas. This migration also happens in response to extreme events such as Hurricane Katrina, when more than 200,000 migrants were temporarily housed in Houston and 42% indicated they would try to remain there (Ch. 9: Human Health, Figure 9.10).[27]

Homes and infrastructure in low-lying areas are increasingly vulnerable to flooding due to storm surge as sea level rises.

Highway 1 to Port Fourchon: Vulnerability of a Critical Link for U.S. Oil

Figure 17.7. Highway 1 in southern Louisiana is the only road to Port Fourchon, whose infrastructure supports 18% of the nation's oil and 90% of the nation's offshore oil and gas production. Flooding is becoming more common on Highway 1 in Leeville (inset photo from flooding in 2004), on the way to Port Fourchon. See also Ch. 25: Coasts, Figure 25.5. (Figure and photo sources: Louisiana Department of Transportation and Development; State of Louisiana 2012[8]).

Furthermore, because income is a key indicator of climate vulnerability, people that have limited economic resources are more likely to be adversely affected by climate change impacts such as sea level rise. In the Gulf region, nearly 100% of the "most socially vulnerable people live in areas unlikely to be protected from inundation," bringing equity issues and environmental justice into coastal planning efforts.[28]

Ecosystems of the Southeast and Caribbean are exposed to and at risk from sea level rise, especially tidal marshes and swamps. Some tidal freshwater forests are already retreating, while mangrove forests (adapted to coastal conditions) are expanding landward.[29] The pace of sea level rise will increasingly lead to inundation of coastal wetlands in the region. Such a crisis in land loss has occurred in coastal Louisiana for several decades, with 1,880 square miles having been lost since the 1930s as a result of natural and man-made factors.[8,30] With tidal wetland loss, protection of coastal lands and people against storm surge will be compromised.

Reduction of wetlands also increases the potential for losses of important fishery habitat. Additionally, ocean warming could support shifts in local species composition, invasive or new locally viable species, changes in species growth rates, shifts in migratory patterns or dates, and alterations to spawning seasons.[4,31] Any of these could affect the local or regional seafood output and thus the local economy.

In some southeastern coastal areas, changes in salinity and water levels due to a number of complex interactions (including subsidence, availability of sediment, precipitation, and sea level rise) can happen so fast that local vegetation cannot adapt quickly enough and those areas become open water.[32] Fire, hurricanes, and other disturbances have similar effects, causing ecosystems to cross thresholds at which dramatic changes occur over short time frames.[33]

The impacts of sea level rise on agriculture derive from decreased freshwater availability, land loss, and saltwater intrusion. Saltwater intrusion is projected to reduce the availability of fresh surface and groundwater for irrigation, thereby limiting crop production in some areas.[34] Agricultural areas around Miami-Dade County and southern Louisiana with shallow groundwater tables are at risk of increased inundation and future loss of cropland with a projected loss of 37,500 acres in Florida with a 27-inch sea level rise,[35] which is well within the 1- to 4-foot range of sea level rise projected by 2100 (Ch. 2: Our Changing Climate, Key Message 10).

There are basically three types of adaptation options to rising sea levels: protect (such as building levees or other "hard" methods), accommodate (such as raising structures or using "soft" or natural protection measures such as wetlands restoration), and retreat.[15,32] Individuals and communities are using all of these strategies. However, regional cooperation among local, state, and federal governments can greatly improve the success of adapting to impacts of climate change and sea level rise. An excellent example is the Southeast Florida Regional Compact. Through collaboration of county, state, and federal agencies, a comprehensive action plan was developed that includes hundreds of actions and special Adaptation Action Areas.[37]

South Florida: Uniquely Vulnerable to Sea Level Rise

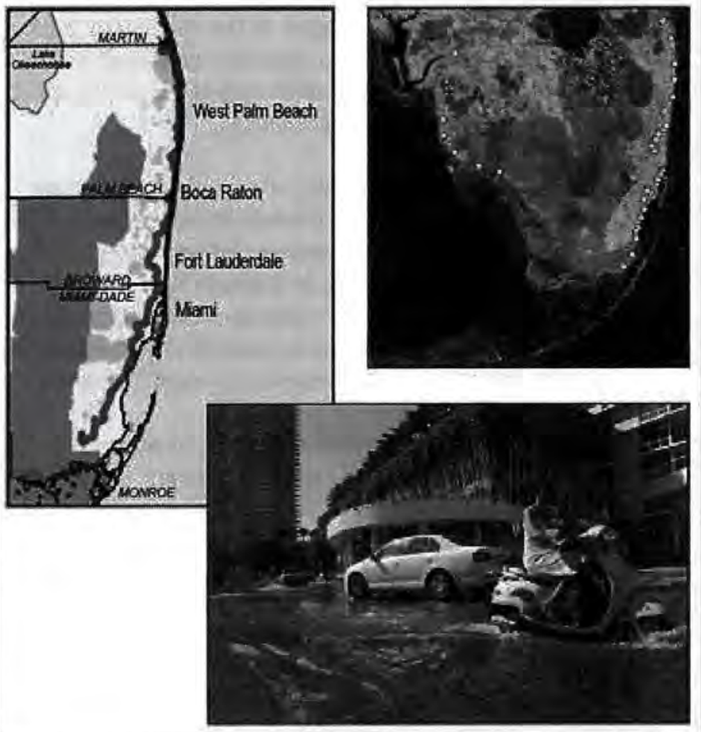


Figure 17.8. Sea level rise presents major challenges to South Florida's existing coastal water management system due to a combination of increasingly urbanized areas, aging flood control facilities, flat topography, and porous limestone aquifers. For instance, South Florida's freshwater well field protection areas (left map: pink areas) lie close to the current interface between saltwater and freshwater (red line), which will shift inland with rising sea level, affecting water managers' ability to draw drinking water from current resources. Coastal water control structures (right map: yellow circles) that were originally built about 60 years ago at the ends of drainage canals to keep saltwater out and to provide flood protection to urbanized areas along the coast are now threatened by sea level rise. Even today, residents in some areas such as Miami Beach are experiencing seawater flooding their streets (lower photo). (Maps from The South Florida Water Management District.[36] Photo credit: Luis Espinoza, Miami-Dade County Department of Regulatory and Economic Resources).

Key Message 2: Increasing Temperatures

Increasing temperatures and the associated increase in frequency, intensity, and duration of extreme heat events will affect public health, natural and built environments, energy, agriculture, and forestry.

The negative effects of heat on human cardiovascular, cerebral, and respiratory systems are well established (Ch. 9: Human Health)(for example: Kovats and Hajat 2008; O'Neill and Ebi 2009[38]). Atlanta, Miami, New Orleans, and Tampa have already had increases in the number of days with temperatures exceeding 95°F, during which the number of deaths is above average.[39] Higher temperatures also contribute to the formation of harmful air pollutants and allergens.[40] Ground-level ozone is projected to increase in the 19 largest urban areas of the Southeast, leading to an increase in deaths.[41] A rise in hospital admissions due to respiratory illnesses, emergency room visits for asthma, and lost school days is expected.[42]

Local Planning

Figure 17.9. Miami-Dade County staff leading workshop on incorporating climate change considerations in local planning. (Photo credit: Armando Rodriguez, Miami-Dade County).

The climate in many parts of the Southeast and Caribbean is suitable for mosquitoes carrying malaria and yellow and dengue fevers. The small island states in the Caribbean already have a high health burden from climate-sensitive disease, including vector-borne and zoonotic (animal to human) diseases.[43] It is still uncertain how regional climate changes will affect vector-borne and zoonotic disease transmissions. While higher temperatures are likely to shorten both development and incubation time,[44] vectors (like disease-carrying insects) also need

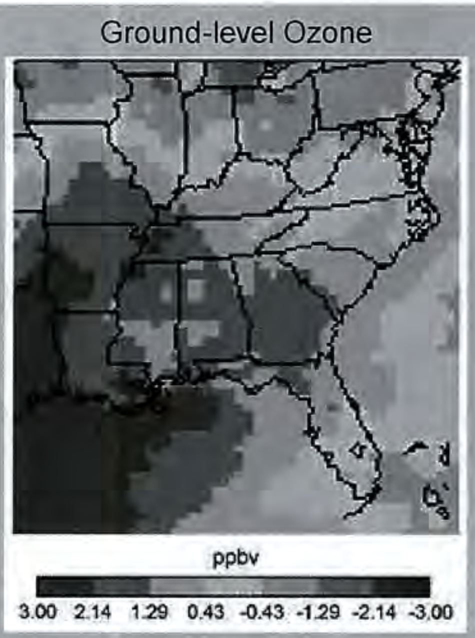


Figure 17.10. Ground-level ozone is an air pollutant that is harmful to human health and which generally increases with rising temperatures. The map shows projected changes in average annual ground level ozone pollution concentration in 2050 as compared to 2001, using a mid-range emissions scenario (A1B, which assumes gradual reductions from current emissions trends beginning around mid-century). (Figure source: adapted from Tagaris et al. 2009[42]).

the right conditions for breeding (water), for dispersal (vegetation and humidity), and access to susceptible vertebrate hosts to complete the disease transmission cycle.[5] While these transmission cycles are complex, increasing temperatures have the potential to result in an expanded region with more favorable conditions for transmission of these diseases.[45,46]

Climate change is expected to increase harmful algal blooms and several disease-causing agents in inland and coastal waters, which were not previously problems in the region.[47,48,49] For instance, higher sea surface temperatures are associated with higher rates of ciguatera fish poisoning,[48,50] one of the most common hazards from algal blooms in the region.[51] The algae that causes this food-borne illness is moving northward, following increasing sea surface temperatures.[52] Certain species of bacteria (*Vibrio,* for example) that grow in warm coastal waters and are present in Gulf Coast shellfish can cause infections in humans. Infections are now frequently reported both earlier and later by one month than traditionally observed.[53]

Coral reefs in the Southeast and Caribbean, as well as worldwide, are susceptible to climate change, especially warming waters and ocean acidification, whose impacts are exacerbated when coupled with other stressors, including disease, runoff, over-exploitation, and invasive species.[4,5]

An expanding population and regional land-use changes have reduced land available for agriculture and forests faster in the Southeast than in any other region in the contiguous United States.[54] Climate change is also expected to change the unwanted spread and locations of some non-native plants, which will result in new management challenges.[55]

Heat stress adversely affects dairy and livestock production.[56] Optimal temperatures for milk production are between 40ºF and 75ºF, and additional heat stress could shift dairy production northward.[57] A 10% decline in livestock yield is projected across the Southeast with a 9ºF increase in temperatures (applied as an incremental uniform increase in temperature between 1990 and 2060), related mainly to warmer summers.[58]

Summer heat stress is projected to reduce crop productivity, especially when coupled with increased drought (Ch. 6: Agriculture). The 2007 drought cost the Georgia agriculture industry $339 million in crop losses,[59] and the 2002 drought cost the agricultural industry in North Carolina $398 million.[5] A 2.2ºF increase in temperature would likely reduce overall productivity for corn, soybeans, rice, cotton, and peanuts across the South – though rising CO_2 levels could partially offset these decreases based on a crop yield simulation model.[60] In Georgia, climate projections indicate corn yields could decline by 15% and wheat yields by 20% through 2020.[61] In addition, many fruit crops from long-lived trees and bushes require chilling periods and may need to be replaced in a warming climate.[60]

Adaptation for agriculture involves decisions at many scales, from infrastructure investments (like reservoirs) to management decisions (like cropping patterns).[62] Dominant adaptation strategies include altering local planting choices to better match new climate conditions[62] and developing heat-tolerant crop varieties and breeds of livestock.[5,57] Most critical for effective adaptation is the delivery of climate risk information to decision-makers at appropriate temporal and spatial scales[57,62] and a focus on cropping systems that increase water-use efficiency, shifts toward irrigation, and more precise control of irrigation delivery (see also Ch. 28: Adaptation, Table 28.6).[5,57]

The southeastern U.S. (data include Texas and Oklahoma, not Puerto Rico) leads the nation in number of wildfires, averaging 45,000 fires per year,[63] and this number continues to increase.[64,65] Increasing temperatures contribute to increased fire frequency, intensity, and size,[63] though at some level of fire frequency, increased fire frequency would lead to decreased fire intensity. Lightning is a frequent initiator of wildfires,[66] and the Southeast currently has the greatest frequency of lightning strikes of any region of the country.[67] Increasing temperatures and changing atmospheric patterns may affect the number of lightning strikes in the Southeast, which could influence air quality, direct injury, and wildfires. Drought often correlates with large wildfire events, as seen with the Okeefenokee (2007) and Florida fires (1998). The 1998 Florida fires led to losses of more than $600 million.[68] Wildfires also affect human health through reduced air quality and direct injuries.[68,69,70] Expanding population and associated land-use fragmentation will limit the application of prescribed burning, a useful adaptive strategy.[65] Growth management could enhance the ability to pursue future adaptive management of forest fuels.

Forest disturbances caused by insects and pathogens are altered by climate changes due to factors such as increased tree stress, shifting phenology, and altered insect and pathogen lifecycles.[71] Current knowledge provides limited insights into specific impacts on epidemics, associated tree growth and mortality, and economic loss in the Southeast, though the overall extent and virulence of some insects and pathogens have been on the rise (for example, Hemlock Woolly Adelgid in the Southern Appalachians), while recent declines in southern pine beetle (*Dendroctonus frontalis* Zimmerman) epidemics in Louisiana and East Texas have been attributed to rising temperatures.[72] Due to southern forests' vast size and the high cost of management options, adaptation strategies are limited, except through post-epidemic management responses – for example, sanitation cuts and species replacement.

The Southeast has the existing power plant capacity to produce 32% of the nation's electricity.[73] Energy use is approximately 27% of the U.S. total, more than any other region.[5] Net energy demand is projected to increase, largely due to higher temperatures and increased use of air conditioning. This will potentially stress electricity generating capacity, distribution infrastructure, and energy costs. Energy costs are of particular concern for lower income households, the elderly, and other vulnerable communities, such as native tribes.[5,10] Long periods of extreme heat could also damage roadways by softening asphalt and cause deformities of railroad tracks, bridge joints, and other transportation infrastructure.[74]

Increasing temperatures will affect many facets of life in the Southeast and Caribbean region. For each impact there could be many possible responses. Many adaptation responses are described in other chapters in this document. For examples, please see the sector chapter of interest and Ch. 28: Adaptation.

Key Message 3: Water Availability

Decreased water availability, exacerbated by population growth and land-use change, will continue to increase competition for water and affect the region's economy and unique ecosystems.

Water resources in the Southeast are abundant and support heavily populated urban areas, rural communities, unique ecosystems, and economies based on agriculture, energy, and tourism. The region also experiences extensive droughts, such as the 2007 drought in Atlanta, Georgia, that created water conflicts among three states.[11,75] In northwestern Puerto Rico, water was rationed for more than 200,000 people during the winter and spring of 1997-1998 because of low reservoir levels.[76] Droughts are one of the most frequent climate hazards in the Caribbean, resulting in economic losses.[77] Water supply and demand in the Southeast and Caribbean are influenced by many changing factors, including climate (for example, temperature increases that contribute to increased transpiration from plants and evaporation from soils and water bodies), population, and land use.[4,5] While change in projected precipitation for this region has high uncertainty (Ch. 2: Our Changing Climate), there is still a reasonable expectation that there will be reduced water availability due to the increased evaporative losses resulting from rising temperatures alone.

With projected increases in population, the conversion of rural areas, forestlands, and wetlands into residential, commercial, industrial, and agricultural zones is expected to intensify.[54] The continued development of urbanized areas will increase water demand, exacerbate saltwater intrusion into freshwater aquifers, and threaten environmentally sensitive wetlands bordering urban areas.[24]

Additionally, higher sea levels will accelerate saltwater intrusion into freshwater supplies from rivers, streams, and groundwater sources near the coast. The region's aquaculture industry also may be compromised by climate-related stresses on groundwater quality and quantity.[78] Porous aquifers in some areas make them particularly vulnerable to saltwater intrusion.[36,79] For example, officials in the city of Hallandale Beach, Florida, have already abandoned six of their eight drinking water wells.[80]

With increasing demand for food and rising food prices, irrigated agriculture will expand in some states. Also, population expansion in the region is expected to increase domestic water demand. Such increases in water demand by the energy, agricultural, and urban sectors will increase the competition for water, particularly in situations where environmental water needs conflict with other uses.[5]

As seen from Figure 17.11, the net water supply availability in the Southeast is expected to decline over the next several decades, particularly in the western part of the region.[82] Analysis of current and future water resources in the Caribbean shows

Trends in Water Availability

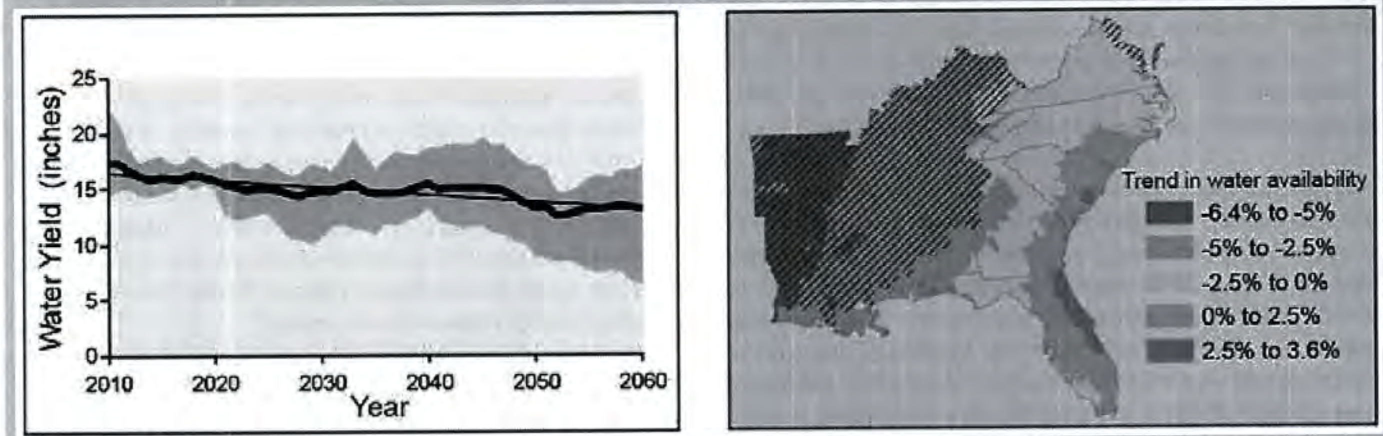


Figure 17.11. Left: Projected trend in Southeast-wide annual water yield (equivalent to water availability) due to climate change. The green area represents the range in predicted water yield from four climate model projections based on the A1B and B2 emissions scenarios. Right: Spatial pattern of change in water yield for 2010-2060 (decadal trend relative to 2010). The hatched areas are those where the predicted negative trend in water availability associated with the range of climate scenarios is statistically significant (with 95% confidence). As shown on the map, the western part of the Southeast region is expected to see the largest reductions in water availability. (Figure source: adapted from Sun et al. 2013[82]).

many of the small islands would be exposed to severe water stress under all climate change scenarios.[83]

New freshwater well fields may have to be established inland to replenish water supply lost from existing wells closer to the ocean once they are compromised by saltwater intrusion. Programs to increase water-use efficiency, reuse of wastewater, and water storage capacity are options that can help alleviate water supply stress.

The Southeast and Caribbean, which has a disproportionate number of the fastest-growing metropolitan areas in the country and important economic sectors located in low-lying coastal areas, is particularly vulnerable to some of the expected impacts of climate change. The most severe and widespread impacts are likely to be associated with sea level rise and changes in temperature and precipitation, which ultimately affect water availability. Changes in land use and land cover, more rapid in the Southeast and Caribbean than most other areas of the country, often interact with and serve to amplify the effects of climate change on regional ecosystems.

A Southeast River Basin Under Stress

Figure 17.12. The Apalachicola-Chattahoochee-Flint River Basin in Georgia exemplifies a place where many water uses are in conflict, and future climate change is expected to exacerbate this conflict.[84] The basin drains 19,600 square miles in three states and supplies water for multiple, often competing, uses, including irrigation, drinking water and other municipal uses, power plant cooling, navigation, hydropower, recreation, and ecosystems. Under future climate change, this basin is likely to experience more severe water supply shortages, more frequent emptying of reservoirs, violation of environmental flow requirements (with possible impacts to fisheries at the mouth of the Apalachicola), less energy generation, and more competition for remaining water. Adaptation options include changes in reservoir storage and release procedures and possible phased expansion of reservoir capacity.[84,85] Additional adaptation options could include water conservation and demand management. (Figure source: Georgakakos et al. 2010[84]).

WATER RECYCLING

Because of Clayton County, Georgia's, innovative water recycling project during the 2007-2008 drought, they were able to maintain reservoirs at near capacity and an abundant supply of water while neighboring Lake Lanier, the water supply for Atlanta, was at record lows. Clayton County developed a series of constructed wetlands used to filter treated water that recharges groundwater and supplies surface reservoirs. They have also implemented efficiency and leak detection programs[81] (for additional specific information see the Clayton County Water Authority website at: http://www.ccwa.us/).

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SUPPLEMENTAL MATERIAL

TRACEABLE ACCOUNTS

Process for Developing Key Messages

A central component of the process was the Southeast Regional Climate Assessment Workshop that was held on September 26-27, 2011, in Atlanta, with approximately 75 attendees. This workshop began the process leading to a foundational Technical Input Report (TIR). That 341-page foundational "Southeast Region Technical Report to the National Climate Assessment"[5] comprised 14 chapters from over 100 authors, including all levels of government, non-governmental organizations, and business.

The writing team held a 2-day meeting in April 2012 in Ft. Lauderdale, engaged in multiple teleconference and webinar technical discussions, which included careful review of the foundational TIR,[5] nearly 60 additional technical inputs provided by the public, and other published literature and professional judgment. Discussions were followed by expert deliberation of draft key messages by the authors, and targeted consultation with additional experts by the Southeast chapter writing team and lead author of each key message.

KEY MESSAGE #1 TRACEABLE ACCOUNT

Sea level rise poses widespread and continuing threats to both natural and built environments and to the regional economy.

Description of evidence base

The key message and supporting text summarize extensive evidence documented in the Southeast Technical Input Report.[5] A total of 57 technical inputs on a wide range of southeast-relevant topics (including sea level rise) were also received and reviewed as part of the Federal Register Notice solicitation for public input.

Evidence that the rate of sea level rise has increased is based on satellite altimetry data and direct measurements such as tide gauges (Ch. 2: Our Changing Climate, Key Message 10). Numerous peer-reviewed publications describe increasing hazards associated with sea level rise and storm surge, heat waves, and intense precipitation for the Southeast.[5] For sea level rise, the authors relied on the NCA Sea Level Change Scenario[16] and detailed discussion in the foundational TIR.[5]

Evidence that sea level rise is a threat to natural and human environments is documented in detail within the foundational TIR[5] and other technical inputs, as well as considerable peer-reviewed literature (for example, Campanella 2010).[19] Field studies document examples of areas that are being flooded more regularly, saltwater intrusion into fresh water wells,[80] and changes from fresh to saltwater in coastal ecosystems (for example, freshwater marshes) causing them to die,[32] and increases in vulnerability of many communities to coastal erosion. Economic impacts are seen in the cost to avoid flooded roads, buildings, and ports;[23] the need to drill new fresh water wells;[80] and the loss of coastal ecosystems and their storm surge protection.

New information and remaining uncertainties

Tremendous improvement has been made since the last Intergovernmental Panel on Climate Change evaluation of sea level rise in 2007,[86] with strong evidence of mass loss of Greenland icecap and glaciers worldwide (Ch. 2: Our Changing Climate). Improved analyses of tide gauges, coastal elevations, and circulation changes in offshore waters have also provided new information on accelerating rates of rise (Ch. 2: Our Changing Climate, Figure 2.26). These have been documented in the NCA Sea Level Change Scenario publication.[16]

Uncertainties in the rate of sea level rise through this century stems from a combination of large differences in projections among different climate models, natural climate variability, uncertainties in the melting of land-based glaciers and the Antarctic and Greenland ice sheets especially, and uncertainties about future rates of fossil fuel emissions. A further key uncertainty is the rate of vertical land movement at specific locations. The two factors – sea level rise and subsidence – when combined, increase the impact of global sea level rise in any specific area. A third area of uncertainty is where and what adaptive plans and actions are being undertaken to avoid flooding and associated impacts on people, communities, facilities, infrastructure, and ecosystems.

Assessment of confidence based on evidence

Sea level is expected to continue to rise for several centuries, even if greenhouse gas emissions are stabilized, due to the time it takes for the ocean to absorb heat energy from the atmosphere. Because sea levels determine the locations of human activities and ecosystems along the coasts, increases in sea level and in the rate of rise will nearly certainly have substantial impacts on natural and human systems along the coastal area. What specific locations will be impacted under what specific levels of sea level rise needs to be determined location-by-location. However, given that many locations are already being affected by rising seas, more and more locations will be impacted as sea levels continue to rise. Confidence in this key message is therefore judged to be very high.

Confidence Level	
Very High	Strong evidence (established theory, multiple sources, consistent results, well documented and accepted methods, etc.), high consensus
High	Moderate evidence (several sources, some consistency, methods vary and/or documentation limited, etc.), medium consensus
Medium	Suggestive evidence (a few sources, limited consistency, models incomplete, methods emerging, etc.), competing schools of thought
Low	Inconclusive evidence (limited sources, extrapolations, inconsistent findings, poor documentation and/or methods not tested, etc.), disagreement or lack of opinions among experts

KEY MESSAGE #2 TRACEABLE ACCOUNT

Increasing temperatures and the associated increase in frequency, intensity, and duration of extreme heat events will affect public health, natural and built environments, energy, agriculture, and forestry.

Description of evidence base

The key message and supporting text summarize extensive evidence documented in the Southeast Technical Input Report.[5] Technical inputs (57) on a wide range of topics were also received and reviewed as part of the Federal Register Notice solicitation for public input.

Numerous peer-reviewed publications describe increasing hazards associated with heat events and rising temperatures for the Southeast. The authors of a report on the Southeast climate[11] worked closely with the region's state climatologists on both the climatology and projections for temperature and associated heat events. Evidence of rising temperatures and current impacts[38,39] is based on an extensive set of field measurements.

There is considerable evidence of the effects of high air temperatures across a wide range of natural and managed systems in the Southeast. Increased temperatures affect human health and hospital admissions.[38,40,42]

Rising water temperatures also increase risks of bacterial infection from eating Gulf Coast shellfish[53] and increase algal blooms that have negative human health effects.[47,48] There is also evidence that there will be an increase in favorable conditions for mosquitoes that carry diseases.[46] Higher temperatures are detrimental to natural and urban environments, through increased wildfires in natural areas and managed forests[63,64,65,70] and increased invasiveness of some non-native plants.[55] High temperatures also contribute to more roadway damage and deformities of transportation infrastructure such as railroad tracks and bridges (Ch. 5: Transportation).[74] In addition, high temperatures increase net energy demand and costs, placing more stress on electricity generating plants and distribution infrastructure.

Increasing temperatures in the Southeast cause more stresses on crop and livestock agricultural systems. Heat stress reduces dairy and livestock production[56] and also reduces yields of various crops grown in this region (corn, soybean, peanuts, rice, and cotton).[60,61]

New information and remaining uncertainties

Since 2007, studies on impacts of higher temperatures have increased in many areas. Most of the publications cited above concluded that increasing temperatures in the Southeast will result in negative impacts on human health, the natural and built environments, energy, agriculture, and forestry.

A key issue (uncertainty) is the detailed mechanistic responses, including adaptive capacities and/or resilience, of natural and built environments, the public health system, energy systems, agriculture, and forests to increasing temperatures and extreme heat events.

Another uncertainty is how combinations of stresses, for example lack of water in addition to extreme heat, will affect outcomes. There is a need for more monitoring to document the extent and location of vulnerable areas (natural and human), and then research to assess how those impacts will affect productivity of key food and forest resources and human well-being. There is also a need for research that develops or identifies more resilient, adapted systems.

Assessment of confidence based on evidence

Increasing Temperatures: There is **high** confidence in documentation that projects increases in air temperatures (but not in the precise amount) and associated increases in the frequency, intensity, and duration of extreme heat events. Projections for increases in temperature are more certain in the Southeast than projections of changes in precipitation.

Impacts of increasing temperatures: Rising temperatures and the substantial increase in duration of high temperatures (for either the low [B1] or high [A2] emissions scenarios) above critical thresholds will have significant impacts on the population, agricultural industries, and ecosystems in the region. There is **high** confidence in documentation that increases in temperature in the Southeast will result in higher risks of negative impacts on human health, agricultural, and forest production; on natural systems; on the built environment; and on energy demand. There is **lower** confidence in the magnitude of these impacts, partly due to lack of information on how these systems will adapt (without human intervention) or be adapted (by people) to higher temperatures, and partly due to the limited knowledge base on the wide diversity that exists across this region in climates and human and natural systems.

KEY MESSAGE #3 TRACEABLE ACCOUNT

Decreased water availability, exacerbated by population growth and land-use change, will continue to increase competition for water and affect the region's economy and unique ecosystems.

Description of evidence base

The key message and supporting text summarize extensive evidence documented in the Southeast Technical Input Report (TIR).[5] Technical inputs (57) on a wide range of topics were also received and reviewed as part of the Federal Register Notice solicitation for public input.

Chapter 2, Our Changing Climate, describes evidence for drought and precipitation in its key messages. Numerous salient studies support the key message of decreased water availability, as summarized for the Southeast in the TIR.[5]

Evidence for the impacts on the region's economy and unique ecosystems is also detailed in the TIR[5] and the broader literature surveyed by the authors.[77]

New information and remaining uncertainties

Many studies have been published since 2007 documenting increasing demands for water in the Southeast due to increases in populations and irrigated agriculture, in addition to water shortages due to extensive droughts.[5,11] There is also new evidence of losses in fresh water wells near coastlines due to saltwater intrusion[79,80] and of continuing conflicts among states for water use, particularly during drought periods.[5,84]

It is a virtual certainty that population growth in the Southeast will continue in the future and will be accompanied by a significant change in patterns of land use, which is projected to include a larger fraction of urbanized areas, reduced agricultural areas, and reduced forest cover.[54] With increasing population and human demand, competition for water among the agriculture, urban, and environment sectors is projected to continue to increase. However, the projected population increases for the lower (B1) versus higher (A2) emissions scenarios differ significantly (33% versus 151%).[11] Consequently, the effect of climate change on urban water demand for the lower emissions scenario is projected to be much lower than for that of the higher emissions scenario. Land-use change will also alter the regional hydrology significantly. Unless measures are adopted to increase water storage, availability of freshwater during dry periods will decrease, partly due to drainage and other human activities.

Projected increase in temperature will increase evaporation, and in areas (the western part of the region[87]) where precipitation is projected to decrease in response to climate change, the net amount of water supply for human and environmental uses may decrease significantly.

Along the coastline of the Southeast, accelerated intrusion of saltwater due to sea level rise will impact both freshwater well fields and potentially freshwater intakes in rivers and streams connected to the ocean. Although sea level rise (SLR) corresponding to the higher emissions scenario is much higher (twice as much), even the SLR for the lower emissions scenario will increasingly impact water supply availability in low-lying areas of the region, as these areas are already being impacted by SLR and land subsidence.

Projections of specific spatial and temporal changes in precipitation in the Southeast remain highly uncertain and it is important to know with a reasonable confidence the sign and the magnitude of this change in various parts of the large Southeast region.

For the Southeast, there are no reliable projections of evapotranspiration, another major factor that determines water yield. This adds to uncertainty about water availability.

There are inadequate regional studies at basin scales to determine the future competition for water supply among sectors (urban, agriculture, and environment).

There is a need for more accurate information on future changes in drought magnitude and frequency.

Assessment of confidence based on evidence

There is **high** confidence in each aspect of the key message: it is virtually certain that the water demand for human consumption in the Southeast will increase as a result of population growth. The past evidence of impacts during droughts and the projected changes in drivers (land-use change, population growth, and climate change) suggest that there is a **high** confidence of the above assessment of future water availability. However, without additional studies, the resilience and the adaptive capacity of the socioeconomic and environmental systems are not known.

Water supply is critical for sustainability of the region, particularly in view of increasing population and land-use changes. Climate models' precipitation projections are uncertain. Nonetheless, the combined effects of possible decreases in precipitation, increasing evaporation losses due to warming, and increasing demands for water due to higher populations (under either lower [B1] or higher [A2] emissions scenarios) will have a significant impact on water availability for all sectors.

Climate Change Impacts in the United States

CHAPTER 18
MIDWEST

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On the Web: http://nca2014.globalchange.gov/report/regions/midwest

INFORMATION DRAWN FROM THIS CHAPTER IS INCLUDED IN THE HIGHLIGHTS REPORT AND IS IDENTIFIED BY THIS ICON

18 MIDWEST

KEY MESSAGES

1. **In the next few decades, longer growing seasons and rising carbon dioxide levels will increase yields of some crops, though those benefits will be progressively offset by extreme weather events. Though adaptation options can reduce some of the detrimental effects, in the long term, the combined stresses associated with climate change are expected to decrease agricultural productivity.**
2. **The composition of the region's forests is expected to change as rising temperatures drive habitats for many tree species northward. The role of the region's forests as a net absorber of carbon is at risk from disruptions to forest ecosystems, in part due to climate change.**
3. **Increased heat wave intensity and frequency, increased humidity, degraded air quality, and reduced water quality will increase public health risks.**
4. **The Midwest has a highly energy-intensive economy with per capita emissions of greenhouse gases more than 20% higher than the national average. The region also has a large and increasingly utilized potential to reduce emissions that cause climate change.**
5. **Extreme rainfall events and flooding have increased during the last century, and these trends are expected to continue, causing erosion, declining water quality, and negative impacts on transportation, agriculture, human health, and infrastructure.**
6. **Climate change will exacerbate a range of risks to the Great Lakes, including changes in the range and distribution of certain fish species, increased invasive species and harmful blooms of algae, and declining beach health. Ice cover declines will lengthen the commercial navigation season.**

The Midwest has a population of more than 61 million people (about 20% of the national total) and generates a regional gross domestic product of more than $2.6 trillion (about 19% of the national total).[1] The Midwest is home to expansive agricultural lands, forests in the north, the Great Lakes, substantial industrial activity, and major urban areas, including eight of the nation's 50 most populous cities. The region has experienced shifts in population, socioeconomic changes, air and water pollution, and landscape changes, and exhibits multiple vulnerabilities to both climate variability and climate change.

In general, climate change will tend to amplify existing climate-related risks from climate to people, ecosystems, and infrastructure in the Midwest (Ch. 10: Energy, Water, and Land). Direct effects of increased heat stress, flooding, drought, and late spring freezes on natural and managed ecosystems may be multiplied by changes in pests and disease prevalence, increased competition from non-native or opportunistic native species, ecosystem disturbances, land-use change, landscape fragmentation, atmospheric pollutants, and economic shocks such as crop failures or reduced yields due to extreme weather events. These added stresses, when taken collectively, are projected to alter the ecosystem and socioeconomic patterns and processes in ways that most people in the region would consider detrimental. Much of the region's fisheries, recreation, tourism, and commerce depend on the Great Lakes and expansive northern forests, which already face pollution and invasive species pressure that will be exacerbated by climate change.

Most of the region's population lives in cities, which are particularly vulnerable to climate change related flooding and life-threatening heat waves because of aging infrastructure and other factors. Climate change may also augment or intensify other stresses on vegetation encountered in urban environments, including increased atmospheric pollution, heat island effects, a highly variable water cycle, and frequent exposure to new pests and diseases. Some cities in the region are already engaged in the process of capacity building or are actively building resilience to the threats posed by climate change. The region's highly energy-intensive economy emits a disproportionately large amount of the gases responsible for warming

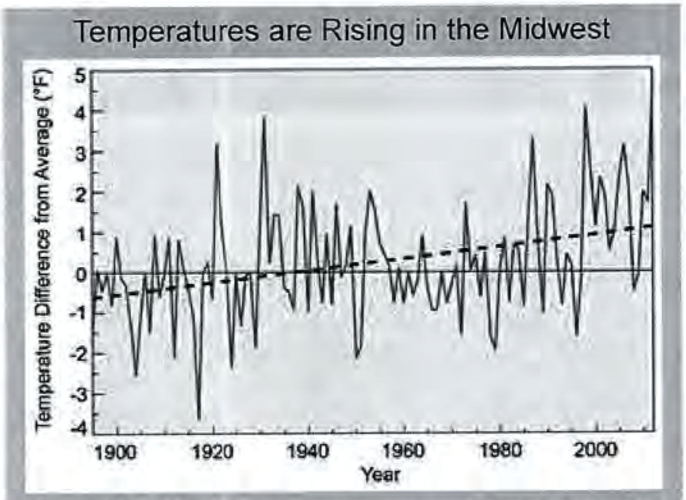

Figure 18.1. Annual average temperatures (red line) across the Midwest show a trend towards increasing temperature. The trend (dashed line) calculated over the period 1895-2012 is equal to an increase of 1.5°F. (Figure source: updated from Kunkel et al. 2013[4]).

the climate (called greenhouse gases or heat-trapping gases). But as discussed below, it also has a large and increasingly realized potential to reduce these emissions.

The rate of warming in the Midwest has markedly accelerated over the past few decades. Between 1900 and 2010, the average Midwest air temperature increased by more than 1.5°F (Figure 18.1). However, between 1950 and 2010, the average temperature increased twice as quickly, and between 1980 and 2010, it increased three times as quickly as it did from 1900 to 2010.[1] Warming has been more rapid at night and during winter. These trends are consistent with expectations of increased concentrations of heat-trapping gases and observed changes in concentrations of certain particles in the atmosphere.[1,2]

The amount of future warming will depend on changes in the atmospheric concentration of heat-trapping gases. Projections for regionally averaged temperature increases by the middle of the century (2046-2065) relative to 1979-2000 are approximately 3.8°F for a scenario with substantial emissions reductions (B1) and 4.9°F with continued growth in global emissions (A2). The projections for the end of the century (2081-2100) are approximately 5.6°F for the lower emissions scenario and 8.5°F for the higher emissions scenario (see Ch. 2: Our Changing Climate, Key Message 3).[3]

In 2011, 11 of the 14 U.S. weather-related disasters with damages of more than $1 billion affected the Midwest.[5] Several types of extreme weather events have already increased in frequency and/or intensity due to climate change, and further increases are projected (Ch. 2: Our Changing Climate, Key Message 7).[6]

Key Message 1: Impacts to Agriculture

In the next few decades, longer growing seasons and rising carbon dioxide levels will increase yields of some crops, though those benefits will be progressively offset by extreme weather events. Though adaptation options can reduce some of the detrimental effects, in the long term, the combined stresses associated with climate change are expected to decrease agricultural productivity.

Agriculture dominates Midwest land use, with more than two-thirds of land designated as farmland.[3] The region accounts for about 65% of U.S. corn and soybean production,[7] mostly from non-irrigated lands.[1] Corn and soybeans constitute 85% of Midwest crop receipts, with high-value crops such as fruits and vegetables making up most of the remainder.[8] Corn and soybean yields increased markedly (by a factor of more than 5) over the last century largely due to technological innovation, but are still vulnerable to year-to-year variations in weather conditions.[9]

The Midwest growing season lengthened by almost two weeks since 1950, due in large part to earlier occurrence of the last spring freeze.[10] This trend is expected to continue,[3,11] though the potential agricultural consequences are complex and vary by crop. For corn, small long-term average temperature increases will shorten the duration of reproductive development, leading to yield declines,[12] even when offset by carbon dioxide (CO_2) stimulation.[13] For soybeans, yields have a two in three chance of increasing early in this century due to CO_2 fertilization, but these increases are projected to be offset later in the century by higher temperature stress[14] (see Figure 18.2 for projections of increases in the frost-free season length and the number of summer days with temperatures over 95°F).

Future crop yields will be more strongly influenced by anomalous weather events than by changes in average temperature or annual precipitation (Ch. 6: Agriculture). Cold injury due to a freeze event after plant budding can decimate fruit crop production,[15] as happened in 2002, and again in 2012, to Michigan's $60 million tart cherry crop. Springtime cold air outbreaks (at least two consecutive days during which the daily average surface air temperature is below 95% of the simulated average wintertime surface air temperature) are projected to continue to occur throughout this century.[16] As a result, increased productivity of some crops due to higher temperatures, longer growing seasons, and elevated CO_2 concentrations could be offset by increased freeze damage.[17] Heat waves during pollination of field crops such as corn and soybean also reduce yields (Figure 18.3).[12] Wetter springs may reduce crop yields and profits,[18] especially if growers are forced to switch to late-planted, shorter-season varieties. A recent study suggests the volatility of U.S. corn prices is more sensitive to near-term climate change than to energy policy influences or to use of agricultural products for energy production, such as biofuel.[19]

Agriculture is responsible for about 8% of U.S. heat-trapping gas emissions,[20] and there is tremendous potential for farming practices to reduce emissions or store more carbon in soil.[21] Although large-scale agriculture in the Midwest historically led to decreased carbon in soils, higher crop residue inputs and adoption of different soil management techniques have reversed this trend. Other techniques, such as planting cover crops and no-till soil management, can further increase CO_2 uptake and reduce energy use.[22,23] Use of agricultural best management practices can also improve water quality by reducing the loss of sediments and nutrients from farm fields. Methane released from animals and their wastes can be reduced by altered diets and methane capture systems, and nitrous oxide production can be reduced by judicious fertilizer use[24] and improved waste handling.[21] In addition, if biofuel crops are grown sustainably,[25] they offer emissions reduction opportunities by substituting for fossil fuel-based energy (Ch. 10: Energy, Water, and Land).

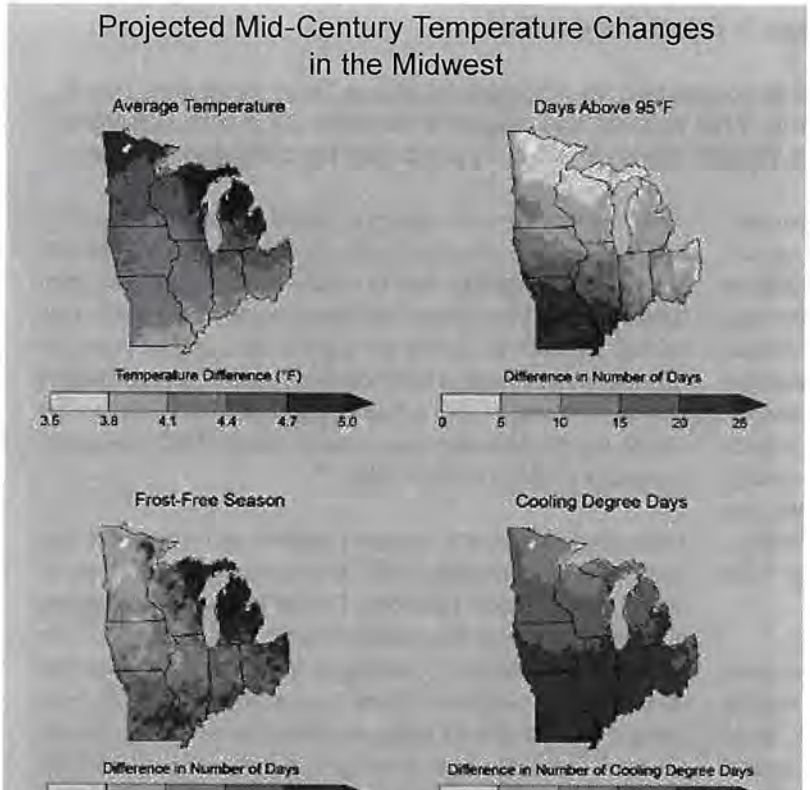

Figure 18.2. Projected increase in annual average temperatures (top left) by mid-century (2041-2070) as compared to the 1971-2000 period tell only part of the climate change story. Maps also show annual projected increases in the number of the hottest days (days over 95°F, top right), longer frost-free seasons (bottom left), and an increase in cooling degree days (bottom right), defined as the number of degrees that a day's average temperature is above 65°F, which generally leads to an increase in energy use for air conditioning. Projections are from global climate models that assume emissions of heat-trapping gases continue to rise (A2 scenario). (Figure source: NOAA NCDC / CICS-NC).

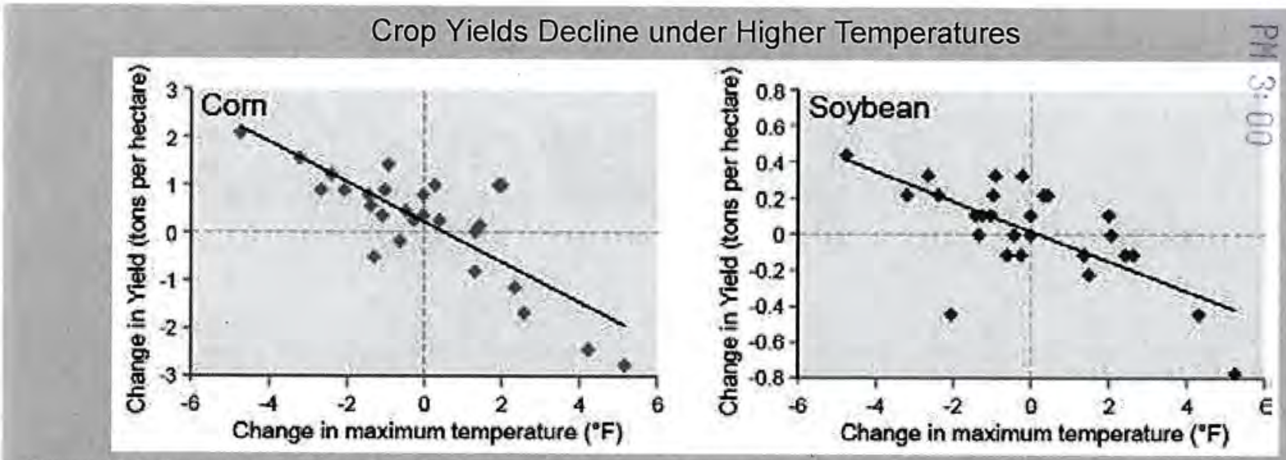

Figure 18.3. Crop yields are very sensitive to temperature and rainfall. They are especially sensitive to high temperatures during the pollination and grain filling period. For example, corn (left) and soybean (right) harvests in Illinois and Indiana, two major producers, were lower in years with average maximum summer (June, July, and August) temperatures higher than the average from 1980 to 2007. Most years with below-average yields are both warmer and drier than normal.[26,27] There is high correlation between warm and dry conditions during Midwest summers[28] due to similar meteorological conditions and drought-caused changes.[29] (Figure source: Mishra and Cherkauer 2010[26]).

Key Message 2: Forest Composition

The composition of the region's forests is expected to change as rising temperatures drive habitats for many tree species northward. The role of the region's forests as a net absorber of carbon is at risk from disruptions to forest ecosystems, in part due to climate change.

The Midwest is characterized by a rich diversity of native species juxtaposed on one of the world's most productive agricultural systems.[30] The remnants of intact natural ecosystems in the region,[31] including prairies, forests, streams, and wetlands, are rich with varied species.[32] The combined effects of climate change, land-use change, and increasing numbers of invasive species are the primary threats to Midwest natural ecosystems.[33] Species most vulnerable to climate change include those that occur in isolated habitats; live near their physiological tolerance limits; have specific habitat requirements, low reproductive rates, or limited dispersal capability; are dependent on interactions with specific other species; and/or have low genetic variability.[34]

Among the varied ecosystems of the region, forest systems are particularly vulnerable to multiple stresses. The habitat ranges of many iconic tree species such as paper birch, quaking aspen, balsam fir, and black spruce are projected to decline substantially across the northern Midwest as they shift northward, while species that are common farther south, including several oaks and pines, expand their ranges northward into the region (Figure 18.4).[35,36] There is considerable variability in the likelihood of a species' habitat changing and the adaptability of the species with regard to climate change.[37] Migration to accommodate changed habitat is expected to be slow for many Midwest species, due to relatively flat topography, high latitudes, and fragmented habitats including the Great Lakes barrier. To reach areas that are 1.8°F cooler, species in mountainous terrains need to shift 550 feet higher in altitude (which can be achieved in only a few miles), whereas species in flat terrain like the Midwest must move as much as 90 miles north to reach a similarly cooler habitat.[38]

Although global forests currently capture and store more carbon each year than they emit,[39] the ability of forests to act as large, global carbon absorbers ("sinks") may be reduced by projected increased disturbances from insect outbreaks,[40] forest fire,[41] and drought,[42] leading to increases in tree mortality and carbon emissions. Some regions may even shift from being a carbon sink to being an atmospheric carbon dioxide source,[43,44] though large uncertainties exist, such as whether projected disturbances to forests will be chronic or episodic.[45] Midwest forests are more resilient to forest carbon losses than most western forests because of relatively high moisture availability, greater nitrogen deposition (which tends to act as a fertilizer), and lower wildfire risk.[43,46]

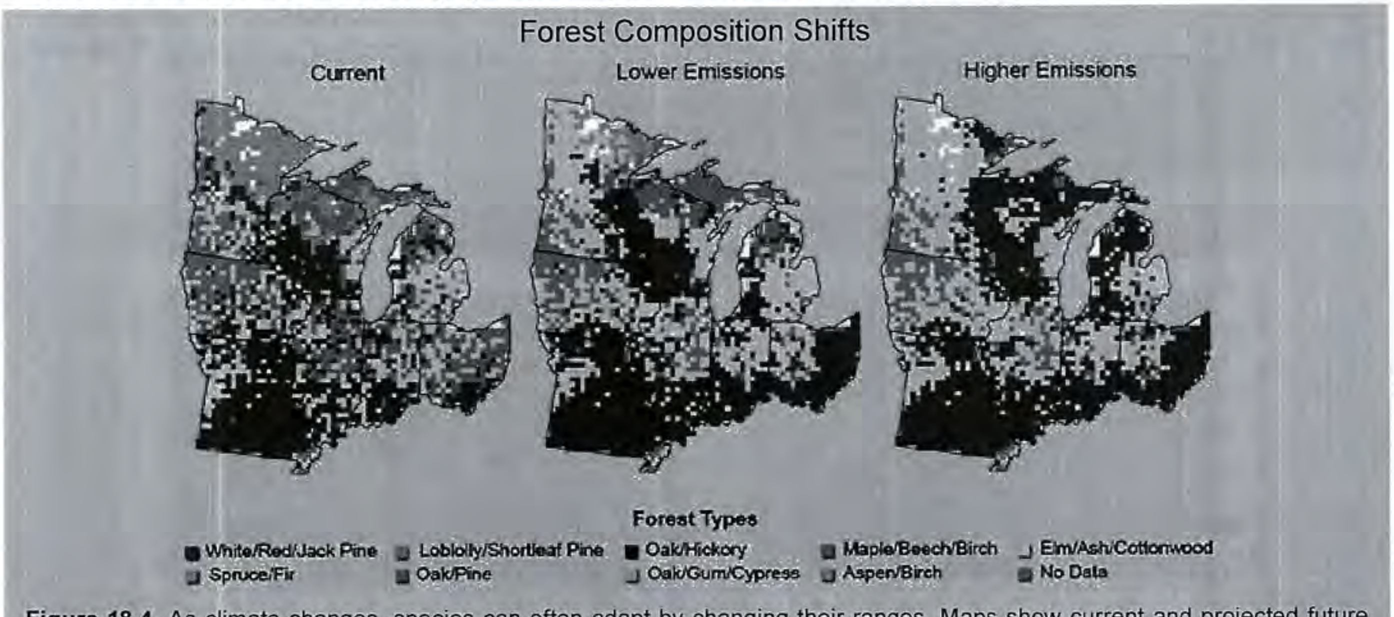

Figure 18.4. As climate changes, species can often adapt by changing their ranges. Maps show current and projected future distribution of habitats for forest types in the Midwest under two emissions scenarios, a lower scenario that assumes reductions in heat-trapping gas emissions (B1), and a very high scenario that assumes continued increases in emissions (A1FI). Habitats for white/red/jack pine, maple/beech/birch, spruce/fir, and aspen/birch forests are projected to greatly decline from the northern forests, especially under higher emissions scenarios, while various oak forest types are projected to expand.[37] While some forest types may not remain dominant, they will still be present in reduced quantities. Therefore, it is more appropriate to assess changes on an individual species basis, since all species within a forest type will not exhibit equal responses to climate change. (Figure source: Prasad et al. 2007[37]).

Key Message 3: Public Health Risks

Increased heat wave intensity and frequency, increased humidity, degraded air quality, and reduced water quality will increase public health risks.

The frequency of major heat waves in the Midwest has increased over the last six decades.[47] For the United States, mortality increases 4% during heat waves compared with non-heat wave days.[48] During July 2011, 132 million people across the U.S. were under a heat alert – and on July 20 of that year, the majority of the Midwest experienced temperatures in excess of 100°F. Heat stress is projected to increase as a result of both increased summer temperatures and humidity.[49,50] One study projected an increase of between 166 and 2,217 excess deaths per year from heat wave-related mortality in Chicago alone by 2081-2100.[51] The lower number assumes a climate scenario with significant reductions in emissions of greenhouse gases (B1), while the upper number assumes a scenario under which emissions continue to increase (A2). These projections are significant when compared to recent Chicago heat waves, where 114 people died from the heat wave of 1999 and about 700 died from the heat wave of 1995.[52] Heat response plans and early warning systems save lives, and from 1975 to 2004, mortality rates per heat event declined.[53] However, many municipalities lack such plans.[54]

More than 20 million people in the Midwest experience air quality that fails to meet national ambient air quality standards.[1] Degraded air quality due to human-induced emissions[55] and increased pollen season duration[56] are projected to be amplified with higher temperatures,[57] and pollution and pollen exposures, in addition to heat waves, can harm human health (Ch. 9: Human Health). Policy options exist (for example, see "Alternative Transportation Options Create Multiple Benefits") that could reduce emissions of both heat-trapping gases and other air pollutants, yielding benefits for human health and fitness. Increased temperatures and changes in precipitation patterns could also increase the vulnerability of Midwest residents to diseases carried by insects and rodents (Ch. 9: Human Health).[58]

ALTERNATIVE TRANSPORTATION OPTIONS CREATE MULTIPLE BENEFITS

The transportation sector produces one-third of U.S. greenhouse gas emissions, and automobile exhaust also contains precursors to fine particulate matter ($PM_{2.5}$) and ground-level ozone (O_3), which pose threats to public health. Adopting a low-carbon transportation system with fewer automobiles, therefore, could have immediate health "co-benefits" of both reducing climate change and improving human health via both improved air quality and physical fitness.

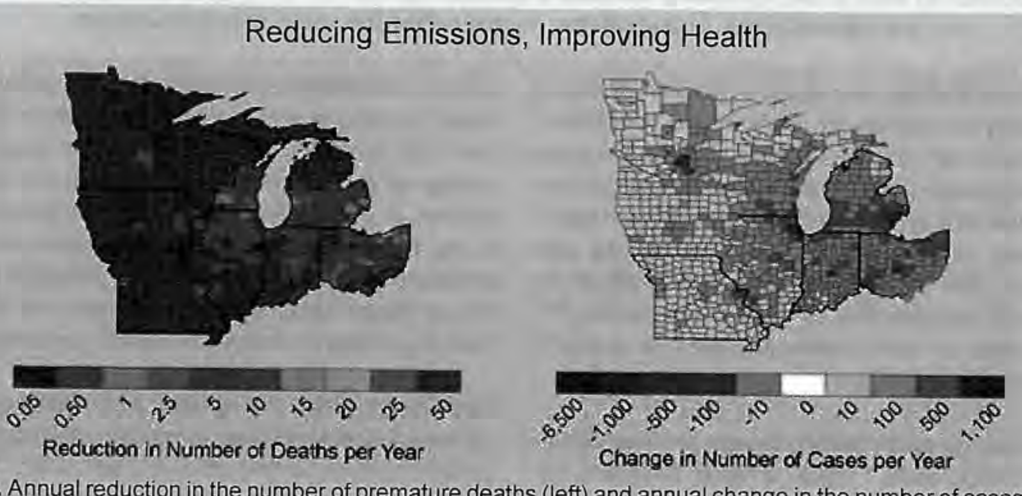

Figure 18.5. Annual reduction in the number of premature deaths (left) and annual change in the number of cases with acute respiratory symptoms (right) due to reductions in particulate matter and ozone caused by reducing automobile exhaust. The maps project health benefits if automobile trips shorter than five miles (round-trip) were eliminated for the 11 largest metropolitan areas in the Midwest. Making 50% of these trips by bicycle just during four summer months would save 1,295 lives and yield savings of more than $8 billion per year from improved air quality, avoided mortality, and reduced health care costs for the upper Midwest alone. (Figure source: Grabow et al. 2012; reproduced with permission from Environmental Health Perspectives[59]).

Key Message 4: Fossil-Fuel Dependent Electricity System

The Midwest has a highly energy-intensive economy with per capita emissions of greenhouse gases more than 20% higher than the national average. The region also has a large and increasingly utilized potential to reduce emissions that cause climate change.

The Midwest is a major exporter of electricity to other U.S. regions and has a highly energy-intensive economy (Ch. 10: Energy, Water, and Land, Figure 10.4). Energy use per dollar of gross domestic product is approximately 20% above the national average, and per capita greenhouse gas emissions are 22% higher than the national average due, in part, to the reliance on fossil fuels, particularly coal for electricity generation.[1] A large range in seasonal air temperature causes energy demand for both heating and cooling, with the highest demand for winter heating. The demand for heating in major midwestern cities is typically five to seven times that for cooling,[1] although this is expected to shift as a result of longer summers, more frequent heat waves, and higher humidity, leading to an increase in the number of cooling degree days. This increased demand for cooling by the middle of this century is projected to exceed 10 gigawatts (equivalent to at least five large conventional power plants), requiring more than $6 billion in infrastructure investments.[60] Further, approximately 95% of the electrical generating infrastructure in the Midwest is susceptible to decreased efficiency due to higher temperatures.[60]

Climate change presents the Midwest's energy sector with a number of challenges, in part because of its current reliance on coal-based electricity[1] and an aging, less-reliable electric distribution grid[61] that will require significant reinvestment even without additional adaptations to climate change.[62]

Increased use of natural gas in the Midwest has the potential to reduce emissions of greenhouse gases. The Midwest also has potential to produce energy from zero- and low-carbon sources, given its wind, solar, and biomass resources, and potential for expanded nuclear power. The Midwest does not have the highest solar potential in the country (that is found in the Southwest), but its potential is nonetheless vast, with some parts of the Midwest having as good a solar resource as Florida.[63] More than one-quarter of national installed wind energy capacity, one-third of biodiesel capacity, and more than two-thirds of ethanol production are located in the Midwest (see also Ch. 4: Energy and Ch. 10: Energy, Water, and Land).[1] Progress toward increasing renewable energy is hampered by electricity prices that are distorted through a mix of direct and indirect subsidies and unaccounted-for costs for conventional energy sources.[64]

Key Message 5: Increased Rainfall and Flooding

Extreme rainfall events and flooding have increased during the last century, and these trends are expected to continue, causing erosion, declining water quality, and negative impacts on transportation, agriculture, human health, and infrastructure.

Precipitation in the Midwest is greatest in the east, declining towards the west. Precipitation occurs about once every seven days in the western part of the region and once every three days in the southeastern part.[65] The 10 rainiest days can contribute as much as 40% of total precipitation in a given year.[65] Generally, annual precipitation increased during the past century (by up to 20% in some locations), with much of the increase driven by intensification of the heaviest rainfalls.[65,66] This tendency towards more intense precipitation events is projected to continue in the future.[67]

Model projections for precipitation changes are less certain than those for temperature.[3,4] Under a higher emissions scenario (A2), global climate models (GCMs) project average winter and spring precipitation by late this century (2071-2099) to increase 10% to 20% relative to 1971-2000, while changes in summer and fall are not expected to be larger than natural variations. Projected changes in annual precipitation show increases larger than natural variations in the north and smaller in the south (Ch. 2: Our Changing Climate, Key Message 5).[4] Regional climate models (RCMs) using the same emissions scenario also project increased spring precipitation (9% in 2041-2062 relative to 1979-2000) and decreased summer precipitation (by an average of about 8% in 2041-2062 relative to 1979-2000) particularly in the southern portions of the Midwest.[3] Increases in the frequency and intensity of extreme precipitation are projected across the entire region in both GCM and RCM simulations (Figure 18.6), and these increases are generally larger than the projected changes in average precipitation.[3,4]

Flooding can affect the integrity and diversity of aquatic ecosystems. Flooding also causes major human and economic consequences by inundating urban and agricultural land and by disrupting navigation in the region's roads, rivers, and reservoirs (see Ch. 5: Transportation, Ch. 9: Human Health, and Ch. 11: Urban). For example, the 2008 flooding in the Midwest caused 24 deaths, $15 billion in losses via reduced agricultural yields, and closure of key transportation routes.[1] Water infrastructure for flood control, navigation, and other purposes is susceptible to climate change impacts and other forces because the de-

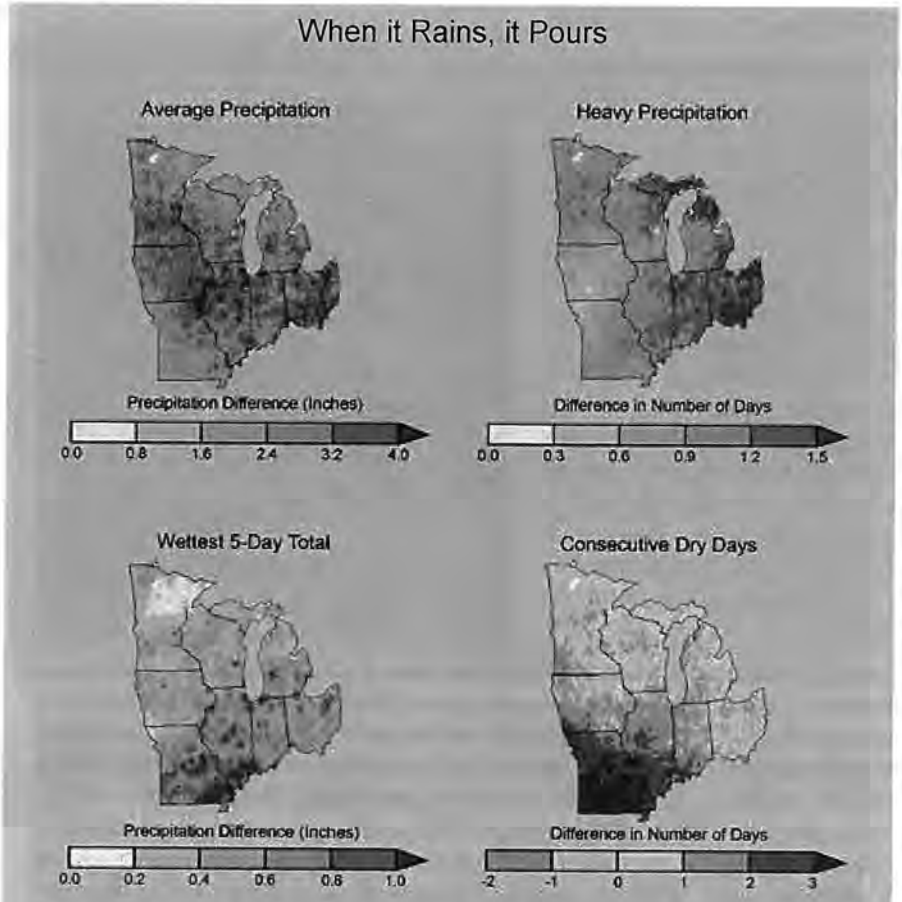

Figure 18.6. Precipitation patterns affect many aspects of life, from agriculture to urban storm drains. These maps show projected changes for the middle of the current century (2041-2070) relative to the end of the last century (1971-2000) across the Midwest under continued emissions (A2 scenario). Top left: the changes in total annual average precipitation. Across the entire Midwest, the total amount of water from rainfall and snowfall is projected to increase. Top right: increase in the number of days with very heavy precipitation (top 2% of all rainfalls each year). Bottom left: increases in the amount of rain falling in the wettest 5-day period over a year. Both (top right and bottom left) indicate that heavy precipitation events will increase in intensity in the future across the Midwest. Bottom right: change in the average maximum number of consecutive days each year with less than 0.01 inches of precipitation. An increase in this variable has been used to indicate an increase in the chance of drought in the future. (Figure source: NOAA NCDC / CICS-NC).

signs are based upon historical patterns of precipitation and streamflow, which are no longer appropriate guides.

Snowfall varies across the region, comprising less than 10% of total precipitation in the south, to more than half in the north, with as much as two inches of water available in the snowpack at the beginning of spring melt in the northern reaches of the river basins.[68] When this amount of snowmelt is combined with heavy rainfall, the resulting flooding can be widespread and catastrophic (see "Cedar Rapids: A Tale of Vulnerability and Response").[69] Historical observations indicate declines in the frequency of high magnitude snowfall years over much of the Midwest,[70] but an increase in lake effect snowfall.[71] These divergent trends and their inverse relationships with air temperatures make overall projections of regional impacts of the associated snowmelt extremely difficult. Large-scale flooding can also occur due to extreme precipitation in the absence of snowmelt (for example, Rush Creek and the Root River, Minnesota, in August 2007 and multiple rivers in southern Minnesota in September 2010).[72] These warm-season events are projected to increase in magnitude. Such events tend to be more regional and less likely to cover as large an area as those that occur in spring, in part because soil water storage capacity is typically much greater during the summer.

Changing land use and the expansion of urban areas are reducing water infiltration into the soil and increasing surface runoff. These changes exacerbate impacts caused by increased precipitation intensity. Many major Midwest cities are served by combined storm and sewage drainage systems. As surface area has been increasingly converted to impervious surfaces (such as asphalt) and extreme precipitation events have intensified, combined sewer overflow has degraded water quality, a phenomenon expected to continue to worsen with increased urbanization and climate change.[75] The U.S. Environmental Protection Agency (EPA) estimates there are more than 800 billion gallons of untreated combined sewage released into the nation's waters annually.[76] The Great Lakes, which provide drinking water to more than 40 million people and are home to more than 500 beaches,[75] have been subject to recent sewage overflows. For example, stormwater across the city of Milwaukee recently showed high human fecal pathogen levels at all 45 outflow locations, indicating widespread sewage contamination.[77] One study estimated that increased storm events will lead to an increase of up to 120% in combined sewer overflows into Lake Michigan by 2100 under a very high emissions scenario (A1FI),[75] leading to additional human health issues and beach closures. Municipalities may be forced to invest in new infrastructure to protect human health and water quality in the Great Lakes, and local communities could face tourism losses from fouled nearshore regions.

Increased precipitation intensity also increases erosion, damaging ecosystems and increasing delivery of sediment and subsequent loss of reservoir storage capacity. Increased storm-induced agricultural runoff and rising water temperatures

CEDAR RAPIDS: A TALE OF VULNERABILITY AND RESPONSE

Cedar Rapids, Des Moines, Iowa City, and Ames, Iowa, have all suffered multi-million-dollar losses from floods since 1993. In June 2008, a record flood event exceeded the once-in-500-year flood level by more than 5 feet, causing $5 to $6 billion in damages from flooding, or more than $40,000 per resident of the city of Cedar Rapids.[73] The flood inundated much of the downtown, damaging more than 4,000 structures, including 80% of government offices, and displacing 25,000 people.[74] The record flood at Cedar Rapids was the result of low reservoir capacity and extreme rainfall on soil already saturated from unusually wet conditions. Rainfall amounts comparable to those in 1993 (8 inches over two weeks) overwhelmed a flood control system designed largely for a once-in-100-year flood event. Such events are consistent with observations and projections of wetter springs and more intense precipitation events (see Figure 18.6). With the help of more than $3 billion in funding from the federal and state government, Cedar Rapids is recovering and has taken significant steps to reduce future flood damage, with buyouts of more than 1,000 properties, and numerous buildings adapted with flood protection measures.


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have increased non-point source pollution problems in recent years.[78] This has led to increased phosphorus and nitrogen loading, which in turn is contributing to more and prolonged occurrences of low-oxygen "dead zones" and to harmful, lengthy, and dense algae growth in the Great Lakes and other Midwest water bodies.[79] (Such zones and their causes are also discussed in Ch. 25: Coasts, Ch. 15: Biogeochemical Cycles, and Ch. 3: Water, Key Message 6). Watershed planning can be used to reduce water quantity and quality problems due to changing climate and land use.

While there was no apparent change in drought duration in the Midwest region as a whole over the past century,[80] the average number of days without precipitation is projected to increase in the future. This could lead to agricultural drought and suppressed crop yields.[9] This would also increase thermoelectric power plant cooling water temperatures and decrease cooling efficiency and plant capacity because of the need to avoid discharging excessively warm water (see also Ch. 4: Energy, and Ch. 10: Energy, Water, and Land).[60]

Key Message 6: Increased Risks to the Great Lakes

Climate change will exacerbate a range of risks to the Great Lakes, including changes in the range and distribution of certain fish species, increased invasive species and harmful blooms of algae, and declining beach health. Ice cover declines will lengthen the commercial navigation season.

The Great Lakes, North America's largest freshwater feature, have recently recorded higher water temperatures and less ice cover as a result of changes in regional climate (see also Ch. 2: Our Changing Climate, Key Message 11). Summer surface water temperatures in Lakes Huron increased 5.2°F and in Lake Ontario, 2.7°F, between 1968 and 2002,[81] with smaller increases in Lake Erie.[81,82] Due to the reduction in ice cover, the temperature of surface waters in Lake Superior during the summer increased 4.5°F, twice the rate of increase in air temperature.[83] These lake surface temperatures are projected to rise by as much as 7°F by 2050 and 12.1°F by 2100.[84,85] Higher temperatures, increases in precipitation, and lengthened growing seasons favor production of blue-green and toxic algae that can harm fish, water quality, habitats, and aesthetics,[79,84,86] and could heighten the impact of invasive species already present.[87]

In the Great Lakes, the average annual maximum ice coverage during 2003-2013 was less than 43% compared to the 1962-2013 average of 52%,[88] lower than any other decade during the period of measurements (Figure 18.7), although there is substantial variability from year to year. During the 1970s, which included several extremely cold winters, maximum ice coverage averaged 67%. Less ice, coupled with more frequent and intense storms (as indicated by some analyses of historical wind speeds),[89] leaves shores vulnerable to erosion and flooding and could harm property and fish habitat.[84,90] Reduced ice cover also has the potential to lengthen the shipping season.[91] The navigation season increased by an average of eight days between 1994 and 2011, and the Welland Canal in the St. Lawrence River remained open nearly two weeks longer. Increased shipping days benefit commerce but could also increase shoreline scouring and bring in more invasive species.[91,92]

Changes in lake levels can also influence the amount of cargo that can be carried on ships. On average, a 1000-foot ship sinks into the water by one inch per 270 tons of cargo;[93] thus if a ship is currently limited by water depth, any lowering of lake levels will result in a proportional reduction in the amount of cargo that it can transport to Great Lakes ports. However, current estimates of lake level changes are uncertain, even for continued increases in global greenhouse gas emissions (A2 scenario). The most recent projections suggest a slight decrease or even a small rise in levels.[94] Recent studies have also indicated that earlier approaches to computing evapotranspiration estimates from temperature may have overestimated evaporation losses.[94,95,96,97] The recent studies, along with the large spread in existing modeling results, indicate that projections of Great Lakes water levels represent evolving research and are still subject to considerable uncertainty (see Appendix 3: Climate Science Supplemental Message 8).

Ice Cover in the Great Lakes

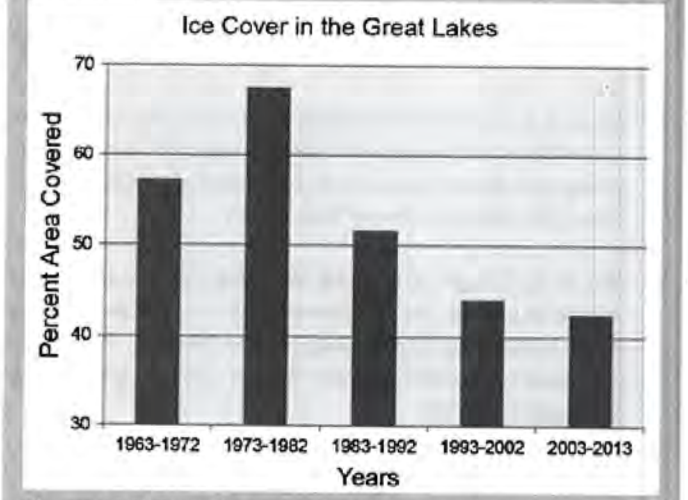

Figure 18.7. Bars show decade averages of annual maximum Great Lakes ice coverage from the winter of 1962-1963, when reliable coverage of the entire Great Lakes began, to the winter of 2012-2013. Bar labels indicate the end year of the winter; for example, 1963-1972 indicates the winter of 1962-1963 through the winter of 1971-1972. The most recent period includes the eleven years from 2003 to 2013. (Data updated from Bai and Wang, 2012[88]).

18: MIDWEST

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SUPPLEMENTAL MATERIAL
TRACEABLE ACCOUNTS

Process for Developing Key Messages:
The assessment process for the Midwest Region began with a workshop was that was held July 25, 2011, in Ann Arbor, Michigan. Ten participants discussed the scope and authors for a foundational Technical Input Report (TIR) report entitled "Midwest Technical Input Report."[98] The report, which consisted of nearly 240 pages of text organized into 13 chapters, was assembled by 23 authors representing governmental agencies, non-governmental organizations (NGOs), tribes, and other entities.

The Chapter Author Team engaged in multiple technical discussions via teleconferences that permitted a careful review of the foundational TIR[98] and of approximately 45 additional technical inputs provided by the public, as well as the other published literature, and professional judgment. The Chapter Author Team convened teleconferences and exchanged extensive emails to define the scope of the chapter for their expert deliberation of input materials and to generate the chapter text and figures. Each expert drafted key messages, initial text and figure drafts and traceable accounts that pertained to their individual fields of expertise. These materials were then extensively discussed by the team and were approved by the team members.

KEY MESSAGE #1 TRACEABLE ACCOUNT

In the next few decades, longer growing seasons and rising carbon dioxide levels will increase yields of some crops, though those benefits will be progressively offset by extreme weather events. Though adaptation options can reduce some of the detrimental effects, in the long term, the combined stresses associated with climate change are expected to decrease agricultural productivity.

Description of evidence base
The key message and supporting text summarize extensive evidence documented in the Technical Input Report.[98] Technical input reports on a wide range of topics were also received and reviewed as part of the Federal Register Notice solicitation for public input.

Evidence for altered growing seasons across the U.S. are discussed in Chapter 2 (Our Changing Climate, Key Message 4) and its Traceable Accounts. "Climate Trends and Scenarios for the U.S. National Climate Assessment"[4] and its references provide specific details for the Midwest. Evidence for longer growing seasons in the Midwest is based on regional temperature records and is incontrovertible, as is evidence for increasing carbon dioxide concentrations.

U.S. Department of Agriculture data tables provide evidence for the importance of the eight Midwest states for U.S. agricultural production.[8] Evidence for the effect of future elevated carbon dioxide concentrations on crop yields is based on scores of greenhouse and field experiments that show a strong fertilization response for C_3 plants such as soybeans and wheat and a positive but not as strong a response for C_4 plants such as corn. Observational data, evidence from field experiments, and quantitative modeling are the evidence base of the negative effects of extreme weather events on crop yield: early spring heat waves followed by normal frost events have been shown to decimate Midwest fruit crops; heat waves during flowering, pollination, and grain filling have been shown to significantly reduce corn and wheat yields; more variable and intense spring rainfall has delayed spring planting in some years and can be expected to increase erosion and runoff; and floods have led to crop losses.[12,13,14]

New information and remaining uncertainties
Key issues (uncertainties) are: a) the rate at which grain yield improvements will continue to occur, which could help to offset the overall negative effect of extreme events at least for grain crops (though not for individual farmers); and b) the degree to which genetic improvements could make some future crops more tolerant of extreme events such as drought and heat stress. Additional uncertainties are: c) the degree to which accelerated soil carbon loss will occur as a result of warmer winters and the resulting effects on soil fertility and soil water availability; and d) the potential for increased pest and disease pressure as southern pests such as soybean rust move northward and existing pests better survive milder Midwest winters.

Assessment of confidence based on evidence

Because nearly all studies published to date in the peer-reviewed literature agree that Midwest crops benefit from CO_2 fertilization and some benefit from a longer growing season, there is **very high** confidence in this component of the key message.

Studies also agree that full benefits of climate change will be offset partly or fully by more frequent heat waves, early spring thaws followed by freezing temperatures, more variable and intense rainfall events, and floods. Again, there is **very high** confidence in this aspect.

There is less certainty (**high**) about pest effects and about the potential for adaptation actions to significantly mitigate the risk of crop loss.

Confidence Level

Very High

Strong evidence (established theory, multiple sources, consistent results, well documented and accepted methods, etc.), high consensus

High

Moderate evidence (several sources, some consistency, methods vary and/or documentation limited, etc.), medium consensus

Medium

Suggestive evidence (a few sources, limited consistency, models incomplete, methods emerging, etc.), competing schools of thought

Low

Inconclusive evidence (limited sources, extrapolations, inconsistent findings, poor documentation and/or methods not tested, etc.), disagreement or lack of opinions among experts

Key Message #2 Traceable Account

The composition of the region's forests is expected to change as rising temperatures drive habitats for many tree species northward. The role of the region's forests as a net absorber of carbon is at risk from disruptions to forest ecosystems, in part due to climate change.

Description of evidence

The key message and supporting text summarize extensive evidence documented in the Technical Input Report.[98] Technical inputs on a wide range of topics were also received and reviewed as part of the Federal Register Notice solicitation for public input.

Evidence for increased temperatures and altered growing seasons across the U.S. is discussed in Chapter 2 (Our Changing Climate, Key Messages 3 and 4) and its Traceable Accounts. "Climate Trends and Scenarios for the U.S. National Climate Assessment,"[4] with its references, provides specific details for the Midwest. Evidence that species have been shifting northward or ascending in altitude has been mounting for numerous species, though less so for long-lived trees. Nearly all studies to date published in the peer-reviewed literature agree that many of the boreal species of the north will eventually retreat northward. The question is when. Multiple models and paleoecological evidence show these trends have occurred in the past and are projected to continue in the future.[36]

The forests of the eastern United States (including the Midwest) have been accumulating large quantities of carbon over the past century,[23] but evidence shows this trend is slowing in recent decades. There is a large amount of forest inventory data supporting the gradual decline in carbon accumulation throughout the eastern United States,[99] as well as evidence of increasing disturbances and disturbance agents that are reducing overall net productivity in many of the forests.

New information and remaining uncertainties

A key issue (uncertainty) is the rate of change of habitats and for organisms adapting or moving as habitats move. The key questions are: How much will the habitats change (what scenarios and model predictions will be most correct)? As primary habitats move north, which species will be able to keep up with changing habitats on their own or with human intervention through assisted migration, management of migration corridors, or construction or maintenance of protected habitats within species' current landscapes?

Viable avenues to improving the information base are determining which climate models exhibit the best ability to reproduce the historical and potential future change in habitats, and determining how, how fast, and how far various species can move or adapt.

An additional key source of uncertainty is whether projected disturbances to forests are chronic or episodic in nature.[45]

Assessment of confidence based on evidence

There is **very high** confidence in this key message, given the evidence base and remaining uncertainties.

KEY MESSAGE #3 TRACEABLE ACCOUNT

Increased heat wave intensity and frequency, increased humidity, degraded air quality, and reduced water quality will increase public health risks.

Description of evidence

The key message and supporting text summarize extensive evidence documented in the Technical Input Report.[98] Technical inputs on a wide range of topics were also received and reviewed as part of the Federal Register Notice solicitation for public input.

Evidence for extreme weather such as heat waves across the U.S. are discussed in Chapter 2 (Our Changing Climate, Key Message 7) and its Traceable Accounts. Specific details for the Midwest are in "Climate Trends and Scenarios for the U.S. National Climate Assessment"[4] with its references. A recent book[100] also contains chapters detailing the most current evidence for the region.

Heat waves: The occurrence of heat waves in the recent past has been well-documented,[1,15,49] as have health outcomes (particularly with regards to mortality). Projections of thermal regimes indicate increased frequency of periods with high air temperatures (and high apparent temperatures, which are a function of both air temperature and humidity). These projections are relatively robust and consistent between studies.

Humidity: Evidence on observed and projected increased humidity can be found in a recent study.[49]

Air quality: In 2008, in the region containing North Dakota, South Dakota, Nebraska, Kansas, Minnesota, Iowa, Missouri, Wisconsin, Illinois, Michigan, Indiana, and Ohio, over 26 million people lived in counties that failed the National Ambient Air Quality Standards (NAAQS) for $PM_{2.5}$ (particles with diameter below 2.5 microns), and over 24 million lived in counties that failed the NAAQS for ozone (O_3).[1] Because not all counties have air quality measurement stations in place, these data must be considered a lower bound on the actual number of counties that violate the NAAQS. Given that the NAAQS were designed principally with the goal of protecting human health, failure to meet these standards implies a significant fraction of the population live in counties characterized by air quality that is harmful to human health. While only relatively few studies have sought to make detailed air quality projections for the future, those that have[1] generally indicate declining air quality (see uncertainties below).

Water quality: The EPA estimates there are more than 800 billion gallons of untreated combined sewage released into the nation's waters annually.[76] Combined sewers are designed to capture both sanitary sewage and stormwater. Combined sewer overflows lead to discharge of untreated sewage as a result of precipitation events, and can threaten human health. While not all urban areas within the Midwest have combined sewers for delivery to wastewater treatment plants, many do (for example, Chicago and Milwaukee), and such systems are vulnerable to combined sewer overflows during extreme precipitation events. Given projected increases in the frequency and intensity of extreme precipitation events in the Midwest (Chapter 2: Our Changing Climate, Key Message 6),[75] it appears that sewer overflow will continue to constitute a significant current health threat and a critical source of climate change vulnerability for major urban areas within the Midwest.

New information and remaining uncertainties

Key issues (uncertainties) are: Human health outcomes are contingent on a large number of non-climate variables. For example, morbidity and mortality outcomes of extreme heat are strongly determined by a) housing stock and access to air-conditioning in residences; b) existence and efficacy of heat wave warning and response plans (for example, foreign-language-appropriate communications and transit plans to public cooling centers, especially for the elderly); and c) co-stressors (for example, air pollution). Further, heat stress is dictated by apparent temperature, which is a function of both air temperature and humidity. Urban heat islands tend to exacerbate elevated temperatures and are largely determined by urban land use and human-caused heat emissions. Urban heat island reduction plans (for example, planted green roofs) represent one ongoing intervention. Nevertheless, the occurrence of extreme heat indices will increase under all climate scenarios. Thus, in the absence of policies to reduce heat-related illness/death, these impacts will increase in the future.

Air quality is a complex function not only of physical meteorology but emissions of air pollutants and precursor species. However, since most chemical reactions are enhanced by warmer temperatures, as are many air pollutant emissions, warmer temperatures may lead to worsening of air quality, particularly with respect to tropospheric ozone (see Ch. 9: Human Health). Changes in humidity are more difficult to project but may amplify the increase in heat stress due to rising temperatures alone.[49]

Combined sewer overflow is a major threat to water quality in some midwestern cities now. The tendency towards increased magnitude of extreme rain events (documented in the historical record and projected to continue in downscaling analyses) will cause an increased risk of waterborne disease outbreaks in the absence of infrastructure overhaul. However, mitigation actions are available, and the changing structure of cities (for example, reducing impervious surfaces) may offset the impact of the changing climate.

Assessment of confidence based on evidence

In the absence of concerted efforts to reduce the threats posed by heat waves, increased humidity, degraded air quality and degraded water quality, climate change will increase the health risks associated with these phenomena. However, these projections are contingent on underlying assumptions regarding socioeconomic conditions and demographic trends in the region. Confidence is therefore **high** regarding this key message.

KEY MESSAGE #4 TRACEABLE ACCOUNT

The Midwest has a highly energy-intensive economy with per capita emissions of greenhouse gases more than 20% higher than the national average. The region also has a large and increasingly utilized potential to reduce emissions that cause climate change.

Description of evidence

The key message and supporting text summarize extensive evidence documented in the Technical Input Report.[98] Technical inputs on a wide range of topics were also received and reviewed as part of the Federal Register Notice solicitation for public input.

The Midwest's disproportionately large reliance on coal for electricity generation and the energy intensity of its agricultural and manufacturing sectors are all well documented in both government and industry records, as is the Midwest's contribution to greenhouse gases.[1] The region's potential for zero- and lower-carbon energy production is also well documented by government and private assessments. Official and regular reporting by state agencies and non-governmental organizations demonstrates the Midwest's progress toward a decarbonized energy mix (Ch. 4: Energy; Ch. 10: Energy, Water, and Land).[1]

There is evidence that the Midwest is steadily decarbonizing its electricity generation through a combination of new state-level policies (for example, energy efficiency and renewable energy standards) and will continue to do so in response to low natural gas prices, falling prices for renewable electricity (for example, wind and solar), greater market demand for lower-carbon energy from consumers, and new EPA regulations governing new power plants. Several midwestern states have established Renewable Portfolio Standards (see https://www.misoenergy.org/WhatWeDo/StrategicInitiatives/Pages/RenewablePortfolioStandards.aspx).

New information and remaining uncertainties

There are four key uncertainties. The first uncertainty is the net effect of emerging EPA regulations on the future energy mix of the Midwest. Assessments to date suggest a significant number of coal plants will be closed or repowered with lower-carbon natural gas; and even coal plants that are currently thought of as "must run" (to maintain the electric grid's reliability) may be able to be replaced in some circumstances with the right combination of energy efficiency, new transmission lines, demand response, and distributed generation. A second key uncertainty is whether or not natural gas prices will remain at their historically low levels. Given that there are really only five options for meeting electricity demand – energy efficiency, renewables, coal, nuclear, and natural gas – the replacement of coal with natural gas for electricity production would have a significant impact on greenhouse gas emissions in the region. Third is the uncertain future for federal policies that have spurred renewable energy development to date, such as the Production Tax Credit for wind. While prices for both wind and solar continue to fall, the potential loss of tax credits may dampen additional market penetration of these technologies. A fourth uncertainty is the net effect of climate change on energy demand, and the cost of meeting that new demand profile. Research to date suggests the potential for a significant swing from the historically larger demand for heating in the winter to more demand in the summer instead, due to a warmer, more humid climate.[3]

Assessment of confidence based on evidence

There is no dispute about the energy intensity of the midwestern economy, nor its disproportionately large contribution of greenhouse gas emissions. Similarly, there is broad agreement about the Midwest's potential for—and progress toward—lower-carbon electricity production. There is therefore **very high** confidence in this statement.

KEY MESSAGE #5 TRACEABLE ACCOUNT

Extreme rainfall events and flooding have increased during the last century, and these trends are expected to continue, causing erosion, declining water quality, and negative impacts on transportation, agriculture, human health, and infrastructure.

Description of evidence

The key message and supporting text summarize extensive evidence documented in the Technical Input Report.[98] Technical inputs on a wide range of topics were also received and reviewed as part of the Federal Register Notice solicitation for public input.

Evidence for extreme weather and increased precipitation across the U.S. are discussed in Chapter 2 (Our Changing Climate, Key Messages 5, 6, and 7) and its Traceable Accounts. Specific details for the Midwest are detailed in "Climate Trends and Scenarios for the U.S. National Climate Assessment"[4] with its references. A recent book[100] also contains chapters detailing the most current evidence for the region.

There is compelling evidence that annual total precipitation has been increasing in the region, with wetter winters and springs, drier summers, an increase in extreme precipitation events, and changes in snowfall patterns. These observations are consistent with climate model projections. Both the observed trends and climate models suggest these trends will increase in the future.

Recent records also indicate evidence of a number of high-impact flood events in the region. Heavy precipitation events cause increased kinetic energy of surface water and thus increase erosion. Heavy precipitation events in the historical records have been shown to be associated with discharge of partially or completely untreated sewage due to the volumes of water overwhelming combined sewer systems that are designed to capture both domestic sewage and stormwater.

Climate downscaling projections tend to indicate an increase in the frequency and duration of extreme events (both heavy precipitation and meteorological drought) in the future.

An extensive literature survey and synthetic analysis is presented in chapters in a recent book[100] for impacts on water quality, transportation, agriculture, health, and infrastructure.

New information and remaining uncertainties

Precipitation is much less readily measured or modeled than air temperature.[3] Thus both historical tendencies and projections for precipitation are inherently less certain than for temperature. Most regional climate models still have a positive bias in precipitation frequency but a negative bias in terms of precipitation amount in extreme events.

Flood records are very heterogeneous and there is some ambiguity about the degree to which flooding is a result of atmospheric conditions.[69] Flooding is not solely the result of incident precipitation but is also a complex function of the preceding conditions such as soil moisture content and extent of landscape infiltration. A key issue (uncertainty) is the future distribution of snowfall. Records indicate that snowfall is decreasing in the southern parts of the region, along with increasing lake effect snow. Climate models predict these trends will increase. There is insufficient knowledge about how this change in snowfall patterns will affect flooding and associated problems, but it is projected to affect the very large spring floods that typically cause the worst flooding in the region. In addition, recent data and climate predictions indicate drier summer conditions, which could tend to offset the effects of higher intensity summer storms by providing increased water storage in the soils. The relative effects of these offsetting trends need to be assessed. To determine future flooding risks, hydrologic modeling is needed that includes the effects of the increase in extreme events, changing snow patterns, and shifts in rainfall patterns. Adaptation measures to reduce soil erosion and combined sewer overflow (CSO) events are available and could be widely adopted.

The impacts of increased magnitude of heavy precipitation events on water quality, agriculture, human health, transportation, and infrastructure will be strongly determined by the degree to which the resilience of such systems is enhanced (for example, some cities are already implementing enhanced water removal systems).

Assessment of confidence based on evidence

There have been improvements in agreement between observed precipitation patterns and model simulations. Also an increase in extreme precipitation events is consistent with first-order reasoning and increased atmospheric water burdens due to increased air temperature. Recent data suggest an increase in flooding in the region but there is uncertainty about how changing snow patterns will affect flood events in the future. Thus there is **high** confidence in increases in high-magnitude rainfall events and extreme precipitation events, and that these trends are expected to continue.

There is **medium** confidence that, in the absence of substantial adaptation actions, the enhancement in extreme precipitation and other tendencies in land use and land cover result in a projected increase in flooding. There is **medium** confidence that, in the absence of major adaptation actions, the enhancement in extreme precipitation will tend to increase the risk of erosion, declines in water quality, and negative impacts on transportation, agriculture, human health, and infrastructure.[3]

KEY MESSAGE #6 TRACEABLE ACCOUNT

Climate change will exacerbate a range of risks to the Great Lakes, including changes in the range and distribution of certain fish species, increased invasive species and harmful blooms of algae, and declining beach health. Ice cover declines will lengthen the commercial navigation season.

Description of evidence

The key message and supporting text summarize extensive evidence documented in the Technical Input Report.[98] Technical inputs on a wide range of topics were also received and reviewed as part of the Federal Register Notice solicitation for public input.

Evidence for changes in ice cover due to increased temperatures across the U.S. are discussed in Chapter 2 (Our Changing Climate, Key Message 11) and its Traceable Accounts. Specific details for the Midwest are detailed in "Climate Trends and Scenarios for the U.S. National Climate Assessment"[4] with its references. A recent book[100] also contains chapters detailing the most current evidence for the region.

Altered fish communities: Warmer lakes and streams will certainly provide more habitat for warmwater species as conditions in northern reaches of the basin become more suitable for warmwater fish and as lakes and streams are vacated by cool- and coldwater species.[84] Habitat for coldwater fish, though not expected to disappear, will shrink substantially, though it could also expand in some areas, such as Lake Superior. Whether climate change expands the range of any type of fish is dependent on the availability of forage fish, as higher temperatures also necessitate greater food intake.

Increased abundances of invasive species: As climate change alters water temperatures, habitat, and fish communities, conditions that once were barriers to alien species become conduits for establishment and spread.[84] This migration will alter drastically the fish communities of the Great Lakes basin. Climate change is also projected to heighten the impact of invasive species already present in the Great Lakes basin. Warmer winter conditions, for instance, have the potential to benefit alewife, round gobies, ruffe, sea lamprey, rainbow smelt, and other non-native species. These species have spread rapidly throughout the basin and have already inflicted significant ecological and economic harm.

Declining beach health and harmful algal blooms: Extreme events increase runoff, adding sediments, pollutants, and nutrients to the Great Lakes. The Midwest has experienced rising trends in precipitation and runoff. Agricultural runoff, in combination with increased water temperatures, has caused considerable non-point source pollution problems in recent years, with increased phosphorus and nitrogen loadings from farms contributing to more frequent and prolonged occurrences of anoxic "dead zones" and harmful, dense algae growth for long periods. Stormwater runoff that overloads urban sewer systems during extreme events adds to increased levels of toxic substances, sewage, and bacteria in the Great Lakes, affecting water quality, beach health, and human well-being. Increased storm events caused by climate change will lead to an increase in combined sewer overflows.[84]

Decreased ice cover: Increasingly mild winters have shortened the time between when a lake freezes and when it thaws.[101] Scientists have documented a relatively constant decrease in Great Lakes ice cover since the 1970s, particularly for Lakes Superior, Michigan, Huron, and Ontario. The loss of ice cover on the Great Lakes has both ecological and economic implications. Ice serves to protect shorelines and habitat from storms and wave power. Less ice—coupled with more frequent and intense storms—leaves shores vulnerable to erosion and flooding and could harm property and fish habitat.

Water levels: The 2009 NCA[102] included predictions of a significant drop in Great Lakes levels by the end of the century, based on methods of linking climate models to hydrologic models. These methods have been significantly improved by fully coupling the hydrologic cycle among land, lake, and atmosphere.[97] Without accounting for that cycle of interactions, a study[96] concluded that increases in precipitation would be negated by increases in winter evaporation from less ice cover and by increases in summer evaporation and evapotranspiration from warmer air temperatures, under a scenario of continued increases in global emissions (SRES A2 scenario). Declines of 8 inches to 2 feet have been projected by the end of this century, depending on the specific lake in question.[96] A recent comprehensive assessment,[94] however, has concluded that with a continuation of current rising emissions trends (A2), the lakes will experience a slight decrease or even a rise in water levels; the difference from earlier studies is because earlier studies tended to overstress the amount of evapotranspiration expected to occur. The range of potential future lake levels remains large and includes the earlier projected decline. Overall, however, scientists project an increase in precipitation in the Great Lakes region (with extreme events projected to contribute to this increase), which will contribute to maintenance of or an increase in Great Lakes water levels. However, water level changes are not predicted to be uniform throughout the basin.

Shipping: Ice cover is expected to decrease dramatically by the end of the century, possibly lengthening the shipping season and, thus, facilitating more shipping activity. Current science suggests water levels in the Great Lakes are projected to fall slightly or might even rise over the short run. However, by causing even a small drop in water levels, climate change could make the costs of shipping increase substantially. For instance, for every inch of draft a 1000-foot ship gives up, its capacity is reduced by 270 tons.[93] Lightened loads today already add about $200,000 in costs to each voyage.

New information and remaining uncertainties

Key issues (uncertainties) are: Water levels are influenced by the amount of evaporation from decreased ice cover and warmer air temperatures, by evapotranspiration from warmer air temperatures, and by potential increases in inflow from more precipitation. Uncertainties about Great Lakes water levels are high, though most models suggest that the decrease in ice cover will lead to slightly lower water levels, beyond natural fluctuations.

The spread of invasive species into the system is near-certain (given the rate of introductions over the previous 50 years) without major policy and regulatory changes. However, the changes in Great Lakes fish communities are based on extrapolation from known fishery responses to projected responses to expected changing conditions in the basin. Moreover, many variables beyond water temperature and condition affect fisheries, not the least of which is the availability of forage fish. Higher water temperatures necessitate greater food intake, yet the forage base is changing rapidly in many parts of the Great Lakes basin, thus making the projected impact of climate change on fisheries difficult to discern with very high certainty.

Assessment of confidence based on evidence

Peer-reviewed literature about the effects of climate change are in broad agreement that air and surface water temperatures are rising and will continue to do so, that ice cover is declining steadily, and that precipitation and extreme events are on the rise. For large lake ecosystems, these changes have well-documented effects, such as effects on algal production, stratification (change in water temperature with depth), beach health, and fisheries. Key uncertainties exist about Great Lakes water levels and the impact of climate change on fisheries.

A qualitative summary of climate stressors and coastal margin vulnerabilities for the Great Lakes is given in a technical input report.[84] We have high confidence that the sum of these stressors will exceed the risk posed by any individual stressor. However, quantifying the cumulative impacts of those stressors is very challenging.

Given the evidence and remaining uncertainties, there is **very high** confidence in this key message, except **high** confidence for lake levels changing, and **high** confidence that declines in ice cover will continue to lengthen the commercial navigation season. There is limited information regarding exactly how invasive species may respond to changes in the regional climate, resulting in **medium** confidence for that part of the key message.

Climate Change Impacts in the United States

CHAPTER 19
GREAT PLAINS

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INFORMATION DRAWN FROM THIS CHAPTER IS INCLUDED IN THE HIGHLIGHTS REPORT AND IS IDENTIFIED BY THIS ICON

19 GREAT PLAINS

KEY MESSAGES

1. **Rising temperatures are leading to increased demand for water and energy. In parts of the region, this will constrain development, stress natural resources, and increase competition for water among communities, agriculture, energy production, and ecological needs.**
2. **Changes to crop growth cycles due to warming winters and alterations in the timing and magnitude of rainfall events have already been observed; as these trends continue, they will require new agriculture and livestock management practices.**
3. **Landscape fragmentation is increasing, for example, in the context of energy development activities in the northern Great Plains. A highly fragmented landscape will hinder adaptation of species when climate change alters habitat composition and timing of plant development cycles.**
4. **Communities that are already the most vulnerable to weather and climate extremes will be stressed even further by more frequent extreme events occurring within an already highly variable climate system.**
5. **The magnitude of expected changes will exceed those experienced in the last century. Existing adaptation and planning efforts are inadequate to respond to these projected impacts.**

The Great Plains is a diverse region where climate and water are woven into the fabric of life. Day-to-day, month-to-month, and year-to-year changes in the weather can be dramatic and challenging for communities and their commerce. The region experiences multiple climate and weather hazards, including floods, droughts, severe storms, tornadoes, hurricanes, and winter storms. In much of the Great Plains, too little precipitation falls to replace that needed by humans, plants, and animals. These variable conditions in the Great Plains already stress communities and cause billions of dollars in damage; climate change will add to both stress and costs.

The people of the Great Plains historically have adapted to this challenging climate. Although projections suggest more frequent and more intense droughts, severe rainfall events, and heat waves, communities and individuals can reduce vulnerabilities through the use of new technologies, community-driven policies, and the judicious use of resources. Adaptation (means of coping with changed conditions) and mitigation (reducing emissions of heat-trapping gases to reduce the speed and amount of climate change) choices can be locally driven, cost effective, and beneficial for local economies and ecosystem services.


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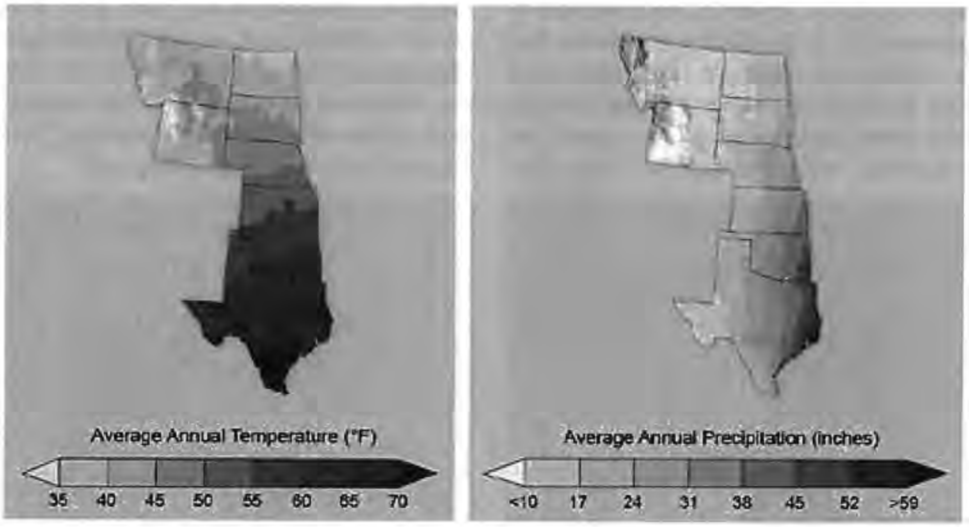

Temperature and Precipitation Distribution in the Great Plains

Figure 19.1. The region has a distinct north-south gradient in average temperature patterns (left), with a hotter south and colder north. For precipitation (right), the regional gradient runs west-east, with a wetter east and a much drier west. Averages shown here are for the period 1981-2010. (Figure source: adapted from Kunkel et al. 2013[4]).

Significant climate-related challenges are expected to involve 1) resolving increasing competition among land, water, and energy resources; 2) developing and maintaining sustainable agricultural systems; 3) conserving vibrant and diverse ecological systems; and 4) enhancing the resilience of the region's people to the impacts of climate extremes. These growing challenges will unfold against a changing backdrop that includes a growing urban population and declining rural population, new economic factors that drive incentives for crop and energy production, advances in technology, and shifting policies such as those related to farm and energy subsidies.

The Great Plains region features relatively flat plains that increase in elevation from sea level to more than 5,000 feet at the base of mountain ranges along the Continental Divide. Forested mountains cover western Montana and Wyoming, extensive rangelands spread throughout the Plains, marshes extend along Texas' Gulf Coast, and desert landscapes distinguish far west Texas.[1] A highly diverse climate results from the region's large north-south extent and change of elevation. This regional diversity also means that climate change impacts will vary across the region.

Great Plains residents already must contend with weather challenges from winter storms, extreme heat and cold, severe thunderstorms, drought, and flood-producing rainfall. Texas' Gulf Coast averages about three tropical storms or hurricanes every four years,[2] generating coastal storm surge and sometimes bringing heavy rainfall and damaging winds hundreds of miles inland. The expected rise in sea level will result in the potential for greater damage from storm surge along the Gulf Coast of Texas (see Ch. 25: Coasts).

Annual average temperatures range from less than 40°F in the mountains of Wyoming and Montana to more than 70°F in South Texas, with extremes ranging from -70°F in Montana to 121°F in North Dakota and Kansas.[3] Summers are long and hot in the south; winters are long and often severe in the north. North Dakota's increase in annual temperature over the past 130 years is the fastest in the contiguous U.S. and is mainly driven by warming winters.[4]

The region has a distinct north-south gradient in average temperature patterns, with a hotter south and colder north (Figure 19.1). Average annual precipitation greater than 50 inches supports lush vegetation in eastern Texas and Oklahoma. For most places, however, average rainfall is less than 30 inches, with some of Montana, Wyoming, and far west Texas receiving less than 15 inches a year. Across much of the region, annual water loss from transpiration by plants and from evaporation is higher than annual precipitation, making these areas particularly susceptible to droughts.

Projected climate change

For an average of seven days per year, maximum temperatures reach more than 100°F in the Southern Plains and about 95°F in the Northern Plains (Figure 19.2). These high temperatures are projected to occur much more frequently, even under a scenario of substantial reductions in heat-trapping gas (also called greenhouse gas) emissions (B1), with days over 100°F projected to double in number in the north and quadruple in the south by mid-century (Ch. 2: Our Changing Climate, Key Message 7).[4] Similar increases are expected in the number of nights with minimum temperatures higher than 80°F in the south and 60°F in the north (cooler in mountain regions; see Figure 19.3). These increases in extreme heat will have many negative consequences, including increases in surface water losses, heat stress, and demand for air conditioning.[5] These negative consequences will more than offset the benefits of warmer winters, such as lower winter heating demand, less cold stress on humans and animals, and a longer growing season, which will be extended by mid-century an average of 24 days relative to the 1971-2000 average.[4,5] More overwintering insect populations are also expected.[5]


Historical Temperature on the 7 Hottest Days of the Year

The historical (1971-2000) distribution of temperature for the hottest 2% of days (about seven days a year) echoes the distinct north-south gradient in average temperatures.

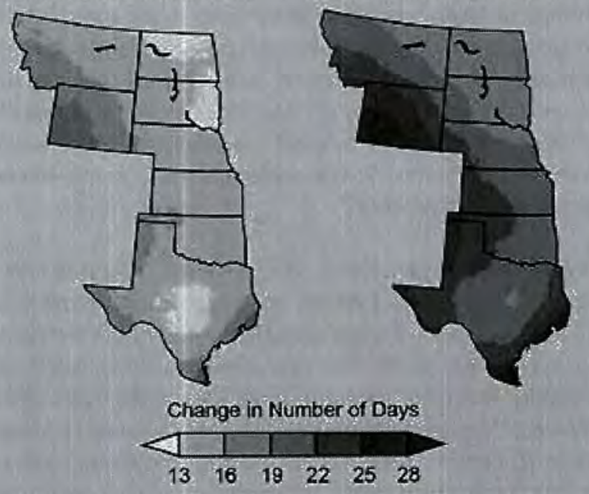
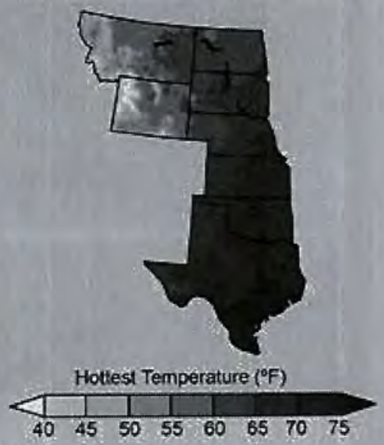

Projected Change in Number of Hot Days

Figure 19.2. The number of days with the hottest temperatures is projected to increase dramatically. By mid-century (2041-2070), the projected change in the number of days exceeding those hottest temperatures is greatest in the western areas and Gulf Coast for both the lower emissions scenario (B1) and for the higher emissions scenario (A2). (Figure source: NOAA NCDC / CICS-NC).


Historical Temperature on the 7 Warmest Nights of the Year

The historical (1971-2000) distribution of temperature for the warmest 2% of nights (about seven days a year) echoes the distinct north-south gradient in average temperatures.

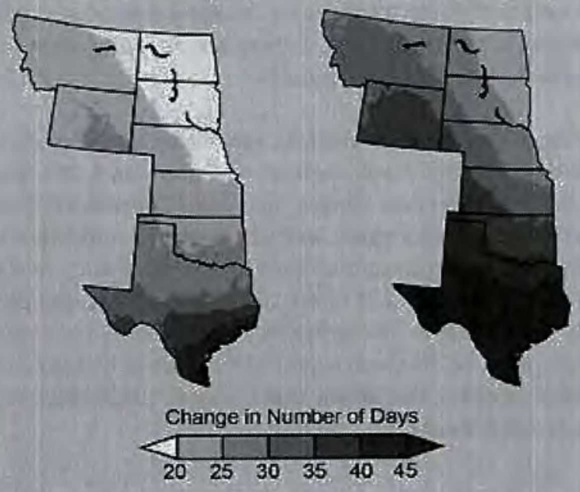

Projected Change in Number of Warm Nights

Figure 19.3. The number of nights with the warmest temperatures is projected to increase dramatically. By mid-century (2041-2070), the projected change in number of nights exceeding those warmest temperatures is greatest in the south for both the lower emissions scenario (B1) and for the higher emissions scenario (A2). (Figure source: NOAA NCDC / CICS-NC).