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5: TRANSPORTATION

SUPPLEMENTAL MATERIAL
TRACEABLE ACCOUNTS

Process for Developing Key Messages
In developing key messages, the chapter author team engaged, via teleconference, in multiple technical discussions from January through May 2012 as they reviewed numerous peer reviewed publications. Technical input reports (21) on a wide range of topics were also received and reviewed as part of the Federal Register Notice solicitation for public input. The author team's review included a foundational Technical Input Report for the National Climate Assessment, "Climate Impacts and U.S. Transportation."[57] Other published literature and professional judgment were also considered as the chapter key messages were developed. The chapter author team met in St. Louis, MO, in April 2012 for expert deliberation and finalization of key messages.

Key Message #1 Traceable Account

The impacts from sea level rise and storm surge, extreme weather events, higher temperatures and heat waves, precipitation changes, Arctic warming, and other climatic conditions are affecting the reliability and capacity of the U.S. transportation system in many ways.

Description of evidence base
Climate impacts in the form of sea level rise, changing frequency of extreme weather events, heat waves, precipitation changes, Arctic warming, and other climatic conditions are documented in Ch. 2: Our Changing Climate of this report.

Climate can be described as the frequency distribution of weather over time. Existing weather conditions, flooding, and storm surge demonstrably affect U.S. transportation systems. By changing the frequency of these weather conditions, climate change will inevitably affect the reliability and capacity of U.S. transportations systems. This view is supported by multiple studies of the impacts of weather and climate change on particular transportation systems or particular regions.

An aggregate summary of impacts of climate change on U.S. transportation can be found in NRC 2008.[7] A paper commissioned for NRC 2008 considers specific impacts of various forms of climate change on infrastructure, for example, possible future constraints on infrastructure.[12] The effects of climate on transit systems are summarized in Hodges 2011.[14] The impact of heat and other climate effects on rail systems are described by Hodges 2011 and Rossetti 2002.[14,19]

Future impacts of sea level rise and other climatic effects on transportation systems in the Gulf Coast were examined by CCSP 2008.[11] The impacts of climate change on New York State, including its transportation system, were undertaken by Rosenzweig et al. 2011.[60] Impacts of sea level rise on transportation infrastructure for the mid-Atlantic were also discussed in CCSP 2009 SAP 4.1, Ch. 7.[27]

Weather impacts on road systems are discussed in "Climate Impacts and U.S. Transportation"[57] and numerous other sources. Weather impacts on aviation operations are discussed in Kulesa 200320 and numerous other sources.

In addition, the key message and supporting text summarize extensive evidence documented in "Climate Impacts and U.S. Transportation."[57]

Additional peer-reviewed publications discuss the fact that Arctic warming is affecting existing Alaskan transportation infrastructure today, and is projected to allow the seasonal opening of the Northwest Passage to freight shipment.[24]

New information and remaining uncertainties
Recent changes in global sea level rise estimates documented in this report (Ch.2: Our Changing Climate, Key Message 10) have not been incorporated into existing regional studies of coastal areas. In addition, recent research by USGS on the interaction between sea level rise, wave action, and local geology have been incorporated in only a few studies.[29]

Specific estimates of climate change impacts on transportation are acutely sensitive to regional projections of climate change and, in particular, to the scale, timing, and type of predicted precipitation. New (CMIP5-based) regional climate projections will therefore affect most existing specific estimates of climate change impacts on transportation. Transportation planning in the face of uncertainties about regional-scale climate impacts presents particular challenges.

Impacts of climate on transportation system operations, including safety and congestion, both on road systems and in aviation, have been little studied to date.

Future characteristics of society, such as land-use patterns, demographics, and the use of information technology to alter transportation patterns, and possible changes to the very nature of future transportation systems themselves all create uncertainty in evaluating climate impacts on the nation's transportation networks. These societal changes will probably occur gradually, however, allowing the transportation systems to adapt. Adaptation can significantly ameliorate impacts on the transportation sector; however, evaluation of adaptation costs and strategies for the transportation sector is at a relatively early stage.

Assessment of confidence based on evidence
Confidence is **high** that transportation systems will be affected by climate change, given current climate projections, particularly regarding sea level rise and extreme weather events.

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

Sea level rise, coupled with storm surge, will continue to increase the risk of major coastal impacts on transportation infrastructure, including both temporary and permanent flooding of airports, ports and harbors, roads, rail lines, tunnels, and bridges.

Description of evidence base
Estimates of global sea level rise are documented in Ch. 2: Our Changing Climate, Key Message 10 of this report.

The prospective impact of sea level rise and storm surge on transportation systems is illustrated by the impact of recent hurricanes on U.S. coastlines. In addition, research on impacts of sea level rise and storm surge on transportation assets in particular regions of the United States demonstrate the potential for major coastal impacts (for example, CCSP 2008, Rosenzweig et al. 2011, and Suarez et al. 2005[11,28,60]). Note that most existing literature on storm surge and sea level rise impacts on transportation systems is based on a global sea level rise of less than one meter (about 3 feet). The most recent projections include a potentially greater rise in global sea level (Ch. 2: Our Changing Climate, Key Message 10).

In addition, the key message and supporting text summarize extensive evidence documented in "Climate Impacts and U.S. Transportation."[57]

New information and remaining uncertainties
As noted above, new estimates of global sea level rise have overtaken most of the existing literature on transportation and sea level rise in the United States. In addition, it is not clear that the existing transportation literature reflects recent USGS work on interactions between sea level rise, wave action, and local geology.[29]

New global sea level rise estimates will enable the development of new regional estimates, as well as revision of regional coastal erosion and flood modeling. Such smaller scale estimates are important because transportation and other infrastructure impacts must necessarily be studied in a local context.

Generally speaking, modeling of sea level rise impacts using existing USGS National Elevation Dataset (NED) data has well-understood limitations. Since NED data is freely and easily available, it is often used for preliminary modeling. More accurate and more recent elevation data may be captured via LIDAR campaigns, and this data collection effort will be necessary for accurate understanding of regional and local sea level rise and storm surge impacts.[27]

Accurate understanding of transportation impacts is specific to particular infrastructure elements, so detailed inventories of local and regional infrastructure must be combined with detailed and accurate elevation data and the best available predictions of local sea level rise and storm surge. Therefore, national assessments of sea level rise must be built on detailed local and regional assessments.

Improved modeling is needed on the interactions among sea level rise, storm surge, tidal movement, and wave action to get a better understanding of the dynamics of the phenomena.

Assessment of confidence based on evidence

The authors have **high** confidence sea levels are rising and storm surge on top of these higher sea levels pose risks to coastal transportation infrastructure.

KEY MESSAGE #3 TRACEABLE ACCOUNT

Extreme weather events currently disrupt transportation networks in all areas of the country; projections indicate that such disruptions will increase.

Description of evidence base

The key message and supporting text summarize extensive evidence documented in "Climate Impacts and U.S. Transportation."[57]

Specific regional climate impacts can be identified in each NCA region of the country. Specific climate impacts on transportation by region include:

In Alaska, rising temperatures cause permafrost to melt, causing damage to roadbeds, airfields, pipelines, and other transportation infrastructure.[25]

In the Northeast, the Chesapeake region is likely to experience particularly severe local sea level rise due to geologic subsidence,[27] and increased precipitation generally (see Ch. 2: Our Changing Climate, Key Message 5, and Ch.16: Northeast), along with an increased incidence of extreme weather events. The presence of large populations with associated transportation systems in coastal areas increases the potential impacts of sea level rise, storm surge, and precipitation-induced flooding.

The Southeast is subject to the interacting effects of sea level rise, increased precipitation, and other extreme events. The Southeast includes Virginia, so it shares the threat of regional sea level rise in the Chesapeake. In Louisiana, climate change poses a significant threat to transportation infrastructure of national significance.[11]

Midwest transportation infrastructure is subject to changing water levels on the Great Lakes.[54] Barge traffic disruptions, due to flooding or drought on the Mississippi/Missouri/Ohio river system, might be induced by changes in precipitation patterns.

A major concern in the Southwest is that declining precipitation (see Ch. 2: Our Changing Climate, Key Message 5) may induce changes in the economy and society that will affect the transportation systems that serve this region. In the Southwest, rail and highway systems may be exposed to increased heat damage from the higher temperatures. San Francisco Bay, which encompasses two major airports and numerous key transportation links, is at risk for sea level rise and storm surge.[61]

Much of the economy of the Northwest is built around electricity and irrigation from a network of dams. The performance of this system may be affected by changing precipitation patterns, with potential consequences for agriculture and industry, and, consequently for transportation systems. In addition, the Seattle area may be affected by sea level rise.[63]

Many relevant and recent climate data and models predict more intense precipitation events in much of the U.S., especially the Great Plains, Midwest, Northeast, and Southeast, with decreased precipitation in parts of the Southwest and Southeast (see Ch. 2: Our Changing Climate, Key Message 5).

New information and remaining uncertainties

Recent data clearly show – and climate models further substantiate – an increase in the intensity of precipitation events throughout much of the U.S.

There is a need for a better definition of the magnitude of increased storm intensity so that accurate return frequency curves can be established.

New regional climate model data from CMIP5 will have a significant impact on regional impact assessments.

Climate and impact data desired by transportation planners may be different from the projections generated by regional climate models. This presents a number of challenges:

Regional scale transportation impacts are often determined by flood risk and by water flows in rivers and streams. Flooding is, of course, linked to precipitation, but the linkage between precipitation and hydrology is very complex. Precipitation, as projected by climate models, is often difficult to convert into predictions of future flooding, which is what infrastructure designers need.

Similarly, an ice storm would be an extreme event for a transportation planner, but the frequency of ice storms has not yet been derived from climate models. More generally, improved methods of deriving the frequency of infrastructure-affecting weather events from regional climate models may be helpful in assessing climate impacts on transportation systems.

There are uncertainties associated with the correlation between a warming climate and increased hurricane intensity.

In regions likely to see decreased precipitation, especially those areas subject to drought, stronger correlations to fire threat and lowered water levels in major waterways are needed as projections of climate models.

Planning tools and models can present a step-by-step process for connecting the risk of impact with specific planning strategies such as assessing the vulnerability of existing and proposed infrastructure and then identifying key adaptation practices to address the risk.

Assessment of confidence based on evidence

Given the evidence base and remaining uncertainties, confidence is **high** that extreme weather events will affect transportation in all areas of the country.

KEY MESSAGE #4 TRACEABLE ACCOUNT

Climate change impacts will increase the total costs to the nation's transportation systems and their users, but these impacts can be reduced through rerouting, mode change, and a wide range of adaptive actions.

Description of evidence base

The economic cost of climate change to the transportation sector has been little studied. However, there is substantial evidence that costs will be significant. A recent study of climate change in New York indicated that a storm surge severe enough to flood Manhattan tunnels might cost as much as $100 billion.[60] The actual experience of Hurricane Sandy, where multiple tunnels were flooded, attests to the scale of the costs and disruption that attend an event of this magnitude (See also Ch. 11: Urban; Box on Hurricane Sandy). A study of the risk to specific infrastructure elements in Alaska[26] estimated the net present value of the extra cost from climate change at $2 to $4 billion through 2030, and $4 to $8 billion through 2080.

The indirect evidence for significant costs from climate change impacts begin with the consequences of recent hurricanes, particularly on the Eastern seaboard, where Hurricane Irene, a rather minor storm, produced unexpectedly heavy infrastructure damage from heavy rains.[75] The economic cost of infrastructure damage is often greater than the cost of repairing or replacing infrastructure.

In addition, a recent study of on-road congestion estimates the annual cost of highway congestion at about $100 billion,[5] and the Federal Highway Administration estimates that weather accounts for about 15% of total delay.[4] Similarly, a recent study of aviation congestion indicates that the annual cost of airline delay is about $33 billion[3] and that weather accounts for more than a third of airline delays. There is a strong circumstantial case to be made that increased frequency of extreme events (as defined by climate scientists) will produce increased traffic and aviation delays. Given the scale of current costs, even small changes in delay can have substantial economic costs.

There is little published material on transportation adaptation costs and benefits in the literature, in part because "adaptation" is an abstraction (see Ch. 28: Adaptation). Climate change is statistical weather, and manifests itself as a change in the frequency of events that would still occur (but with lower frequency) in the absence of climate change. Transportation agencies decide to protect (or not) specific pieces of infrastructure based on a range of considerations, including age and condition, extent of current and future usage, and cost of protection, as well as changing weather patterns. The authors, however, are aware, that transportation systems have always been required to adapt to changing conditions, and that, in general, it is almost always far less expensive to protect useful infrastructure than to wait for it to collapse. This professional experience, based on examination of multitudes of individual engineering studies, is the basis for the conclusion in this report (for example, Caltrans Climate Change Workshop 2011, CCSP 2008, and Meyer 2008[11,12,69]).

There are numerous examples of actions taken by state and local governments to enhance resilience and reduce climate impact costs on transportation, including land-use planning to discourage development in vulnerable areas, establishment of design guidelines to reduce vulnerability to sea level rise, use of effective stormwater management techniques, and coordinated emergency response systems.[7,69]

New information and remaining uncertainties

There is relatively little information on the costs of climate change in the transportation sector, and less on the benefits of adaptation. Much of the available research is focused on the costs of replacing assets that are affected by extreme weather events, with far less effort devoted to both longer-term impacts of climate change on transportation systems (such as inundation of coastal roads due to sea level rise) and to the broader effects of disrupted facilities on network operations or on the community, for example, rerouting of traffic around bottlenecks or evacuation of sensitive populations from vulnerable areas.

Calculating climate impact and adaptation costs and benefits is an exceptionally complex problem, particularly at high levels of aggregation, since both costs and benefits accrue based on a multitude of location-specific events. In addition, all of the methodological issues that are confronted by any long-term forecasting exercise are present. The forecasting problem may be more manageable at the local and regional scales at which most transportation decisions are usually made.

Assessment of confidence based on evidence

The authors have **high** confidence that climate impacts will be costly to the transportation sector, but are far less confident in assessing the exact magnitude of costs, based on the available evidence and their experience. The authors also have **high** confidence, based upon their experience, that costs may be significantly reduced by adaptation action, though, as noted, the magnitude of such potential reductions on a national scale would be difficult to determine.

Climate Change Impacts in the United States

CHAPTER 6
AGRICULTURE

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6 AGRICULTURE

Key Messages

1. **Climate disruptions to agricultural production have increased in the past 40 years and are projected to increase over the next 25 years. By mid-century and beyond, these impacts will be increasingly negative on most crops and livestock.**
2. **Many agricultural regions will experience declines in crop and livestock production from increased stress due to weeds, diseases, insect pests, and other climate change induced stresses.**
3. **Current loss and degradation of critical agricultural soil and water assets due to increasing extremes in precipitation will continue to challenge both rainfed and irrigated agriculture unless innovative conservation methods are implemented.**
4. **The rising incidence of weather extremes will have increasingly negative impacts on crop and livestock productivity because critical thresholds are already being exceeded.**
5. **Agriculture has been able to adapt to recent changes in climate; however, increased innovation will be needed to ensure the rate of adaptation of agriculture and the associated socioeconomic system can keep pace with climate change over the next 25 years.**
6. **Climate change effects on agriculture will have consequences for food security, both in the U.S. and globally, through changes in crop yields and food prices and effects on food processing, storage, transportation, and retailing. Adaptation measures can help delay and reduce some of these impacts.**

The United States produces nearly $330 billion per year in agricultural commodities, with contributions from livestock accounting for roughly half of that value (Figure 6.1).[1] Production of all commodities will be vulnerable to direct impacts (from changes in crop and livestock development and yield due to changing climate conditions and extreme weather events) and indirect impacts (through increasing pressures from pests and pathogens that will benefit from a changing climate). The agricultural sector continually adapts to climate change through changes in crop rotations, planting times, genetic selection, fertilizer management, pest management, water management, and shifts in areas of crop production. These have proven to be effective strategies to allow previous agricultural production to increase, as evidenced by the continued growth in production and efficiency across the United States.

Climate change poses a major challenge to U.S. agriculture because of the critical dependence of the agricultural system on climate and because of the complex role agriculture plays in rural and national social and economic systems (Figure 6.2). Climate change has the potential to both positively and negatively affect the location, timing, and productivity of crop, livestock, and fishery systems at local, national, and global scales. It will also alter the stability of food supplies and create new food security challenges for the United States as the world seeks to feed nine billion people by 2050. U.S. agriculture exists as part of the global economy and agricultural exports have outpaced imports as part of the overall balance of trade. However, climate change will affect the quantity of produce available for export and import as well as prices (Figure 6.3).

The cumulative impacts of climate change will ultimately depend on changing global market conditions as well as responses to local climate stressors, including farmers adjusting planting patterns in response to altered crop yields and crop species, seed producers investing in drought-tolerant varieties, and nations restricting trade to protect food security. Adaptive actions in the areas of consumption, production, education, and research involve seizing opportunities to avoid economic damages and decline in food quality, minimize threats posed by climate stress, and in some cases increase profitability.

Key Message 1: Increasing Impacts on Agriculture

Climate disruptions to agricultural production have increased in the past 40 years and are projected to increase over the next 25 years. By mid-century and beyond, these impacts will be increasingly negative on most crops and livestock.

Impacts on Crop Production

Producers have many available strategies for adapting to the average temperature and precipitation changes projected (Ch. 2: Our Changing Climate)[2] for the next 25 years. These strategies include continued technological advancements, expansion of irrigated acreage, regional shifts in crop acreage and crop species, other adjustments in inputs and outputs, and changes in livestock management practices in response to changing climate patterns.[3,4] However, crop production projections often fail to consider the indirect impacts from weeds, insects, and diseases that accompany changes in both average trends and extreme events, which can increase losses significantly.[2,5] By mid-century, when temperature increases are projected to be between 1.8°F and 5.4°F and precipitation extremes are further intensified, yields of major U.S. crops and farm profits are expected to decline.[6,7] There have already been detectable impacts on production due to increasing temperatures.[8] Over time, climate change is expected to increase the annual variation in crop and livestock production because of its effects on weather patterns and because of increases in some types of extreme weather events.[9,10] Overall implications for production are for increased uncertainty in production totals, which affects both domestic and international markets and food prices. Recent analysis suggests that climate change has an outsized influence on year-to-year swings in corn prices in the United States.[11]

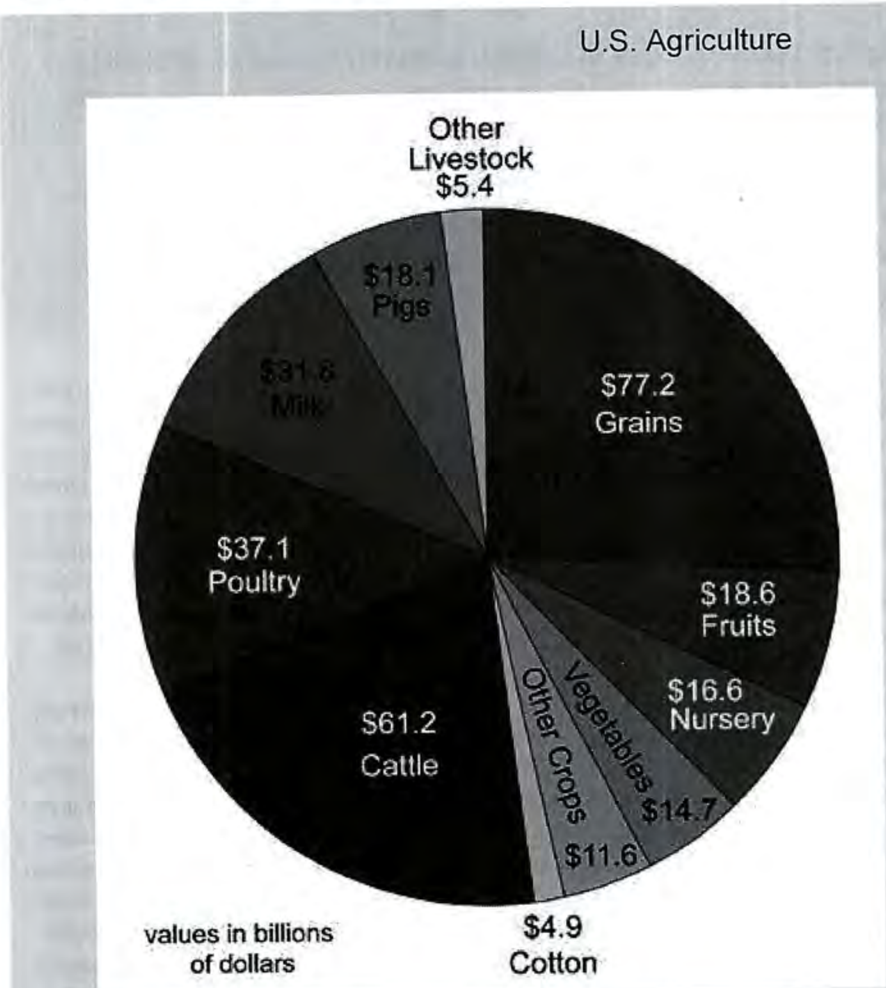

Figure 6.1. U.S. agriculture includes 300 different commodities with a nearly equal division between crop and livestock products. This chart shows a breakdown of the monetary value of U.S. agriculture products by category. (Data from 2007 Census of Agriculture, USDA National Agricultural Statistics Service 2008[12]).

Agricultural Distribution

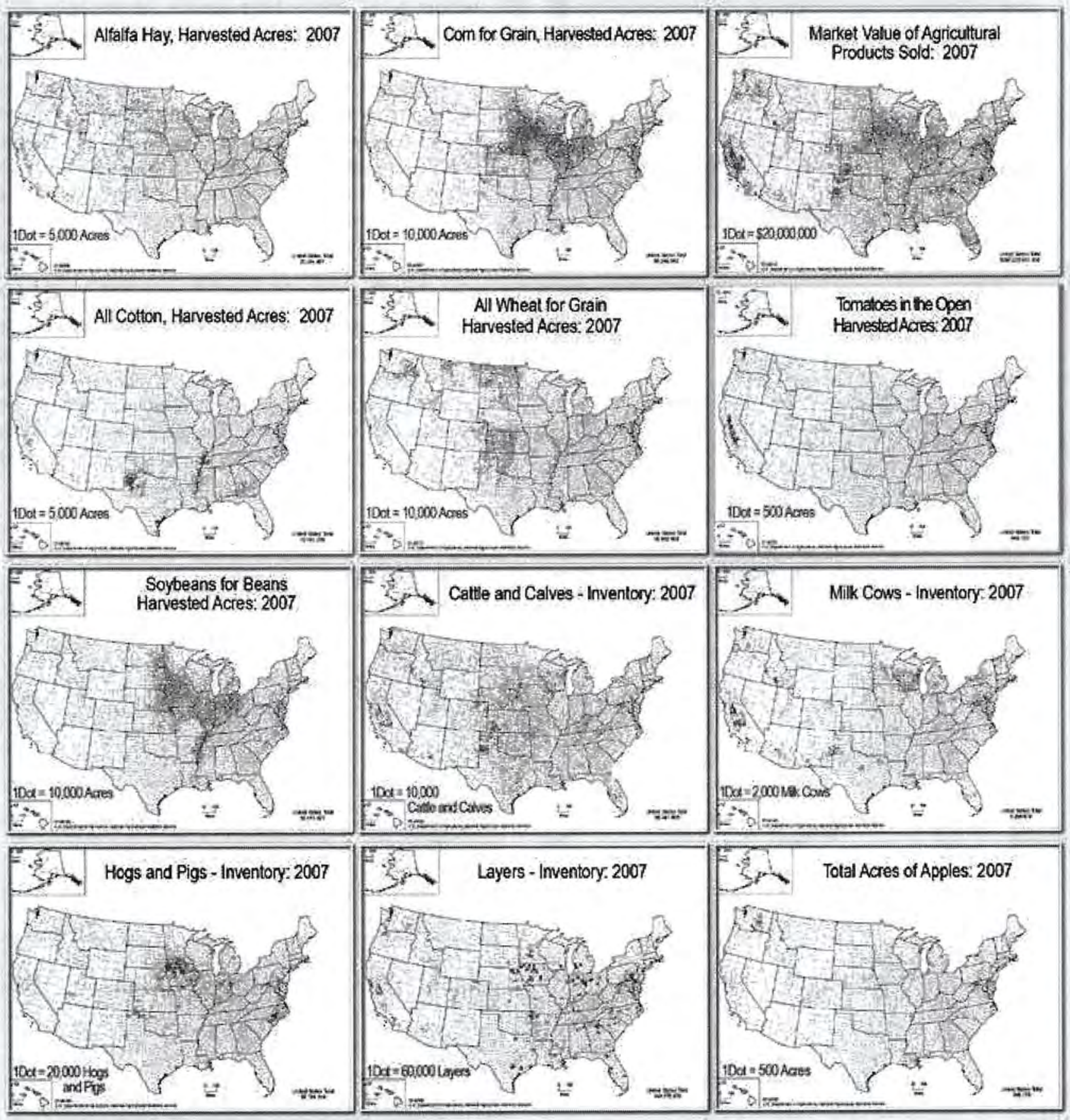

Figure 6.2. Agricultural activity is distributed across the U.S. with market value and crop types varying by region. In 2010, the total market value was nearly $330 billion. Wide variability in climate, commodities, and practices across the U.S. will likely result in differing responses, both in terms of yield and management. (Figure source: USDA National Agricultural Statistics Service 2008[13]).

Figure 6.3. U.S. agriculture exists in the context of global markets. Climate is among the important factors that affect these markets. For example, the increase in U.S. food exports in the 1970s is attributed to a combination of rising incomes in other nations, changes in national currency values and farm policies, and poor harvests in many nations in which climate was a factor. Through seasonal weather impacts on harvests and other impacts, climate change will continue to be a factor in global markets. The graph shows U.S. imports and exports for 1935-2011 in adjusted dollar values. (Data from USDA Economic Research Service 2012[14]).

Plant response to climate change is dictated by complex interactions among carbon dioxide (CO_2), temperature, solar radiation, and precipitation. Each crop species has a temperature range for growth, along with an optimum temperature.[9] Plants have specific temperature tolerances, and can only be grown in areas where their temperature thresholds are not exceeded. As temperatures increase over this century, crop production areas may shift to follow the temperature range for optimal growth and yield of grain or fruit. Temperature effects on crop production are only one component; production over years in a given location is more affected by available soil water during the growing season than by temperature, and increased variation in seasonal precipitation, coupled with shifting patterns of precipitation within the season, will create more variation in soil water availability.[9,15] The use of a model to evaluate the effect of changing temperatures in the absence of changes in water availability reveals that crops in California's Central Valley will respond differently to projected temperature increases, as illustrated in Figure 6.4. This example demonstrates one of the methods available for studying the potential effects of climate change on agriculture.

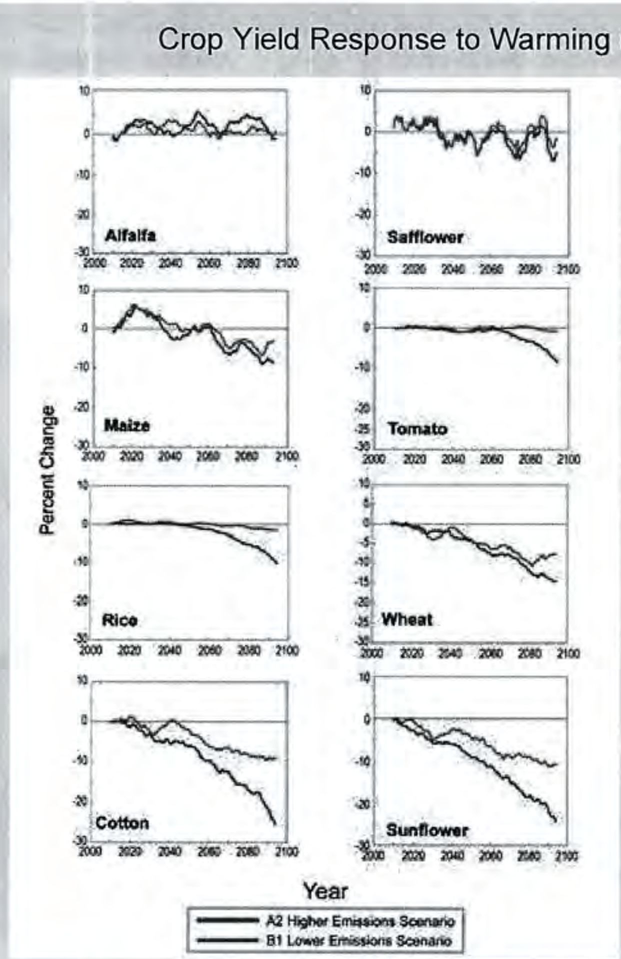

Figure 6.4. Changes in climate through this century will affect crops differently because individual species respond differently to warming. This figure is an example of the potential impacts on different crops within the same geographic region. Crop yield responses for eight crops in the Central Valley of California are projected under two emissions scenarios, one in which heat-trapping gas emissions are substantially reduced (B1) and another in which these emissions continue to grow (A2). This analysis assumes adequate water supplies (soil moisture) and nutrients are maintained while temperatures increase. The lines show five-year moving averages for the period from 2010 to 2094, with the yield changes shown as differences from the year 2009. Yield response varies among crops, with cotton, maize, wheat, and sunflower showing yield declines early in the period. Alfalfa and safflower showed no yield declines during the period. Rice and tomato do not show a yield response until the latter half of the period, with the higher emissions scenario resulting in a larger yield response. (Figure source: adapted from Lee et al. 2011[16]).

One critical period in which temperatures are a major factor is the pollination stage; pollen release is related to development of fruit, grain, or fiber. Exposure to high temperatures during this period can greatly reduce crop yields and increase the risk of total crop failure. Plants exposed to high nighttime temperatures during the grain, fiber, or fruit production period experience lower productivity and reduced quality.[15] These effects have already begun to occur; high nighttime temperatures affected corn yields in 2010 and 2012 across the Corn Belt. With the number of nights with hot temperatures projected to increase as much as 30%, yield reductions will become more prevalent.[9]

Projected Changes in Key Climate Variables Affecting Agricultural Productivity

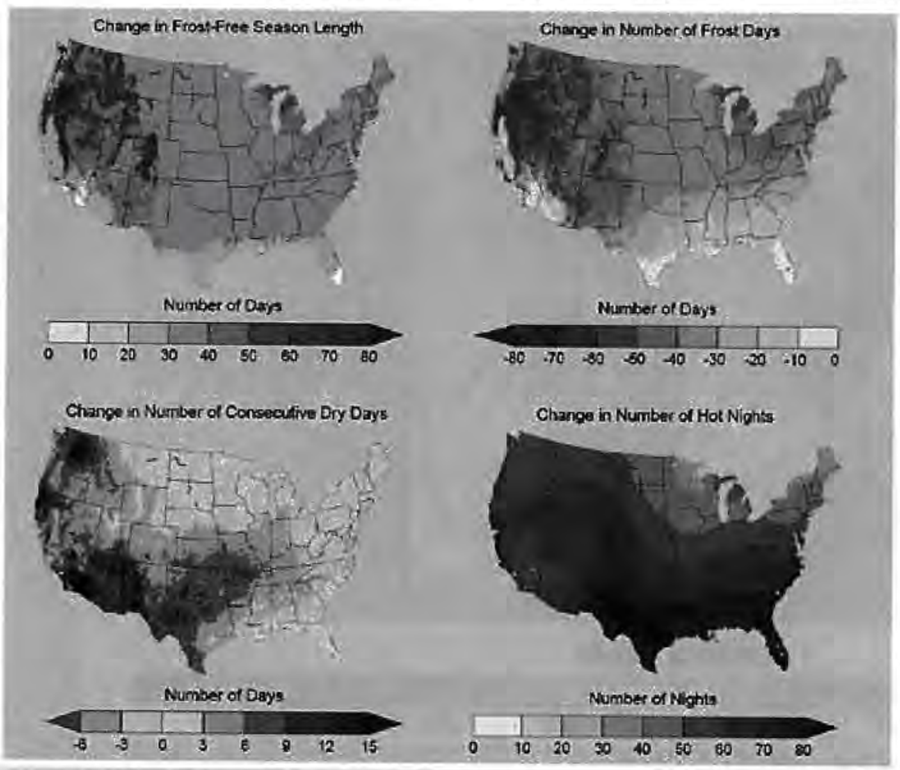

Figure 6.5. Many climate variables affect agriculture. The maps above show projected changes in key climate variables affecting agricultural productivity for the end of the century (2070-2099) compared to 1971-2000. Changes in climate parameters critical to agriculture show lengthening of the frost-free or growing season and reductions in the number of frost days (days with minimum temperatures below freezing), under an emissions scenario that assumes continued increases in heat-trapping gases (A2). Changes in these two variables are not identical, with the length of the growing season increasing across most of the United States and more variation in the change in the number of frost days. Warmer-season crops, such as melons, would grow better in warmer areas, while other crops, such as cereals, would grow more quickly, meaning less time for the grain itself to mature, reducing productivity.[9] Taking advantage of the increasing length of the growing season and changing planting dates could allow planting of more diverse crop rotations, which can be an effective adaptation strategy. On the frost-free map, white areas are projected to experience no freezes for 2070-2099, and gray areas are projected to experience more than 10 frost-free years during the same period. In the lower left graph, consecutive dry days are defined as the annual maximum number of consecutive days with less than 0.01 inches of precipitation. In the lower right graph, hot nights are defined as nights with a minimum temperature higher than 98% of the minimum temperatures between 1971 and 2000. (Figure source: NOAA NCDC / CICS-NC).

Temperature and precipitation changes will include an increase in both the number of consecutive dry days (days with less than 0.01 inches of precipitation) and the number of hot nights (Figure 6.5). The western and southern parts of the nation show the greatest projected increases in consecutive dry days, while the number of hot nights is projected to increase throughout the U.S. These increases in consecutive dry days and hot nights will have negative impacts on crop and animal production. High nighttime temperatures during the grain-filling period (the period between the fertilization of the ovule and the production of a mature seed in a plant) increase the rate of grain-filling and decrease the length of the grain-filling period, resulting in reduced grain yields. Exposure to multiple hot nights increases the degree of stress imposed on animals resulting in reduced rates of meat, milk, and egg production.[17]

Though changes in temperature, CO_2 concentrations, and solar radiation may benefit plant growth rates, this does not equate to increased production. Increasing temperatures cause cultivated plants to grow and mature more quickly. But because the soil may not be able to supply nutrients at required rates for faster growing plants, plants may be smaller, reducing grain, forage, fruit, or fiber production. Reduction in solar radiation in agricultural areas due to increased clouds and humidity in the last 60 years[18] is projected to continue[19] and may partially offset the acceleration of plant growth due to higher temperatures and CO_2 levels, depending on the crop. In vegetables, exposure to temperatures in the range of 1.8°F to 7.2°F above optimal moderately reduces yield, and exposure to temperatures more than 9°F to 12.6°F above optimal often leads to severe if not total production losses. Selective breeding and genetic engineering for both plants and animals provides some opportunity for adapting to climate change; however, development of new varieties in perennial specialty crops commonly requires 15 to 30 years or more, greatly limiting adaptive opportunity, unless varieties could be introduced from other areas. Additionally, perennial crops require time to reach their production potential.

A warmer climate will affect growing conditions, and the lack of cold temperatures may threaten perennial crop production (Figure 6.6). Perennial specialty crops have a winter chilling requirement (typically expressed as hours when temperatures are between 32°F and 50°F) ranging from 200 to 2,000 cumulative hours. Yields decline if the chilling requirement is not completely satisfied, because flower emergence and viability is low.[20] Projections show that chilling requirements for fruit and nut trees in California will not be met by the middle to the end of this century.[21] For most of the Northeast, a 400-hour chilling requirement for apples is projected to continue to be met during this century, but crops with prolonged chilling re-

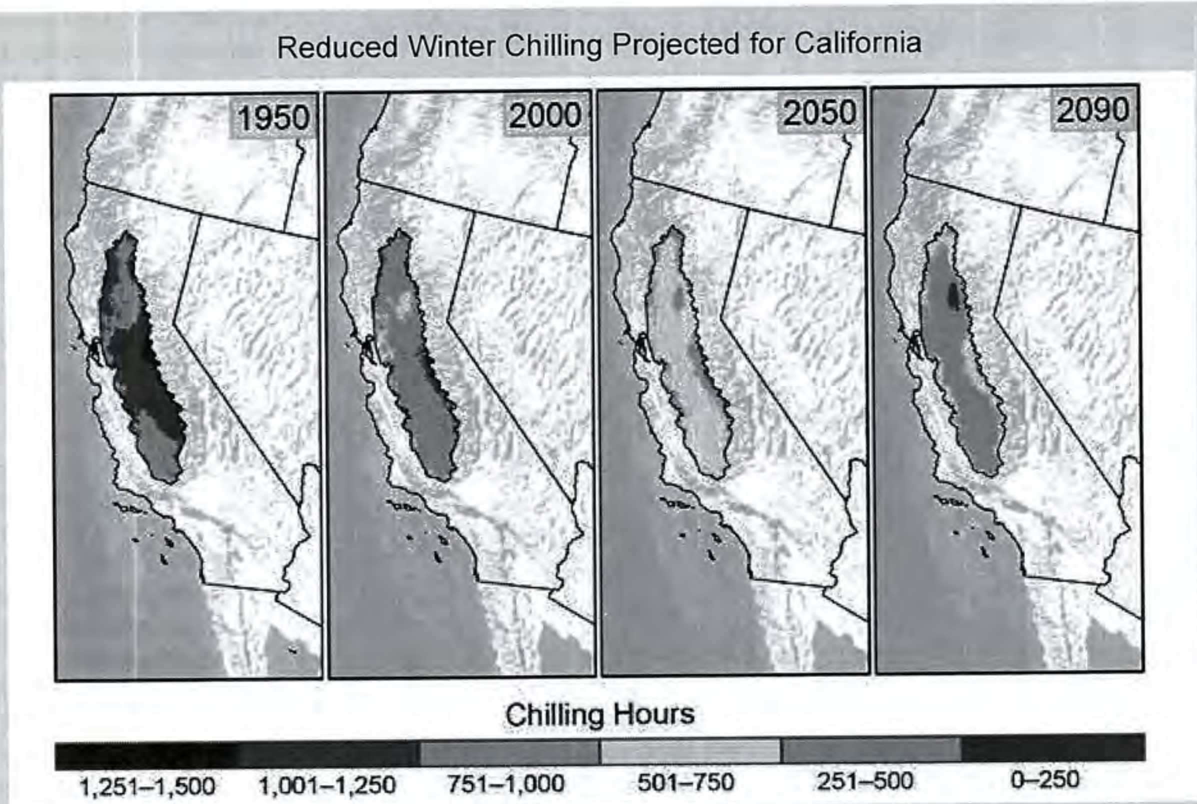

Figure 6.6. Many perennial plants (such as fruit trees and grape vines) require exposure to particular numbers of chilling hours (hours in which the temperatures are between 32°F and 50°F over the winter). This number varies among species, and many trees require chilling hours before flowering and fruit production can occur. With rising temperatures, chilling hours will be reduced. One example of this change is shown here for California's Central Valley, assuming that observed climate trends in that area continue through 2050 and 2090. Under such a scenario, a rapid decrease in the number of chilling hours is projected to occur.

By 2000, the number of chilling hours in some regions was 30% lower than in 1950. Based on the A2 emissions scenario that assumes continued increases in heat-trapping gases relative to 1950, the number of chilling hours is projected to decline by 30% to 60% by 2050 and by up to 80% by 2100. These are very conservative estimates of the reductions in chilling hours because climate models project not just simple continuations of observed trends (as assumed here), but temperature trends rising at an increasing rate.[21] To adapt to these kinds of changes, trees with a lower chilling requirement would have to be planted and reach productive age.

Various trees and grape vines differ in their chilling requirements, with grapes requiring 90 hours, peaches 225, apples 400, and cherries more than 1,000.[21] Increasing temperatures are likely to shift grape production for premium wines to different regions, but with a higher risk of extremely hot conditions that are detrimental to such varieties.[24] The area capable of consistently producing grapes required for the highest-quality wines is projected to decline by more than 50% by late this century.[24] (Figure source: adapted from Luedeling et al. 2009[21]).

quirements, such as plums and cherries (with chilling requirements of more than 700 hours), could be negatively affected, particularly in southern parts of the Northeast.[21,22] Warmer winters can lead to early bud burst or bloom of some perennial plants, resulting in frost damage when cold conditions occur in late spring[15], as was the case with cherries in Michigan in 2012, leading to an economic impact of $220 million (Andresen 2012, personal communication).[23]

The effects of elevated CO_2 on grain and fruit yield and quality are mixed. Some experiments have documented that elevated CO_2 concentrations can increase plant growth while increasing water use efficiency.[25,26] The magnitude of CO_2 growth stimulation in the absence of other stressors has been extensively analyzed for crop and tree species[27,28] and is relatively well understood; however, the interaction with changing temperature, ozone, and water and nutrient constraints creates uncertainty in the magnitude of these responses.[29] In plants such as soybean and alfalfa, elevated CO_2 has been associated with reduced nitrogen and protein content, causing a reduction in grain and forage quality and reducing the ability of pasture and rangeland to support grazing livestock.[30] The growth stimulation effect of increased atmospheric CO_2 concentrations has a disproportionately positive impact on several weed species. This effect will contribute to increased risk of crop loss due to weed pressure.[28,31]

The advantage of increased water-use efficiency due to elevated CO_2 in areas with limited soil water supply may be offset by other impacts from climate change. Rising average temperatures, for instance, will increase crop water demand, increasing the rate of water use by the crop. Rising temperatures coupled with more extreme wet and dry events, or seasonal shifts in precipitation, will affect both crop water demand and plant production.

Impacts on Animal Production from Temperature Extremes

Animal agriculture is a major component of the U.S. agriculture system (Figure 6.1). Changing climatic conditions affect animal agriculture in four primary ways: 1) feed-grain production, availability, and price; 2) pastures and forage crop production and quality; 3) animal health, growth, and reproduction; and 4) disease and pest distributions.[32] The optimal environmental conditions for livestock production include temperatures and other conditions for which animals do not need to significantly alter behavior or physiological functions to maintain relatively constant core body temperature.

Optimum animal core body temperature is often maintained within a 4°F to 5°F range, while deviations from this range can cause animals to become stressed. This can disrupt performance, production, and fertility, limiting the animals' ability to produce meat, milk, or eggs. In many species, deviations in core body temperature in excess of 4°F to 5°F cause significant reductions in productive performance, while deviations of 9°F to 12.6°F often result in death.[33] For cattle that breed during spring and summer, exposure to high temperatures reduces conception rates. Livestock and dairy production are more affected by the number of days of extreme heat than by increases in average temperature.[34] Elevated humidity exacerbates the impact of high temperatures on animal health and performance.

Animals respond to extreme temperature events (hot or cold) by altering their metabolic rates and behavior. Increases in extreme temperature events may become more likely for animals, placing them under conditions where their efficiency in meat, milk, or egg production is affected. Projected increases in extreme heat events (Ch. 2: Our Changing Climate, Key Message 7) will further increase the stress on animals, leading to the potential for greater impacts on production.[34] Meat animals are managed for a high rate of weight gain (high metabolic rate), which increases their potential risk when exposed to high temperature conditions. Exposure to heat stress disrupts metabolic functions in animals and alters their internal temperature when exposure occurs. Exposure to high temperature events can be costly to producers, as was the case in 2011, when heat-related production losses exceeded $1 billion.[35]

Livestock production systems that provide partial or total shelter to reduce thermal environmental challenges can reduce the risk and vulnerability associated with extreme heat. In general, livestock such as poultry and swine are managed in housed systems where airflow can be controlled and housing temperature modified to minimize or buffer against adverse environmental conditions. However, management and energy costs associated with increased temperature regulation will increase for confined production enterprises and may require modification of shelter and increased water use for cooling.

Key Message 2: Weeds, Diseases, and Pests

Many agricultural regions will experience declines in crop and livestock production from increased stress due to weeds, diseases, insect pests, and other climate change induced stresses.

Weeds, insects, and diseases already have large negative impacts on agricultural production, and climate change has the potential to increase these impacts. Current estimates of losses in global crop production show that weeds cause the largest losses (34%), followed by insects (18%), and diseases (16%).[36] Further increases in temperature and changes in precipitation patterns will induce new conditions that will affect insect populations, incidence of pathogens, and the geographic distribution of insects and diseases.[15,37] Increasing CO_2 boosts weed growth, adding to the potential for increased competition between crops and weeds.[38] Several weed species benefit more than crops from higher temperatures and CO_2 levels.[28,31]

One concern involves the northward spread of invasive weeds like privet and kudzu, which are already present in the southern states.[39] Changing climate and changing trade patterns are likely to increase both the risks posed by, and the sources of, invasive species.[40] Controlling weeds costs the U.S. more than $11 billion a year, with most of that spent on herbicides. Both herbicide use and costs are expected to increase as temperatures and CO_2 levels rise.[41] Also, the most widely used herbicide in the United States, glyphosate (also known as RoundUp™ and other brand names), loses its efficacy on weeds grown at CO_2 levels projected to occur in the coming decades.[42] Higher concentrations of the chemical and more frequent sprayings thus will be needed, increasing economic and environmental costs associated with chemical use.

Climate change effects on land-use patterns have the potential to create interactions among climate, diseases, and crops.[37,43] How climate change affects crop diseases depends upon the effect that a combination of climate changes has on both the host and the pathogen. One example of the complexity of the interactions among climate, host, and pathogen is aflatoxin (*Aspergillus flavus*). Temperature and moisture availability are crucial for the production of this toxin, and both pre-harvest and post-harvest conditions are critical in understanding the impacts of climate change. High temperatures and drought stress increase aflatoxin production and at the same time reduce the growth of host plants. The toxin's impacts are augmented by the presence of insects, creating a potential for climate-toxin-insect-plant interactions that further affect crop production.[44] Earlier spring and warmer winter conditions are also expected to increase the survival and proliferation of disease-causing agents and parasites.

Insects are directly affected by temperature and synchronize their development and reproduction with warm periods and are dormant during cold periods.[45] Higher winter temperatures increase insect populations due to overwinter survival and, coupled with higher summer temperatures, increase reproductive rates and allow for multiple generations each year.[46] An example of this has been observed in the European corn borer (*Ostrinia nubialis)* which produces one generation in the northern Corn Belt and two or more generations in the southern Corn Belt.[47] Changes in the number of reproductive generations coupled with the shift in ranges of insects will alter insect pressure in a given region.

Superimposed on these climate change related impacts on weed and insect proliferation will be ongoing land-use and land-cover changes (Ch. 13: Land Use & Land Cover Change). For example, northward movement of non-migratory butterflies in Europe and changes in the range of insects were associated with land-use patterns and climate change.[48]

Livestock production faces additional climate change related impacts that can affect disease prevalence and range. Regional warming and changes in rainfall distribution have the potential to change the distributions of diseases that are sensitive to temperature and moisture, such as anthrax, blackleg, and hemorrhagic septicemia, and lead to increased incidence of ketosis, mastitis, and lameness in dairy cows.[33,49]

These observations illustrate some of the interactions among climate change, land-use patterns, and insect populations. Weeds, insects, and diseases thus cause a range of direct and indirect effects on plants and animals from climate change, although there are no simple models to predict the potential interactions. Given the economic impact of these pests and the potential implications for food security, research is critical to further understand these dynamics.

Key Message 3: Extreme Precipitation and Soil Erosion

Current loss and degradation of critical agricultural soil and water assets due to increasing extremes in precipitation will continue to challenge both rainfed and irrigated agriculture unless innovative conservation methods are implemented.

Several processes act to degrade soils, including erosion, compaction, acidification, salinization, toxification, and net loss of organic matter (Ch. 15: Biogeochemical Cycles). Several of these processes, particularly erosion, will be directly affected by climate change. Rainfall's erosive power is expected to increase as a result of increases in rainfall amount in northern portions of the United States (see Ch. 2: Our Changing Climate), accompanied by further increases in precipitation intensity.[50] Projected increases in rainfall intensity that include more extreme events will increase soil erosion in the absence of conservation practices.[51,52]

Soil and water are essential resources for agricultural production, and both are subject to new conditions as climate changes. Precipitation and temperature affect the *potential* amount of water available, but the *actual* amount of available water also depends on soil type, soil water holding capacity, and the rate at which water filters through the soil (Figure 6.7 and 6.8). Such soil characteristics, however, are sensitive to changing climate conditions; changes in soil carbon content and soil loss will be affected by direct climate effects through changes in soil temperature, soil water availability, and the amount of organic matter input from plants.[53]

It is all about the water!

Soil is a critical component of agricultural systems, and the changing climate affects the amount, distribution, and intensity of precipitation. Soil erosion occurs when the rate of precipitation exceeds the ability of the soil to maintain an adequate infiltration rate. When this occurs, runoff from fields moves water and soil from the field into nearby water bodies.

Figure 6.7

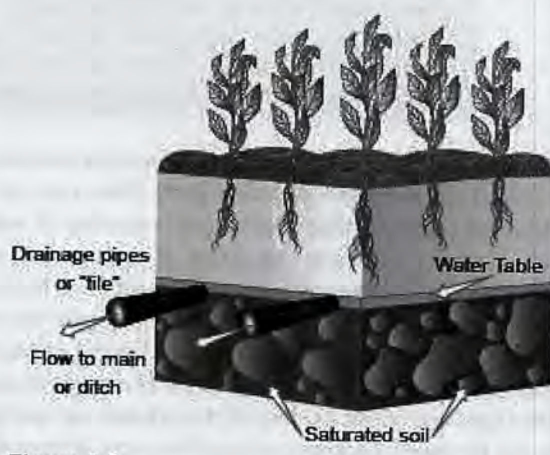

Figure 6.8

Water and soil that are lost from the field are no longer available to support crop growth. The increasing intensity of storms and the shifting of rainfall patterns toward more spring precipitation in the Midwest may lead to more scenes similar to this one (Figure 6.7). An analysis of the rainfall patterns across Iowa has shown there has not been an increase in total annual precipitation; however, there has been a large increase in the number of days with heavy rainfall (Figure 6.9). The increase in spring precipitation is evidenced by a decrease of three days in the number of workable days in the April to May period during 2001 through 2011 in Iowa compared to the period 1980-2000.[15] To offset this increased precipitation, producers have been installing subsurface drainage to remove more water from the fields at a cost of $500 per acre (Figure 6.8). These are elaborate systems designed to move water from the landscape to allow agricultural operations to occur in the spring. Water erosion and runoff is only one portion of the spectrum of extreme precipitation. Wind erosion could increase in areas with persistent drought because of the reduction in vegetative cover. (Photo credit (left): USDA Natural Resources Conservation Service; Figure source (right): NOAA NCDC / CICS-NC).

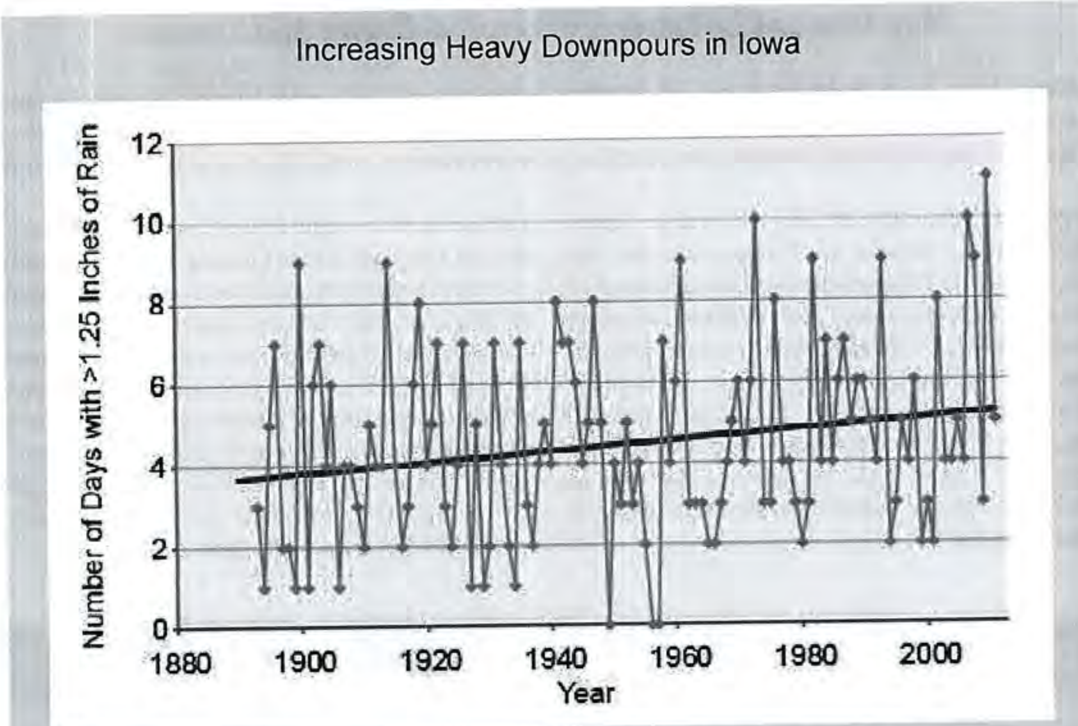

Figure 6.9. Iowa is the nation's top corn and soybean producing state. These crops are planted in the spring. Heavy rain can delay planting and create problems in obtaining a good stand of plants, both of which can reduce crop productivity. In Iowa soils with even modest slopes, rainfall of more than 1.25 inches in a single day leads to runoff that causes soil erosion and loss of nutrients and, under some circumstances, can lead to flooding. The figure shows the number of days per year during which more than 1.25 inches of rain fell in Des Moines, Iowa. Recent frequent occurrences of such events are consistent with the significant upward trend of heavy precipitation events documented in the Midwest.[51,55] (Figure source: adapted from Takle 2011[56]).

A few of the many important ecosystem services provided by soils include the provision of food, wood, fiber such as cotton, and raw materials; flood mitigation; recycling of wastes; biological control of pests; regulation of carbon and other heat-trapping gases; physical support for roads and buildings; and cultural and aesthetic values.[54] Productive soils are characterized by levels of nutrients necessary for the production of healthy plants, moderately high levels of organic matter, a soil structure with good binding of the primary soil particles, moderate pH levels, thickness sufficient to store adequate water for plants, a healthy microbial community, and the absence of elements or compounds in concentrations that are toxic for plant, animal, and microbial life.

Changes in production practices can have more effect than climate change on soil erosion; however, changes in climate will exacerbate the effects of management practices that do not protect the soil surface from the forces of rainfall. Erosion is managed through maintenance of cover on the soil surface to reduce the effect of rainfall intensity. Studies have shown that a reduction in projected crop biomass (and hence the amount of crop residue that remains on the surface over the winter) will increase soil loss.[57,58] Expected increases in soil erosion under climate change also will lead to increased off-site, non-point-source pollution. Soil conservation practices will therefore be an important element of agricultural adaptation to climate change.[59]

Rising temperatures and CO_2 and shifting precipitation patterns will alter crop-water requirements, crop-water availability, crop productivity, and costs of water access across the agricultural landscape. Higher temperatures are projected to increase both evaporative losses from land and water surfaces and transpiration losses (through plant leaves) from non-crop land cover, potentially reducing annual runoff and streamflow for a given amount of precipitation. The resulting shift in crop health will, in turn, drive changes in cropland allocations and production systems.

Key Message 4: Heat and Drought Damage

The rising incidence of weather extremes will have increasingly negative impacts on crop and livestock productivity because critical thresholds are already being exceeded.

Climate change projections suggest an increase in extreme heat, severe drought, and heavy precipitation.[60] Extreme climate conditions, such as dry spells, sustained droughts, and heat waves all have large effects on crops and livestock. The timing of extreme events will be critical because they may occur at sensitive stages in the life cycles of agricultural crops or reproductive stages for animals, diseases, and insects. Extreme events at vulnerable times could result in major impacts on growth or productivity, such as hot-temperature extreme weather events on corn during pollination. By the end of this century, the occurrence of very hot nights and the duration of periods lacking agriculturally significant rainfall are projected to increase. Recent studies suggest that increased average temperatures and drier conditions will amplify future drought severity and temperature extremes.[6,61,62] Crops and livestock will be at increased risk of exposure to extreme heat events. Projected increases in the occurrence of extreme heat events will expose production systems to conditions exceeding maximum thresholds for given species more frequently. Goats, sheep, beef cattle, and dairy cattle are the livestock species most widely managed in extensive outdoor facilities. Within physiological limits, animals can adapt to and cope with gradual thermal changes, though shifts in thermoregulation may result in a loss of productivity.[63] Lack of prior conditioning to rapidly changing or adverse weather events, however, often results in catastrophic deaths in domestic livestock and losses of productivity in surviving animals.[34]

Key Message 5: Rate of Adaptation

Agriculture has been able to adapt to recent changes in climate; however, increased innovation will be needed to ensure the rate of adaptation of agriculture and the associated socioeconomic system can keep pace with climate change over the next 25 years.

There is emerging evidence about the economic impacts of climate change on agriculture and the potential for adaptive strategies.[64] Much of the economic literature suggests that in the short term, producers will continue to adapt to weather changes and shocks as they always have, with changes in the timing of field operations, shifts in crops grown, and changing tillage or irrigation practices.[64] In the longer term, however, existing adaptive technologies will likely not be sufficient to buffer the impacts of climate change without significant impacts to domestic producers, consumers, or both. New strategies for building long-term resilience include both new technologies and new institutions to facilitate appropriate, informed producer response to a changing climate. Furthermore, there are both public and private costs to adjusting agricultural production and infrastructure in a manner that enables adaptation.[2] Limits to public investment and constraints on private investment could slow the speed of adaptation, yet potential constraints and limits are not well understood or integrated into economic impact assessments. The economic implications of changing biotic pressures on crops and livestock, and on the agricultural system as a whole, are not well understood, either in the short or long term.[15] Adaptation may also be limited by the availability of inputs (such as land or water), changing prices of other inputs with climate change (such as energy and fertilizer), and by the environmental implications of intensifying or expanding agricultural production.

Adaptation strategies currently used by U.S. farmers to cope with weather and climate changes include changing selection of crops, the timing of field operations, and the increasing use of pesticides to control increased pressure from pests. Technological innovation increases the tools available to farmers in some agricultural sectors. Diversifying crop rotations, integrating livestock with crop production systems, improving soil quality, minimizing off-farm flows of nutrients and pesticides, and other practices typically associated with sustainable agriculture also increase the resiliency of the agricultural system to productivity impacts of climate change.[65,66] In the Midwest, there have been shifts in the distribution of crops and land-use change partially related to the increased demand for biofuels[67] (see also Ch. 10: Energy, Water, and Land for more discussion on biofuels). In California's Central Valley, an adaptation plan consisting of integrated changes in crop mix, irrigation methods, fertilization practices, tillage practices, and land management may be an effective approach to managing climate risk.[68] These practices are available to all agricultural regions of the United States as potential adaptation strategies.

Based on projected climate change impacts in some areas of the United States, agricultural systems may have to undergo more transformative changes to remain productive and profitable in the long term.[65] Research and development of sustainable natural resource management strategies inform adaptation options for U.S. agriculture. More transformative adaptive strategies, such as conversion to integrated crop-livestock farming, may reduce environmental impacts, improve profitability and sustainability, and enhance ecological resilience to climate change in U.S. livestock production systems.[69]

There are many possible responses to climate change that will allow agriculture to adapt over the next 25 years; however, potential constraints to adaptation must be recognized and addressed. In addition to regional constraints on the availability of critical basic resources such as land and water, there are potential constraints related to farm financing and credit availability in the U.S. and elsewhere. Research suggests that such constraints may be significant, especially for small family farms with little available capital.[22,64,70] In addition to the technical and financial ability to adapt to changing average conditions, farm resilience to climate change is also a function of financial capacity to withstand increasing variability in production and returns, including catastrophic loss.[71] As climate change intensifies, "climate risk" from more frequent and intense weather events will add to the existing risks commonly managed by producers, such as those related to production, marketing, finances, regulation, and personal health and safety factors.[72] The role of innovative management techniques and government policies as well as research and insurance programs will have a substantial impact on the degree to which the agricultural sector increases climate resilience in the longer term.

Modern agriculture has continually adapted to many changing factors, both within and outside of agricultural systems. As a result, agriculture in the U.S. over the past century has steadily increased productivity and integration into world markets. Although agriculture has a long history of successful adaptation to climate variability, the accelerating pace of climate change and the intensity of projected climate change represent new and unprecedented challenges to the sustainability of U.S. agriculture. In the short term, existing and evolving adaptation strategies will provide substantial adaptive capacity, protecting domestic producers and consumers from many of the impacts of climate change, except possibly the occurrence of protracted extreme events. In the longer term, adaptation will be more difficult and costly because the physiological limits of plant and animal species will be exceeded more frequently, and the productivity of crop and livestock systems will become more variable.

Key Message 6: Food Security

Climate change effects on agriculture will have consequences for food security, both in the U.S. and globally, through changes in crop yields and food prices and effects on food processing, storage, transportation, and retailing. Adaptation measures can help delay and reduce some of these impacts.

Climate change impacts on agriculture will have consequences for food security both in the U.S. and globally. Food security includes four components: availability, stability, access, and utilization of food.[73] Following this definition, in 2011, 14.9% of U.S. households did not have secure food supplies at some point during the year, with 5.7% of U.S. households experiencing very low food security.[74] Food security is affected by a variety of supply and demand-side pressures, including economic conditions, globalization of markets, safety and quality of food, land-use change, demographic change, and disease and poverty.[75,76]

Within the complex global food system, climate change is expected to affect food security in multiple ways.[77] In addition to altering agricultural yields, projected rising temperatures, changing weather patterns, and increases in frequency of extreme weather events will affect distribution of food- and water-borne diseases as well as food trade and distribution.[78] This means that U.S. food security depends not only on how climate change affects crop yields at the local and national level, but also on how climate change and changes in extreme events affect food processing, storage, transportation, and retailing, through the disruption of transportation as well as the ability of consumers to purchase food. And because about one-fifth of all food consumed in the U.S. is imported, our food supply and security can be significantly affected by climate variations and changes in other parts of the world. The import share has increased over the last two decades, and the U.S. now imports 13% of grains, 20% of vegetables (much higher in winter months), almost 40% of fruit, 85% of fish and shellfish, and almost all tropical products such as coffee, tea, and bananas (Figure 6.3).[79] Climate extremes in regions that supply these products to the U.S. can cause sharp reductions in production and increases in prices.

In an increasingly globalized food system with volatile food prices, climate events abroad may affect food security in the U.S. while climate events in the U.S. may affect food security globally. The globalized food system can buffer the local impacts of weather events on food security, but can also increase the global vulnerability of food security by transmitting price shocks globally.[80]

The connections of U.S. agriculture and food security to global conditions are clearly illustrated by the recent food price spikes in 2008 and 2011 that highlighted the complex connections of climate, land use, demand, and markets. The doubling of the United Nations Food and Agriculture Organization (FAO) food price index over just a few months in 2010 was caused partly by weather conditions in food-exporting countries such as Australia, Russia, and the United States, but was also driven by increased demand for meat and dairy in Asia, increased energy costs and demand for biofuels, and commodity speculation in financial markets.[81]

Adapting food systems to limit the impacts of climate extremes and changes involves strategies to maintain supply and manage demand as well as an understanding of how other regions of the world adapt their food systems in ways that might affect U.S. agricultural competitiveness, imports, and prices. Supplies can be maintained through adaptations such as reducing waste in the food system, making food distribution systems more resilient to climate risks, protecting food quality and safety in higher temperatures, and policies to ensure food access for disadvantaged populations and during extreme events (Ch. 28 Adaptation).[15,75,76,80,81]

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SUPPLEMENTAL MATERIAL

TRACEABLE ACCOUNTS

Process for Developing Key Messages

A central component of the process was the development of a foundational technical input report (TIR), "Climate Change and Agriculture in the United States: An Assessment of Effects and Potential for Adaptation".[15] A public session conducted as part of the Tri-Societies (https://www.acsmeetings.org/home) meeting held in San Antonio, Texas, on Oct. 16-19, 2011, provided input to this report.

The report team engaged in multiple technical discussions via teleconference, which included careful review of the foundational TIR[15] and of approximately 56 additional technical inputs provided by the public, as well as 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 message.

Key message #1 Traceable Account

Climate disruptions to agricultural production have increased in the past 40 years and are projected to increase over the next 25 years. By mid-century and beyond, these impacts will be increasingly negative on most crops and livestock.

Description of evidence base

The key message and supporting text summarize extensive evidence documented in the Agriculture TIR, "Climate Change and Agriculture in the United States: An Assessment of Effects and Potential for Adaptation.[15] Additional Technical Input Reports (56) on a wide range of topics were also received and reviewed as part of the Federal Register Notice solicitation for public input.

Evidence that climate change has had and will have impacts on crops and livestock is based on numerous studies and is incontrovertible.[6,7,8]

The literature strongly suggests that carbon dioxide, temperature, and precipitation affect livestock and crop production. Plants have an optimal temperature range to which they are adapted, and regional crop growth will be affected by shifts in that region's temperatures relative to each crop's optimal range. Large shifts in temperature can significantly affect seasonal biomass growth, while changes in the timing and intensity of extreme temperature effects are expected to negatively affect crop development during critical windows such as pollination. Crop production will also be affected by changing patterns of seasonal precipitation; extreme precipitation events are expected to occur more frequently and negatively affect production levels. Livestock production is directly affected by extreme temperature as the animal makes metabolic adjustments to cope with heat stress.[15] Further, production costs in confined systems markedly increase when climate regulation is necessary.

New information and remaining uncertainties

Important new evidence (cited above) confirmed many of the findings in the past Synthesis and Assessment Product on agriculture,[82] which informed the 2009 National Climate Assessment.[83]

There is insufficient understanding of the effects on crop production of rising carbon dioxide, changing temperatures and more variable precipitation patterns.[9] The combined effects on plant water demand and soil water availability will be critical to understanding regional crop response. The role of increasing minimum temperatures on water demand and growth and senescence rates of plants is an important factor. There is insufficient understanding of how prolonged exposure of livestock to high or cold temperatures affects metabolism and reproductive variables.[26] For grazing animals, climate conditions during the growing season are critical in determining feed availability and quality on rangeland and pastureland.[69]

The information base can be enhanced by evaluating crop growth and livestock production models. This evaluation would further the understanding of the interactions of climate variables and the biological system. Better understanding of projected changes in precipitation will narrow uncertainty about future yield reductions.[9,69]

Assessment of confidence based on evidence

There are a range of controlled environment and field studies that provide the evidence for these findings. Confidence in this key message is therefore judged to be **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

Many agricultural regions will experience declines in crop and livestock production from increased stress due to weeds, diseases, insect pests, and other climate change induced stresses.

Description of evidence base

The key message and supporting text summarizes extensive evidence documented in the Agriculture TIR, "Climate Change and Agriculture in the United States: An Assessment of Effects and Potential for Adaptation".[15] Additional Technical Input Reports (56) 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 the direct effects of climate on the ecological systems within which crop and livestock operations occur. Many weeds respond more strongly to CO_2 than do crops, and it is believed that the range of many diseases and pests (for both crop and livestock) will expand under warming conditions.[28,31,40] Pests may have increased overwinter survival and fit more generations into a single year, which may also facilitate faster evolution of pesticide resistance. Changing patterns of pressure from weeds, other pests, and disease can affect crop and livestock production in ways that may be costly or challenging to address.[9,15]

New information and remaining uncertainties

Important new evidence (cited above) confirmed many of the findings in the past Synthesis and Assessment Product on agriculture,[82] which informed the 2009 National Climate Assessment.[83]

In addition to extant species already in the U.S., exotic weeds, diseases, and pests have particular significance in that: 1) they can often be invasive (that is, arrive without normal biological/ecological controls) and highly damaging; 2) with increasing international trade, there are numerous high-threat, high-impact species that will arrive on commodities from areas where some species even now are barely known to modern science, but which have the potential to emerge under a changed climate regime to pose significant risk of establishment in the U.S. and economic loss; and 3) can take advantage of "disturbances," where climate variability acts as an additional ecological disturbance. Improved models and observational data related to how many agricultural regions will experience declines in animal and plant production from increased stress due to weeds, diseases, insect pests, and other climate change induced stresses will need to be developed.

A key issue is the extent of the interaction between components of the natural biological system (for example, pests) and the economic biological system (for example, crop or animal). For insects, increased populations are a factor; however, their effect on the plant may be dependent upon the phenological stage of the plant when the insect is at specific phenological stages.[15]

To enhance our understanding of these issues will require a concerted effort to begin to quantify the interactions of pests and the economic crop or livestock system and how each system and their interactions are affected by climate.[15]

Assessment of confidence based on evidence

The scientific literature is beginning to emerge; however, there are still some unknowns about the effects of biotic stresses, and there may well be emergent "surprises" resulting from departures from past ecological equilibria. Confidence is therefore judged to be **medium** that many agricultural regions will experience declines in animal and plant production from increased stress due to weeds, diseases, insect pests, and other climate change induced stresses.

Key message #3 Traceable Account

Current loss and degradation of critical agricultural soil and water assets due to increasing extremes in precipitation will continue to challenge both rainfed and irrigated agriculture unless innovative conservation methods are implemented.

Description of evidence base

The key message and supporting text summarizes extensive evidence documented in the Agriculture TIR, "Climate Change and Agriculture in the United States: An Assessment of Effects and Potential for Adaptation."[15] Additional Technical Input Reports (56) on a wide range of topics were also received and reviewed as part of the Federal Register Notice solicitation for public input.

Soil erosion is affected by rainfall intensity and there is evidence of increasing intensity in rainfall events even where the annual mean is reduced.[53] Unprotected soil surfaces will have increased erosion and require more intense conservation practices.[58,59] Shifts in seasonality and type of precipitation will affect both timing and impact of water availability for both rainfed and irrigated agriculture. Evidence is strong that in the future there will be more precipitation globally, and that rain events will be more intense, even if separated by longer periods without rain.[6]

New information and remaining uncertainties

Important new evidence (cited above) confirmed many of the findings in the past Synthesis and Assessment Product on agriculture,[82] which informed the 2009 National Climate Assessment.[83] Both rainfed and irrigated agriculture will increasingly be challenged, based on improved models and observational data related to the effects of increasing precipitation extremes on loss and degradation of critical agricultural soil and water assets.[51,52]

Precipitation shifts are the most difficult to project, and uncertainty in regional projections increases with time into the future.[61] To improve these projections will require enhanced understanding of shifts in timing, intensity, and magnitude of precipitation events. In the northern U.S., more frequent and severe winter and spring storms are projected, while there is a projected reduction in precipitation in the Southwest (see Ch. 2: Our Changing Climate).

Assessment of confidence based on evidence

The precipitation forecasts are the limiting factor in these assessments; the evidence of the impact of precipitation extremes on soil water availability and soil erosion is well established. Confidence in this key message is therefore judged to be **high**.

Key message #4 Traceable Account

The rising incidence of weather extremes will have increasingly negative impacts on crop and livestock productivity because critical thresholds are already being exceeded.

Description of evidence base

The key message and supporting text summarizes extensive evidence documented in the Agriculture TIR, "Climate Change and Agriculture in the United States: An Assessment of Effects and Potential for Adaptation".[15] Additional Technical Input Reports (56) 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[6,61,62] provide evidence that the occurrence of extreme events is increasing, and exposure of plants or animals to temperatures and soil water conditions (drought, water-logging, flood) outside of the biological range for the given species will cause stress and reduce production.[6,61,62] The direct effects of an extreme event will depend upon the timing of the event relative to the growth stage of the biological system.

New information and remaining uncertainties

Important new evidence (cited above) confirmed many of the findings in the past Synthesis and Assessment Product on agriculture, [82] which informed the 2009 National Climate Assessment.[83]

One key area of uncertainty is the timing of extreme events during the phenological stage of the plant or the growth stage of the animal. For example, plants are more sensitive to extreme high temperatures during the pollination stage compared to vegetative growth stages.[9] A parallel example for animals is relatively strong sensitivity to high temperatures during the conception phase.[34] Milk and egg production are also vulnerable to temperature extremes. The effects of extreme combinations of weather variables must be considered, such as elevated humidity in concert with high temperatures.[34]

Other key uncertainties include inadequate precision in simulations of the timing of extreme events relative to short time periods of crop vulnerability, and temperatures close to key thresholds such as freezing.[22] The uncertainty is amplified by the rarity of extreme events; this rarity means there are infrequent opportunities to study the impact of extreme events. In general, a shift of the distribution of temperatures can increase the frequency of threshold exceedance.[15]

The information base can be enhanced by improving the forecast of extreme events, given that the effect of extreme events on plants or animals is known.[3,61]

Assessment of confidence based on evidence

There is **high** confidence in the effects of extreme temperature events on crops and livestock, and the agreement in the literature is good.

Key message #5 Traceable Account

Agriculture has been able to adapt to recent changes in climate; however, increased innovation will be needed to ensure the rate of adaptation of agriculture and the associated socioeconomic system can keep pace with climate change over the next 25 years.

Description of evidence base

There is emerging evidence about the economic impacts of climate change on agriculture and the potential for adaptive strategies.[64] In the case of crop production, much of the economic literature suggests that in the short term, producers will continue to adapt to weather changes and shocks as they always have, with changes in the timing of field operations, shifts in crops grown, and changing tillage or irrigation practices.[64] In the longer term, however, existing adaptive technologies will likely not be sufficient to buffer the impacts of climate change without significant impacts to domestic producers, consumers, or both.

New strategies for building long-term resilience include both new technologies and new institutions to facilitate appropriate, informed producer response to a changing climate. Furthermore, there are both public and private costs to adjusting agricultural production and infrastructure in a manner that enables adaptation.[2]

New information and remaining uncertainties

Limits to public investment and constraints on private investment could slow the speed of adaptation, yet potential constraints and limits are not well-understood or integrated into economic impact assessments. The economic implications of changing biotic pressures on crops and livestock, and on the agricultural system as a whole, are not well-understood, either in the short or long term.[15] Adaptation may also be limited by availability of inputs (such as land or water), changing prices of other inputs with climate change (such as energy and fertilizer), and by the environmental implications of intensifying or expanding agricultural production.

It is difficult to fully represent the complex interactions of the entire socio-ecological system within which agriculture operates, to assess the relative effectiveness and feasibility of adaptation strategies at various levels. Economic impact assessments require improved understanding of adaptation capacity and agricultural resilience at the system level, including the agri-ecosystem impacts related to diseases and pests. Economic impact assessments also require improved understanding of adaptation opportunities, economic resilience, and constraints to adaptation at the producer level.[2,64] The economic value of ecological services, such as pollination services, is particularly difficult to quantify and incorporate into economic impact efforts.[15]

Assessment of confidence based on evidence

Emerging evidence about adaptation of agricultural systems to changing climate is beginning to be developed. The complex interactions among all of the system components present a limitation to a complete understanding, but do provide a comprehensive framework for the assessment of agricultural responses to climate change. Given the overall and remaining uncertainty, there is **medium** confidence in this message.

KEY MESSAGE #6 TRACEABLE ACCOUNT

Climate change effects on agriculture will have consequences for food security, both in the U.S. and globally, through changes in crop yields and food prices and effects on food processing, storage, transportation, and retailing. Adaptation measures can help delay and reduce some of these impacts.

Description of evidence base

The relationships among agricultural productivity, climate change, and food security have been documented through ongoing investigations by the Food and Agriculture Organization,[81,84] as well as the U.S. Department of Agriculture,[85] and the National Research Council.[77] There are many factors that affect food security, and agricultural yields are only one of them. Climate change is also expected to affect distribution of food- and waterborne diseases, and food trade and distribution.[78]

New information and remaining uncertainties

The components of food security derive from the intersection of political, physical, economic, and social factors. In many ways the impact of climate change on crop yields is the least complex of the factors that affect the four components of food security (availability, stability, access, and utilization). As the globalized food system is subject to conflicting pressures across scales, one approach to reducing risk is a "cross-scale problem-driven" approach to food security.[76] This and other approaches to understanding and responding to the complexities of the global food system need additional research. Climate change will have a direct impact on crop and livestock production by increasing the variability in production levels from year to year, with varying effects across different regions. Climate change will also affect the distribution of food supplies as a result of disruptions in transportation routes. Addressing food security will require integration of multiple factors, including the direct and indirect impacts of climate change.

Assessment of confidence based on evidence

Given the evidence base and remaining uncertainty, there is **high** confidence that climate change impacts will have consequences for food security both in the U.S. and globally through changes in crop yields and food prices, and **very high** confidence that other related factors, including food processing, storage, transportation, and retailing will also be affected by climate change. There is **high** confidence that adaptation measures will help delay and reduce some of these impacts.

Climate Change Impacts in the United States

CHAPTER 7
FORESTS

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7 FORESTS

Key Messages

1. **Climate change is increasing the vulnerability of many forests to ecosystem changes and tree mortality through fire, insect infestations, drought, and disease outbreaks.**
2. **U.S. forests and associated wood products currently absorb and store the equivalent of about 16% of all carbon dioxide (CO_2) emitted by fossil fuel burning in the U.S. each year. Climate change, combined with current societal trends in land use and forest management, is projected to reduce this rate of forest CO_2 uptake.**
3. **Bioenergy could emerge as a new market for wood and could aid in the restoration of forests killed by drought, insects, and fire.**
4. **Forest management responses to climate change will be influenced by the changing nature of private forestland ownership, globalization of forestry markets, emerging markets for bioenergy, and U.S. climate change policy.**

Forests occur within urban areas, at the interface between urban and rural areas (wildland-urban interface), and in rural areas. Urban forests contribute to clean air, cooling buildings, aesthetics, and recreation in parks. Development in the wildland-urban interface is increasing because of the appeal of owning homes near or in the woods. In rural areas, market factors drive land uses among commercial forestry and land uses such as agriculture. Across this spectrum, forests provide recreational opportunities, cultural resources, and social values such as aesthetics.[1]

Economic factors have historically influenced both the overall area and use of private forestland. Private entities (such as corporations, family forest owners, and tribes) own 56% of the forestlands in the United States. The remaining 44% of forests are on public lands: federal (33%), state (9%), and county and municipal government (2%).[2] Market factors can influence management objectives for public lands, but societal values also influence objectives by identifying benefits such as environmental services not ordinarily provided through markets, like watershed protection and wildlife habitat. Different challenges and opportunities exist for public and for private forest management decisions, especially when climate-related issues are considered on a national scale. For example, public forests typically carry higher levels of forest biomass, are more remote, and tend not to be as intensively managed as private forestlands.[1]

Forests provide opportunities to reduce future climate change by capturing and storing carbon, as well as by providing resources for bioenergy production (the use of forest-derived plant-based materials for energy production). The total amount of carbon stored in U.S. forest ecosystems and wood products (such as lumber and pulpwood) equals roughly 25 years of U.S. heat-trapping gas emissions at current rates of emission, providing an important national "sink" that could grow or shrink depending on the extent of climate change, forest management practices, policy decisions, and other factors.[3,4] For example, in 2011, U.S. forest ecosystems and the associated wood products industry captured and stored roughly 16% of all carbon dioxide emitted by fossil fuel burning in the United States.[3]

Management choices for public, private, and tribal forests all involve similar issues. For example, increases in wildfire, disease, drought, and extreme events are projected for some regions (see also Ch. 16: Northeast; Ch. 20: Southwest; Ch. 21: Northwest, Key Message 3; and Ch. 22: Alaska). At the same time, there is growing awareness that forests may play an expanded role in carbon management. Urban expansion fragments forests and may limit forest management options. Addressing climate change effects on forestlands requires considering the interactions among land-use practices, energy options, and climate change.[5]

Key Message 1: Increasing Forest Disturbances

Climate change is increasing the vulnerability of many forests to ecosystem changes and tree mortality through fire, insect infestations, drought, and disease outbreaks.

Insect and pathogen outbreaks, invasive species, wildfires, and extreme events such as droughts, high winds, ice storms, hurricanes, and landslides induced by storms[8] are all disturbances that affect U.S. forests and their management (Figure 7.1). These disturbances are part of forest dynamics, are often interrelated, and can be amplified by underlying trends – for example, decades of rising average temperatures can increase damage to forests when a drought occurs.[9] Disturbances that affect large portions of forest ecosystems occur relatively infrequently and in response to climate extremes. Changes in climate in the absence of extreme climate events (and the forest disturbances they trigger) may result in increased forest productivity, but extreme climate events can potentially overturn such patterns.[10]

Factors affecting tree death – such as drought, physiological water stress, higher temperatures, and/or pests and pathogens – are often interrelated, which means that isolating a single cause of mortality is rare.[11,12,13] However, in western forests there have been recent large-scale die-off events due to one or more of these factors,[14,15,16] and rates of tree mortality are well correlated with both rising temperatures and associated increases in evaporative water demand.[17] In eastern forests, tree mortality at large spatial scales was more sensitive

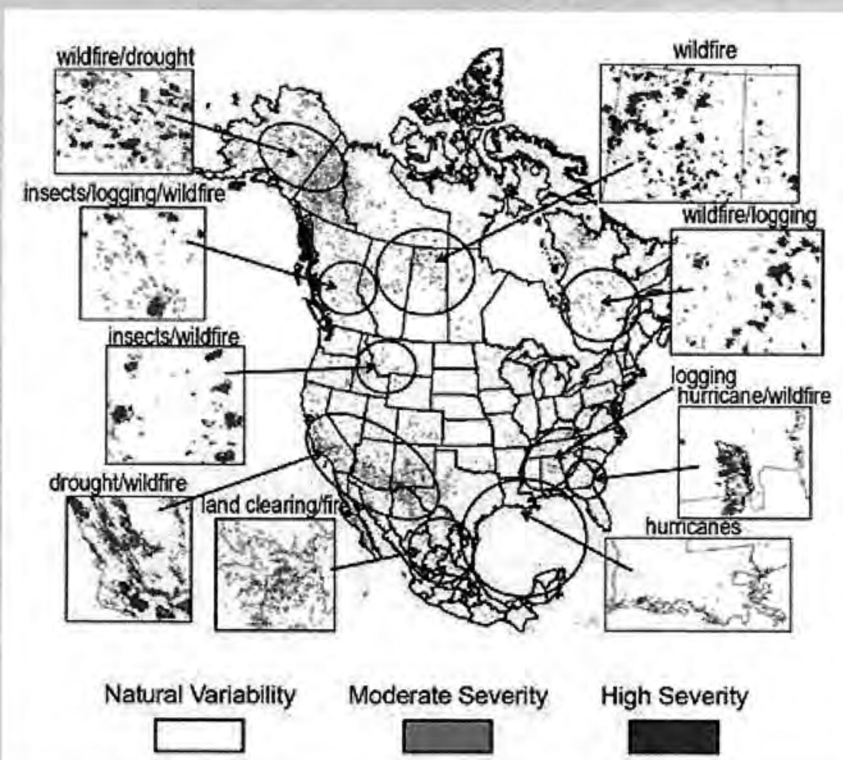

Figure 7.1. An example of the variability and distribution of major ecosystem disturbance types in North America, compiled from 2005 to 2009. Forest disturbance varies by topography, vegetation, weather patterns, climate gradients, and proximity to human settlement. Severity is mapped as a percent change in a satellite-derived Disturbance Index. White areas represent natural annual variability, orange represents moderate severity, and red represents high severity.[6] Fire dominates much of the western forest ecosystems, and storms affect the Gulf Coast. Insect damage is widespread but currently concentrated in western regions, and timber harvest is predominant in the Southeast. (Figure source: modified from Goetz et al. 2012;[7] Copyright 2012 American Geophysical Union).

A Montana saw mill owner inspects a lodgepole pine covered in pitch tubes that show the tree trying, unsuccessfully, to defend itself against the bark beetle. The bark beetle is killing lodgepole pines throughout the western U.S.

Warmer winters allow more insects to survive the cold season, and a longer summer allows some insects to complete two life cycles in a year instead of one. Drought stress reduces trees' ability to defend against boring insects. Above, beetle-killed trees in Rocky Mountain National Park in Colorado.

to forest structure (age, tree size, and species composition) and air pollutants than climate over recent decades. Nonetheless, mortality of some eastern tree groups is related to rising temperature[18] and is expected to increase as climate warms.[19]

Future disturbance rates in forests will depend on changes in the frequency of extreme events as well as the underlying changes in average climate conditions.[9,20] Of particular concern is the potential for increased forest disturbance as the result of drought accompanied with warmer temperatures, which can cause both wildfire and tree death. Temperatures have generally been increasing and are projected to increase in the future (see Ch. 2: Our Changing Climate). Therefore, although it is difficult to predict trends in future extreme events,[21] there is a high degree of confidence that future droughts will be accompanied by generally warmer conditions. Trees die faster when drought is accompanied by higher temperatures, so short droughts can trigger mortality if temperatures are higher.[22] Short droughts occur more frequently than long droughts. Consequently, a direct effect of rising temperatures may be substantially greater tree mortality even with no change in drought frequency.[22]

Given strong relationships between climate and fire, even when modified by land use and management, such as fuel treatments (Figure 7.2), projected climate changes suggest that western forests in the United States will be increasingly affected by large and intense fires that occur more frequently.[16,23,24,25] These impacts are compounded by a legacy of fire suppression that has resulted in many U.S. forests becoming increasingly dense.[26] Eastern forests are less likely to experience immediate increases in wildfire, unless a point is reached at which rising temperatures combine with seasonal dry periods, more protracted drought, and/or insect outbreaks to trigger wildfires – conditions that have been seen in Florida (see Ch. 17: Southeast).

Rising temperatures and CO_2 levels can increase growth or alter migration of some tree species;[1,27] however, the relationship between rising temperature and mortality is complex. For example, most functional groups show a decrease in mortality with higher summer temperatures (with the exception of northern groups), whereas warmer winters are correlated with higher mortality for some functional groups.[18] Tree mortality is often the result of a combination of many factors; thus increases in pollutants, droughts, and wildfires will increase the probability of a tree dying (Figure 7.3). Under projected climate conditions, rising temperatures could work together with forest stand characteristics and these other stressors to increase mortality. Recent die-offs have been more severe than projected.[11,14] As temperatures increase to levels projected for mid-century and beyond, eastern forests may be at risk of die-off.[19] New evidence indicates that most tree species can endure only limited abnormal water stress, reinforcing the idea that trees in wetter as well as semiarid forests are vulnerable to drought-induced mortality under warming climates.[28]

Effectiveness of Forest Management in Reducing Wildfire Risk

Figure 7.2. Forest management that selectively removes trees to reduce fire risk, among other objectives (a practice referred to as "fuel treatments"), can maintain uneven-aged forest structure and create small openings in the forest. Under some conditions, this practice can help prevent large wildfires from spreading. Photo shows the effectiveness of fuel treatments in Arizona's 2002 Rodeo-Chediski fire, which burned more than 400 square miles – at the time the worst fire in state history. Unburned area (left) had been managed with a treatment that removed commercial timber, thinned non-commercial-sized trees, and followed with prescribed fire in 1999. The right side of the photo shows burned area on the untreated slope below Limestone Ridge. (Photo credit: Jim Youtz, U.S. Forest Service).

Climate change is contributing to increases in wildfires across the western U.S. and Alaska.

Forest Vulnerability to Changing Climate

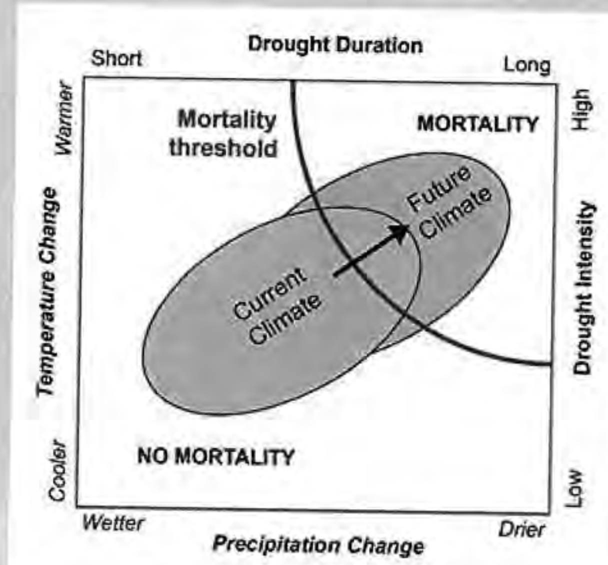

Figure 7.3. The figure shows a conceptual climate envelope analysis of forest vulnerability under current and projected future ranges of variability in climate parameters (temperature and precipitation, or alternatively drought duration and intensity). Climate models project increasing temperatures across the U.S. in coming decades, but a range of increasing or decreasing precipitation depending on region. Episodic droughts (where evaporation far exceeds precipitation) are also expected to increase in duration and/or intensity (see Ch. 2: Our Changing Climate). The overall result will be increased vulnerability of forests to periodic widespread regional mortality events resulting from trees exceeding their physiological stress thresholds.[11] (Figure source: Allen et al. 2010[11]).

Large-scale die-off and wildfire disturbance events could have potential impacts occurring at local and regional scales for timber production, flooding and erosion risks, other changes in water budgets, biogeochemical changes including carbon storage, and aesthetics.[29,30,31] Rising disturbance rates can increase harvested wood output and potentially lower prices; however, higher disturbance rates could make future forest investments more risky (Figure 7.4). Western forests could also lose substantial amounts of carbon storage capacity. For example, an increase in wildfires, insect outbreaks, and droughts that are severe enough to alter soil moisture and nutrient contents can result in changes in tree density or species composition.[10]

Key Message 2: Changing Carbon Uptake

U.S. forests and associated wood products currently absorb and store the equivalent of about 16% of all carbon dioxide (CO_2) emitted by fossil fuel burning in the U.S. each year. Climate change, combined with current societal trends in land use and forest management, is projected to reduce this rate of forest CO_2 uptake.

Climate-related Effects on Trees and Forest Productivity

Forests within the United States grow across a wide range of latitudes and altitudes and occupy all but the driest regions. Current forest cover has been shaped by climate, soils, topography, disturbance frequency, and human activity. Forest growth appears to be slowly accelerating (less than 1% per decade) in regions where tree growth is limited by low temperatures and short growing seasons that are gradually being altered by climate change (for species shifts, see Ch. 8: Ecosystems).[32] Forest carbon storage appears to be increasing both globally and within the United States.[33] Continental-scale satellite measurements document a lengthening growing season in the last thirty years, yet earlier spring growth may be negated by mid-summer drought.[34]

By the end of the century, snowmelt may occur a month earlier, but forest drought stress could increase by two months in the Rocky Mountain forests.[35] In the eastern United States, elevated CO_2 and temperature may increase forest growth and potentially carbon storage if sufficient water is available.[1,31,36] Despite recent increases in forest growth, future net forest carbon storage is expected to decline due to accelerating mortality and disturbance.

Forests can be a Source – or a Sink – for Carbon

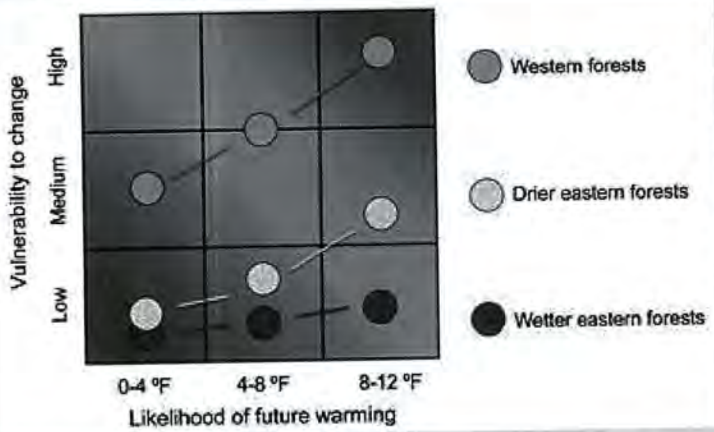

Figure 7.4. Relative vulnerability of different forest regions to climate change is illustrated in this conceptual risk analysis diagram. Forest carbon exchange is the difference between carbon captured in photosynthesis and carbon released by respiration of vegetation and soils. Both photosynthesis and respiration are generally accelerated by higher temperatures, and slowed by water deficits, but the relative strengths of these controls are highly variable. Western forests are inherently limited by evaporation that exceeds precipitation during much of the growing season. Xeric (drier) eastern forests grow on shallow, coarse textured soils and experience water deficits during long periods without rain. Mesic (wetter) eastern forests experience severe water deficits only for relatively brief periods in abnormally dry years so the carbon exchanges are more controlled by temperature fluctuations. (Figure source: adapted from Vose et al. 2012[1]).

Forest Carbon Sequestration and Carbon Management

From the onset of European settlement to the start of the last century, changes in U.S. forest cover due to expansion of agriculture, tree harvests, and settlements resulted in net emissions of carbon.[37,38] More recently, with forests reoccupying land previously used for agriculture, technological advances in harvesting, and changes in forest management, U.S. forests and associated wood products now serve as a substantial carbon sink, capturing and storing more than 227.6 million tons of carbon per year.[3] The amount of carbon taken up by U.S. land is dominated by forests (Figure 7.5), which have annually absorbed 7% to 24% of fossil fuel carbon dioxide (CO_2) emissions in the U.S. over the past two decades. The best estimate is that forests and wood products stored about 16% (833 teragrams, or 918.2 million short tons, of CO_2 equivalent in 2011) of all the CO_2 emitted annually by fossil fuel burning in the United States (see also "Estimating the U.S. Carbon Sink" in Ch. 15: Biogeochemical Cycles).[3]

Forest Growth Provides an Important Carbon Sink

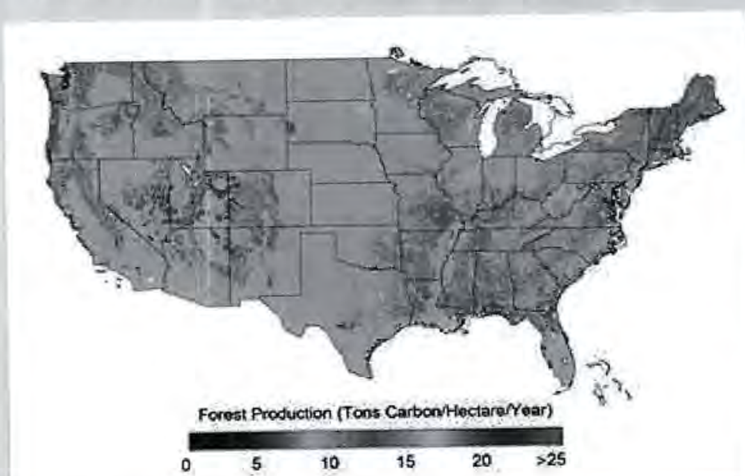

Figure 7.5. Forests are the largest component of the U.S. carbon sink, but growth rates of forests vary widely across the country. Well-watered forests of the Pacific Coast and Southeast absorb considerably more than the arid southwestern forests or the colder northeastern forests. Climate change and disturbance rates, combined with current societal trends regarding land use and forest management, are projected to reduce forest CO_2 uptake in the coming decades.[1] Figure shows average forest growth as measured by net primary production from 2000 to 2006. (Figure source: adapted from Running et al. 2004[46]).

The future role of U.S. forests in the carbon cycle will be affected by climate change through changes in disturbances (see Figures 7.3 and 7.4), as well as shifts in tree species, ranges, and productivity (Figure 7.6).[19,38] Economic factors will affect any future carbon cycle of forests, as the age class and condition of forests are affected by the acceleration of harvesting,[39,40] land-use changes such as urbanization,[41] changes in forest types,[42] and bioenergy development.[41,43,44,45]

Efforts in forestry to reduce atmospheric CO_2 levels have focused on forest management and forest product use. Forest management strategies include land-use change to increase forest area (afforestation) and/or to avoid deforestation and optimizing carbon management in existing forests. Forest product-use strategies include the use of wood wherever possible as a structural substitute for steel and concrete, which require more carbon emissions to produce.[38] The carbon emissions offset from using wood rather than alternate materials for a range of applications can be two or more times the carbon content of the product.[47]

In the U.S., afforestation (active establishment or planting of forests) has the potential to capture and store a maximum of 225 million tons of additional carbon per year from 2010 to 2110[39,48] (an amount almost equivalent to the current annual carbon storage in forests). Tree and shrub encroachment into grasslands, rangelands, and savannas provides a large potential carbon sink that could exceed half of what existing U.S. forests capture and store annually.[48]

Expansion of urban and suburban areas is responsible for much of the current and expected loss of U.S. forestland, although these human-dominated areas often have extensive tree cover and potential carbon storage (see also Ch. 13: Land Use & Land Cover Change).[41] In addition, the increasing prevalence of extreme conditions that encourage wildfires can convert some forests to shrublands and meadows[25] or permanently reduce the amount of carbon stored in existing forests if fires occur more frequently.[49]

Carbon management on existing forests can include practices that increase forest growth, such as fertilization, irrigation, switching to fast-growing planting stock, shorter rotations, and weed, disease, and insect control.[50] In addition, forest management can increase average forest carbon stocks by increasing the interval between harvests, by decreasing harvest intensity, or by focused density/species management.[4,51] Since 1990, CO_2 emissions from wildland forest fires in the lower 48 United States have averaged about 67 million tons of carbon per year.[52,53] While forest management practices can reduce on-site carbon stocks, they may also help reduce future climate change by providing feedstock material for bioenergy production and by possibly avoiding future, potentially larger, wildfire emissions through fuel treatments (Figure 7.2).[1]

Forests and Carbon

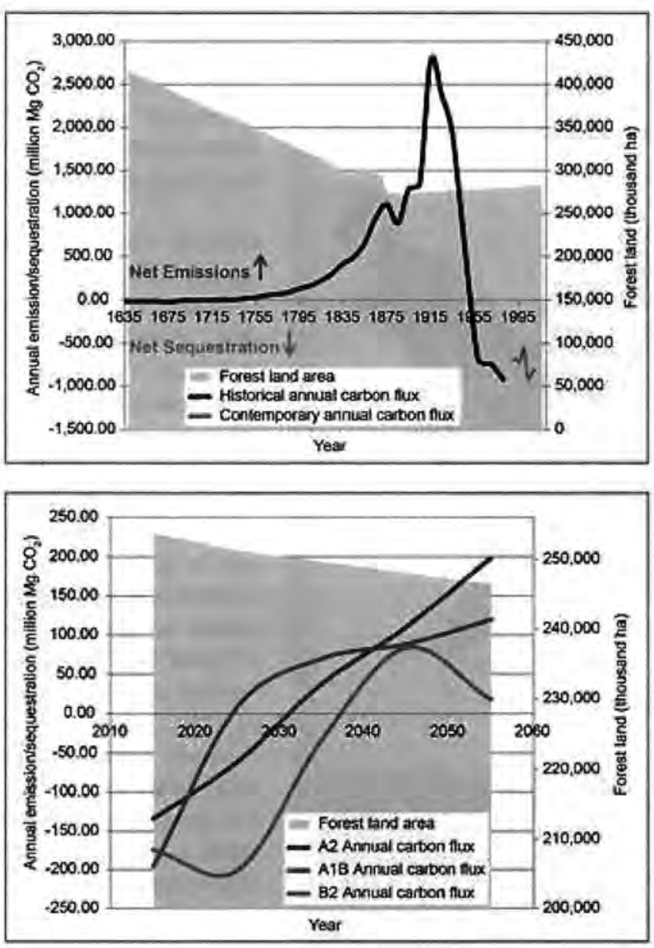

Figure 7.6. Historical, current, and projected annual rates of forest ecosystem and harvested wood product CO_2 net emissions/sequestration in the U.S. from 1635 to 2055. In the top panel, the change in the historical annual carbon emissions (black line) in the early 1900s corresponds to the peak in the transformation of large parts of the U.S. from forested land to agricultural land uses. Green shading shows this decline in forest land area. In the bottom panel, future projections shown under higher (A2) and lower (B2 and A1B) emissions scenarios show forests as carbon sources (due to loss of forest area and accelerating disturbance rates) rather than sinks in the latter half of this century. The A1B scenario assumes similar emissions to the A2 scenario used in this report through 2050, and a slow decline thereafter. (Data from Birdsey 2006;[37] USFS 2012;[41] EPA 2013.[53])

Key Message 3: Bioenergy Potential

Bioenergy could emerge as a new market for wood and could aid in the restoration of forests killed by drought, insects, and fire.

Bioenergy refers to the use of plant-based material to produce energy, and comprises about 28% of the U.S. renewable energy supply (Ch. 10: Energy, Water, and Land). Forest resources potentially could produce bioenergy from 504 million acres of timberland and 91 million acres of other forested land (Figure 7.7). Bioenergy from all sources, including agricultural and forests, could theoretically supply the equivalent of up to 30% of current U.S. petroleum consumption, but only if all relevant policies were optimized.[45] The *maximum* projected potential for forest bioenergy ranges from 3% to 5% of total current U.S. energy consumption.[54]

Forest biomass energy could be one component of an overall bioenergy strategy to reduce emissions of carbon from fossil fuels,[55] while also improving water quality[56,57] and maintaining lands for timber production as an alternative to other socioeconomic options. Active biomass energy markets using wood and forest residues have emerged in the southern and northeastern United States, particularly in states that have adopted renewable fuel standards. The economic viability of using forests for bioenergy depends on regional context and circumstances, such as species type and prior management, land conditions, transport and storage logistics, conversion processes used to produce energy, distribution, and use.[58] The environmental and socioeconomic consequences of bioenergy production vary greatly with region and intensity of human management.

The potential for biomass energy to increase timber harvests has led to debates about whether forest biomass energy leads to higher carbon emissions.[44,59] The debate on biogenic emissions regulations revolves around how to account for emissions related to biomass production and use.[60] The forest carbon balance naturally changes over time and also depends on forest management scenarios. For example, utilizing natural beetle-killed forests will yield a different carbon balance than growing and harvesting a live, fast-growing plantation.

Markets for energy from biomass appear to be ready to grow in response to energy pricing, policy, and demand,[44] although recent increases in the supply of natural gas have reduced the perceived urgency for new biomass projects. Further, because energy facilities typically buy the lowest quality wood at prices that rarely pay much more than cutting and hauling costs, they often require a viable saw timber market nearby to ensure an adequate, low-cost supply of material.[61] Where it is desirable to remove dead wood after disturbances to thin forests or to dispose of residues, a viable bioenergy industry could finance such activities. However, the bioenergy market has yet to be made a profitable enterprise in most U.S. regions.

Location of Potential Forestry Biomass Resources

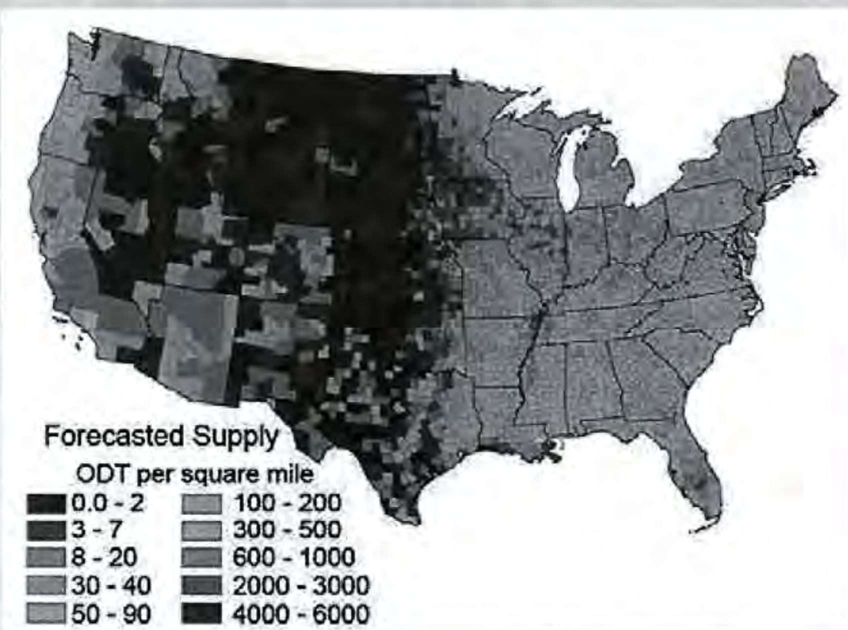

Figure 7.7. Potential forestry bioenergy resources by 2030 at $80 per dry ton of biomass based on current forest area, production rates based on aggressive management for fast-growth, and short rotation bioenergy plantations. Units are oven dry tons (ODT) per square mile at the county level, where an ODT is 2,000 pounds of biomass from which the moisture has been removed. Includes extensive material from existing forestland, such as residues, simulated thinnings, and some pulpwood for bioenergy, among other sources. (Figure source: adapted from U.S. Department of Energy 2011[45]).

Key Message 4: Influences on Management Choices

Forest management responses to climate change will be influenced by the changing nature of private forestland ownership, globalization of forestry markets, emerging markets for bioenergy, and U.S. climate change policy.

Climate change will affect trees and forests in urban areas, the wildland-urban interface, and in rural areas. It will also challenge forest landowners managing forests for commercial products, energy development, environmental services such as watershed protection, or the conversion of forestland to developed and urban uses or agriculture. With increases in urbanization, the value of forests in and around urban areas in providing environmental services required by urban residents will increase.[41] Potentially the greatest shifts in goods and environmental services produced from forests could occur in rural areas where social and economic factors will interact with the effects of climate change at landscape scales.

Owner objectives, markets for forest products, crops and energy, the monetary value of private land, and policies governing private and public forestland all influence the actions taken to manage U.S. forestlands (56% privately owned, 44% public) (Figure 7.8). Ownership changes can bring changes in forest objectives. Among corporate owners (18% of all forestland), ownership has shifted from forest industry to investment management organizations that may or may not have active forest management as a primary objective. Non-corporate private owners, an aging demographic, manage 38% of forestland. Their primary objectives are maintaining aesthetics and the privacy that the land provides as well as preserving the land as part of their family legacy.[62]

A significant economic factor facing private forest owners is the value of their forestlands for conversion to urban or developed uses. Economic opportunities from forests include wood products, non-timber forest products, recreation activities, and in some cases, environmental services.[1,41] Less than 1% of the volume of commercial trees from U.S. forestlands is harvested annually, and 92% of this harvest comes from private forestlands.[2] Markets for wood products in the United States have been affected by increasingly competitive global markets,[63] and timber prices are not projected to increase without substantial increases in wood energy consumption or other new timber demands.[41] Urban conversions of forestland over the next 50 years could result in the loss of 16 to 31 million acres.[41] The willingness of private forest owners to actively manage forests in the face of climate change will be affected primarily by market and policy incentives, not climate change itself.

The ability of public, private, and tribal forest managers to adapt to future climate change will be enhanced by their capacity to alter management regimes relatively rapidly in the face of changing conditions. The response to climate change may be greater on private forestlands where, in the past, owners have been highly responsive to market and policy signals.[64] These landowners may be able to use existing or current forest management practices to reduce disturbance effects, increase the capture and storage of carbon, and modify plant species distributions under climate change. In addition, policy incentives, such as carbon pricing or cap and trade markets, could influence landowner choices. For human communities dependent upon forest resources, maintaining or enhancing their current resilience to change will influence their ability to respond to future stresses from climate change.[65]

On public, private, and tribal lands, management practices that can be used to reduce disturbance effects include altering tree planting and harvest strategies through species selection and timing; factoring in genetic variation; managing for reduced stand densities, which could reduce wildfire risk; reducing other stressors such as poor air quality; using forest management practices to minimize drought stress; and developing regional networks to mitigate impacts on ecosystem goods and services.[1,30,66] Legally binding regulatory requirements may constrain adaptive management where plants, animals, ecosystems, and people are responding to climate change.[67]

Lack of fine-scale information about the possible effects of climate changes on locally managed forests limits the ability of managers to weigh these risks to their forests against the economic risks of implementing forest management practices such as adaptation and/or mitigation treatments. This knowledge gap will impede the implementation of effective management on public or private forestland in the face of climate change.

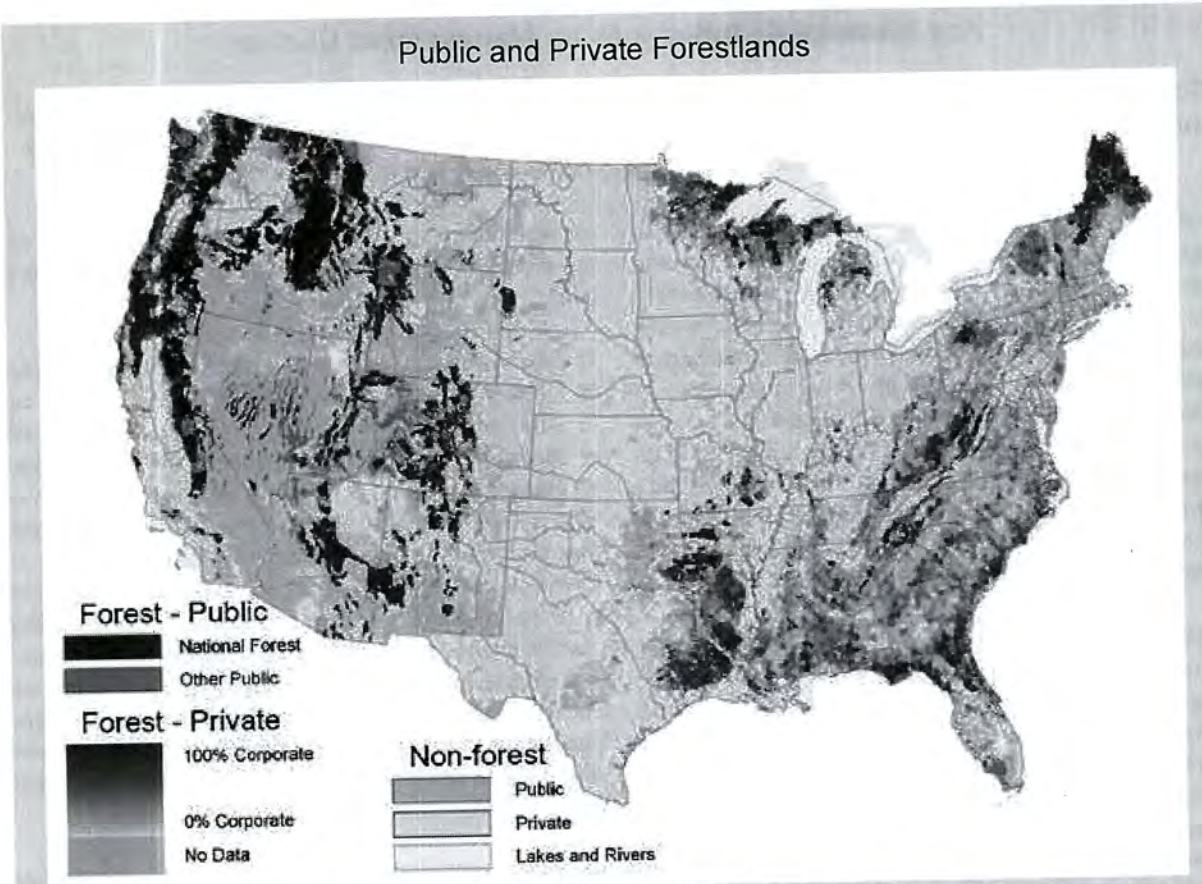

Figure 7.8. The figure shows forestland by ownership category in the contiguous U.S. in 2007.[41] Western forests are most often located on public lands, while eastern forests, especially in Maine and in the Southeast, are more often privately held. (Figure source: U.S. Forest Service 2012[41]).

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SUPPLEMENTAL MATERIAL
TRACEABLE ACCOUNTS

Process for Developing Key Messages:
A central component of the process was a workshop held in July 2011 by the U.S. Department of Agriculture Forest Service to guide the development of the technical input report (TIR). This session, along with numerous teleconferences, led to the foundational TIR, "Effects of Climatic Variability and Change on Forest Ecosystems: A Comprehensive Science Synthesis for the U.S. Forest Sector."[1]

The chapter authors engaged in multiple technical discussions via teleconference between January and June 2012, which included careful review of the foundational TIR and of 58 additional technical inputs provided by the public, as well as 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 message.

Key message #1 Traceable Account

Climate change is increasing the vulnerability of many forests to ecosystem changes and tree mortality through fire, insect infestations, drought, and disease outbreaks.

Description of evidence base
The key message and supporting text summarizes extensive evidence documented in the TIR, "Effects of Climatic Variability and Change on Forest Ecosystems: A Comprehensive Science Synthesis for the U.S. Forest Sector."[1] Technical input reports (58) on a wide range of topics were also received and reviewed as part of the Federal Register Notice solicitation for public input.

Dale et al.[8] addressed a number of climate change factors that will affect U.S. forests and how they are managed. This is supported by additional publications focused on effects of drought and by more large-scale tree die-off events,[11,22] wildfire,[16,23,25] insects and pathogens. [11,22] Other studies support the negative impact of climate change by examining the tree mortality rate due to rising temperatures,[9,11,14,15,16,17,19,22] which is projected to increase in some regions.[22]

Although it is difficult to detect a trend in disturbances because they are inherently infrequent and it is impossible to attribute an individual disturbance event to changing climate, there is nonetheless much that past events, including recent ones, reveal about expected forest changes due to future climate. Observational[17] and experimental[22] studies show strong associations between forest disturbance and extreme climatic events and/or modifications in atmospheric evaporative demand related to warmer temperature. Regarding eastern forests, there are fewer observational or experimental studies, with Dietz and Moorcroft[18] being the most comprehensive.

Pollution and stand age are the most important factors in mortality. Tree survival increases with increased temperature in some groups. However, for other tree groups survival decreases with increased temperature.[18] In addition, this study[18] needs to be considered in the context that there have been fewer severe droughts in this region. However, physiological relationships suggest that trees will generally be more susceptible to mortality under an extreme drought, especially if it is accompanied by warmer temperatures.[13,68] Consequently, it is misleading to assume that, because eastern forests have not yet experienced the types of large-scale die-off seen in the western forests, they are not vulnerable to such events if an extreme enough drought occurs. Although the effect of temperature on the rate of mortality during drought has only been shown for one species,[22] the basic physiological relationships for trees suggest that warmer temperatures will exacerbate mortality for other species as well.[13,68]

Figure 7.1: This figure uses a figure from Goetz et al. 2012[7] which uses the MODIS Global Disturbance Index (MGDI) results from 2005 to 2009 to illustrate the geographic distribution of major ecosystem disturbance types across North America (based on Mildrexler et al. 2007, 2009[6,69]). The MGDI uses remotely sensed information to assess the intensity of the disturbance. Following the occurrence of a major disturbance, there will be a reduction in Enhanced Vegetation Index (EVI) because of vegetation damage; in contrast, Land Surface Temperature (LST) will increase because more absorbed solar radiation will be converted into sensible heat as a result of the reduction in evapotranspiration from less vegetation density. MGDI takes advantage of the contrast changes in EVI and LST following a disturbance to enhance the signal to ef-

fectively detect the location and intensity of disturbances (http://www.ntsg.umt.edu/project/mgdi). Moderate severity disturbance is mapped in orange and represents a 65%-100% divergence of the current-year MODIS Global Disturbance Index value from the range of natural variability, High severity disturbance (in red) signals a divergence of over 100%.[7]

New information and remaining uncertainties

Forest disturbances have large ecosystem effects, but high interannual variability in regional fire and insect activity makes detection of trends more difficult than for changes in mean conditions.[20,21,70] Therefore, there is generally less confidence in assessment of future projections of disturbance events than for mean conditions (for example, growth under slightly warmer conditions).[21]

There are insufficient data on trends in windthrow, ice storms, hurricanes, and landslide-inducing storms to infer that these types of disturbance events are changing.

Factors affecting tree death, such as drought, warmer temperatures, and/or pests and pathogens are often interrelated, which means that isolating a single cause of mortality is rare.[11,12,13,17,22,68]

Assessment of confidence based on evidence

Very High. There is very high confidence that under projected climate changes there is high risk (high risk = high probability and high consequence) that western forests in the United States will be affected increasingly by large and intense fires that occur more frequently.[16,23,25] This is based on the strong relationships between climate and forest response, shown observationally[17] and experimentally.[22] Expected responses will increase substantially to warming and also in conjunction with other changes such as an increase in the frequency and/or severity of drought and amplification of pest and pathogen impacts. Eastern forests are less likely to experience immediate increases in wildfire unless/until a point is reached at which warmer temperatures, concurrent with seasonal dry periods or more protracted drought, trigger wildfires.

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

U.S. forests and associated wood products currently absorb and store the equivalent of about 16% of all carbon dioxide (CO_2) emitted by fossil fuel burning in the U.S. each year. Climate change, combined with current societal trends in land use and forest management, is projected to reduce this rate of forest CO_2 uptake.

Description of evidence base

The key message and supporting text summarizes extensive evidence documented in the TIR, "Effects of Climatic Variability and Change on Forest Ecosystems: A Comprehensive Science Synthesis for the U.S. Forest Sector."[1] Technical input reports (58) on a wide range of topics were also received and reviewed as part of the Federal Register Notice solicitation for public input.

A recent study[3] has shown that forests are a big sink of CO_2 nationally. However, the permanence of this carbon sink is contingent on forest disturbance rates, which are changing, and on economic conditions that may accelerate harvest of forest biomass.[56] Market response can cause changes in the carbon source/sink dynamics through shifts in forest age,[39,40] land-use changes and urbanization that reduce forested areas,[41] forest type changes,[42] and bioenergy development changing forest management.[41,43,44,45] Additionally, publications have reported that fires can convert a forest into a shrubland or meadow,[25] with frequent fires permanently reducing the carbon stock.[49]

New information and remaining uncertainties

That economic factors and societal choices will affect future carbon cycle of forests is known with certainty; the major uncertainties come from the future economic picture, accelerating disturbance rates, and societal responses to those dynamics.

Assessment of confidence based on evidence

Based on the evidence and uncertainties, confidence is **high** that climate change, combined with current societal trends regarding land use and forest management, is projected to reduce forest CO_2 uptake in the U.S. The U.S. has already seen large-scale shifts in forest cover due to interactions between forestland use and agriculture (for example, between the onset of European settlement to the present). There are competing demands for how forestland is used today. The future role of U.S. forests in the carbon cycle will be affected by climate change through changes in disturbances (Key Message 1), growth rates, and harvest demands.

Key message #3 Traceable Account

Bioenergy could emerge as a new market for wood and could aid in the restoration of forests killed by drought, insects, and fire.

Description of evidence base

The key message and supporting text summarize extensive evidence documented in the TIR, "Effects of Climatic Variability and Change on Forest Ecosystems: A Comprehensive Science Synthesis for the U.S. Forest Sector."[1] Technical input reports (58) on a wide range of topics were also received and reviewed as part of the Federal Register Notice solicitation for public input.

Studies have shown that harvesting forest bioenergy can prevent carbon emissions[55] and replace a portion of U.S. energy consumption to help reduce future climate change. Some newer literature has explored how use of forest bioenergy can replace a portion of current U.S. energy production from oil.[20,45] Some more recent publications have reported some environmental benefits, such as improved water quality[56,57] and better management of timber lands,[45] that can result from forest bioenergy implementation.

New information and remaining uncertainties

The implications of forest product use for bioenergy depends on regional context and circumstances, such as feedstock type and prior management, land conditions, transport and storage logistics, conversion processes used to produce energy, distribution and use.[58]

The potential for biomass energy to increase forest harvests has led to debates about whether biomass energy is net carbon neutral.[59] The debate on biogenic emissions regulations revolves around how to account for emissions related to biomass production and use.[60] Deforestation contributes to atmospheric CO_2 concentration, and that contribution has been declining over time. The bioenergy contribution question is largely one of incentives for appropriate management. When forests have no value, they are burned or used inappropriately. Bioenergy can be produced in a way that provides more benefits than costs or vice versa. The market for energy from biomass appears to be ready to grow in response to energy pricing, policy, and demand; however, this industry is yet to be made a large-scale profitable enterprise in most regions of the United States.

Assessment of confidence based on evidence

High. Forest growth substantially exceeds annual harvest for normal wood and paper products, and much forest harvest residue is now unutilized. Forest bioenergy will become viable if policy and economic energy valuations make it competitive with fossil fuels.

Key message #4 Traceable Account

Forest management responses to climate change will be influenced by the changing nature of private forestland ownership, globalization of forestry markets, emerging markets for bioenergy, and U.S. climate change policy.

Description of evidence base

The key message and supporting text summarizes extensive evidence documented in the TIR, "Effects of Climatic Variability and Change on Forest Ecosystems: A Comprehensive Science Synthesis for the U.S. Forest Sector."[1] Technical input reports (58) on a wide range of topics were also received and reviewed as part of the Federal Register Notice solicitation for public input.

The forest management response to climate change in urban areas, the wildland-urban interface, and in rural areas has been studied from varying angles. The literature on urban forests identifies the value of those forests to clean air, aesthetics, and recreation and suggests that under a changing climate, urban communities will continue to enhance their environment with trees and urban forests.[1,41] In the wildland-urban area and the rural areas, the changing composition of private forest landowners will affect the forest management response to climate change. Shifts in corporate owners to include investment organizations that may or may not have forest management as a primary objective has been described nationally.[1,2] Family forest owners are an aging demographic; one in five acres of forestland is owned by someone who is at least 75 years of age.[62] Multiple reasons for ownership are given by family forest owners, including the most commonly cited reasons of beauty/scenery, to pass land on to heirs, privacy, nature protection, and part of home/cabin. Many family forest owners feel it is necessary to keep the woods healthy but many are not familiar with forest management practices.[62] Long-term studies of the forest sector in the southern United States document the adaptive response of forest landowners to market prices as they manage to supply wood and associated products from their forests;[64] however prices are less of an incentive in other parts of the United States.[1,41] Econometric approaches have been used to explore the economic activities in the forest sector, including interactions with other sectors such as agriculture, impact of climate change, and the potential for new markets with bioenergy.[43,44] An earlier study explored the effects of globalization on forest management[63] and a newer study looked at the effect of U.S. climate change policy.[67] One of the biggest challenges is the lack of climate change information that results in inaction from many forest owners.[62]

New information and remaining uncertainties

Human concerns regarding the effects of climate change on forests and the role of adaptation and mitigation will be viewed from the perspective of the values that forests provide to human populations, including timber products, water, recreation, and aesthetic and spiritual benefits.[1] Many people, organizations, institutions, and governments influence the management of U.S. forests. Economic opportunities influence the amount and nature of private forestland (and much is known quantitatively about this dynamic) and societal values have a strong influence on how public forestland is managed. However, it remains challenging to project exactly how humans will respond to climate change in terms of forest management.

Climate change will alter known environmental and economic risks and add new risks to be addressed in the management of forests in urban areas, the wildland-urban interface, and rural areas. The capacity to manage risk varies greatly across landowners. While adaptation strategies provide a means to manage risks associated with climate change, a better understanding of risk perception by forest landowners would enhance the development and implementation of these management strategies. Identification of appropriate monitoring information and associated tools to evaluate monitoring data could facilitate risk assessment. Information and tools to assess environmental and economic risks associated with the impacts of climate change in light of specific management decisions would be informative to forestland managers and owners.

Assessment of confidence based on evidence

Given the evidence base and remaining uncertainty, there is **medium** confidence in this key message. Climate change and global and national economic events will have an integral impact on forest management, but it is uncertain to what magnitude. While forest landowners have shown the capacity to adapt to new economic conditions, potential changes in the international markets coincident with large-scale natural disturbances enhanced by climate change (fire, insects) could challenge this adaptive capacity. An important uncertainty is how people will respond to climate change in terms of forest management.

Climate Change Impacts in the United States

CHAPTER 8
ECOSYSTEMS,
BIODIVERSITY, AND ECOSYSTEM SERVICES

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8 ECOSYSTEMS,
BIODIVERSITY, AND ECOSYSTEM SERVICES

Key Messages

1. **Climate change impacts on ecosystems reduce their ability to improve water quality and regulate water flows.**
2. **Climate change, combined with other stressors, is overwhelming the capacity of ecosystems to buffer the impacts from extreme events like fires, floods, and storms.**
3. **Landscapes and seascapes are changing rapidly, and species, including many iconic species, may disappear from regions where they have been prevalent or become extinct, altering some regions so much that their mix of plant and animal life will become almost unrecognizable.**
4. **Timing of critical biological events, such as spring bud burst, emergence from overwintering, and the start of migrations, has shifted, leading to important impacts on species and habitats.**
5. **Whole system management is often more effective than focusing on one species at a time, and can help reduce the harm to wildlife, natural assets, and human well-being that climate disruption might cause.**

Climate change affects the living world, including people, through changes in ecosystems, biodiversity, and ecosystem services. Ecosystems entail all the living things in a particular area as well as the non-living things with which they interact, such as air, soil, water, and sunlight.[1] Biodiversity refers to the variety of life, including the number of species, life forms, genetic types, and habitats and biomes (which are characteristic groupings of plant and animal species found in a particular climate). Biodiversity and ecosystems produce a rich array of benefits that people depend on, including fisheries, drinking water, fertile soils for growing crops, climate regulation, inspiration, and aesthetic and cultural values.[2] These benefits are called "ecosystem services" – some of which, like food, are more easily quantified than others, such as climate regulation or cultural values. Changes in many such services are often not obvious to those who depend on them.

Ecosystem services contribute to jobs, economic growth, health, and human well-being. Although we interact with ecosystems and ecosystem services every day, their linkage to climate change can be elusive because they are influenced by so many additional entangled factors.[3] Ecosystem perturbations driven by climate change have direct human impacts, including reduced water supply and quality, the loss of iconic species and landscapes, distorted rhythms of nature, and the potential for extreme events to overwhelm the regulating services of ecosystems. Even with these well-documented ecosystem impacts, it is often difficult to quantify human vulnerability that results from shifts in ecosystem processes and services. For example, although it is more straightforward to predict how precipitation will change water flow, it is much harder to pinpoint which farms, cities, and habitats will be at risk of running out of water, and even more difficult to say how people will be affected by the loss of a favorite fishing spot or a wildflower that no longer blooms in the region. A better understanding of how a range of ecosystem responses affects people – from altered water flows to the loss of wildflowers – will help to inform the management of ecosystems in a way that promotes resilience to climate change.

Forests absorb carbon dioxide and provide many other ecosystem services, such as purifying water and providing recreational opportunities.

Key Message 1: Water

Climate change impacts on ecosystems reduce their ability to improve water quality and regulate water flows.

Climate-driven factors that control water availability and quality are moderated by ecosystems. Land-based ecosystems regulate the water cycle and are the source of sediment and other materials that make their way to aquatic ecosystems (streams, rivers, lakes, estuaries, oceans, groundwater). Aquatic ecosystems provide the critically important services of storing water, regulating water quality, supporting fisheries, providing recreation, and carrying water and materials downstream (Ch. 25: Coasts). Humans utilize, on average, the equivalent of more than 40% of renewable supplies of freshwater in more than 25% of all U.S. watersheds.[4] Freshwater withdrawals are even higher in the arid Southwest, where the equivalent of 76% of all renewable freshwater is appropriated by people.[5] In that region, climate change has likely decreased and altered the timing of streamflow due to reduced snowpack and lower precipitation in spring, although the precipitation trends are weak due to large year-to-year variability, as well as geographic variation in the patterns (Ch. 3: Water; Ch. 20: Southwest).[6] Depriving ecosystems of water reduces their ability to provide water to people as well as for aquatic plant and animal habitat (see Figure 8.1).

Habitat loss and local extinctions of fish and other aquatic species are projected from the combined effects of increased water withdrawal and climate change.[7] In the U.S., 47% of trout habitat in the interior West would be lost by 2080 under a scenario (A1B) that assumes similar emissions to the A2 scenario used in this report (Ch. 1: Overview, Ch. 2: Our Changing Climate) through 2050, and a slow decline thereafter.[8]

Across the entire U.S., precipitation amounts and intensity and associated river discharge are major drivers of water pollution in the form of excess nutrients, sediment, and dissolved organic carbon (DOC) (Ch. 3: Water).[9] At high concentrations, nutrients that are required for life (such as nitrogen and phosphorus) can become pollutants and can promote excessive phytoplankton growth – a process known as eutrophication. Currently, many U.S. lakes and rivers are polluted (have concentrations above government standards) by excessive nitrogen, phosphorus, or sediment. There are well-established links among fertilizer use, nutrient pollution, and river discharge, and many studies show that recent increases in rainfall in several regions of the United States have led to higher nitrogen amounts carried by rivers (Northeast,[10,11] California,[12] and Mississippi Basin[13,14]). Over the past 50 years, due to both climate and land-use change, the Mississippi Basin is yielding an additional 32 million acre-feet of water each year – equivalent to four Hudson Rivers – laden with materials washed from its farmlands.[15] This flows into the Gulf of Mexico, which is the site of the nation's largest hypoxic (low oxygen) "dead" zone.[4] The majority of U.S. estuaries are moderately to highly eutrophic.[16]

Links between discharge and sediment transport are well established,[17] and cost estimates for in-stream and off-stream damages from soil erosion range from $2.1 to $10 billion per year.[18,19] These estimates include costs associated with damages to, or losses of, recreation, water storage, navigation, commercial fishing, and property, but do not include costs of biological impacts.[18] Sediment transport, with accompanying nutrients, can play a positive role in the shoreline dynamics of coastlines and the life cycles of coastal and marine plants and animals. However, many commercially and recreationally important fish species such as salmon and trout that lay their eggs in the gravel at the edges of streams are especially sensitive to elevated sediment fluxes in rivers.[20] Sediment loading in lakes has been shown to have substantial detrimental effects on fish population sizes, community composition, and biodiversity.[21]


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Dissolved organic carbon (DOC) fluxes to rivers and lakes are strongly driven by precipitation;[22] thus in many regions where precipitation is expected to increase, DOC loading will also increase. Dissolved organic carbon is the substance that gives many rivers and lakes a brown, tea-colored look. Precipitation-driven increases in DOC concentration not only increase the cost of water treatment for municipal use,[23] but also alter the ability of sunlight to act as nature's water treatment plant. For example, *Cryptosporidium*, a pathogen potentially lethal to the elderly, babies, and people with compromised immune systems, is present in 17% of drinking water supplies sampled in the United States.[24] This pathogen is inactivated by doses of ultraviolet (UV) light equivalent to less than a day of sun exposure.[25] Similarly, UV exposures reduce fungal parasites that infect *Daphnia*, a keystone aquatic grazer and food source for fish.[26] Increasing DOC concentrations may thus reduce the ability of sunlight to regulate these UV-sensitive parasites.

Few studies have projected the impacts of climate change on nitrogen, phosphorus, sediment, or DOC transport from the land to rivers. However, given the tight link between river discharge and all of these potential pollutants, areas of the United States that are projected to see increases in precipitation, and increases in intense rainfalls, like the Northeast, Midwest, and mountainous West,[27] will also see increases in excess nutrients, DOC, and sediments transported to rivers. One of the few future projections available suggests that downstream and coastal impacts of increased nitrogen inputs could be profound for the Mississippi Basin. Under a scenario in which atmospheric CO_2 reaches double pre-industrial levels, a 20% increase in river discharge is expected to lead to higher nitrogen loads and a 50% increase in algae growth in the Gulf of Mexico, a 30% to 60% decrease in deep-water dissolved oxygen concentration, and an expansion of the dead zone.[28] A recent comprehensive assessment[10] shows that, while climate is an important driver, nitrogen carried by rivers to the oceans is most strongly driven by fertilizer inputs to the land. Therefore, in the highly productive agricultural systems of the Mississippi Basin, the ultimate impact of more precipitation on the expansion of the dead zone will depend on agricultural management practices in the Basin.[14,29]

Rising air temperatures can also lead to declines in water quality through a different set of processes. Some large lakes, including the Great Lakes, are warming rapidly.[30] Warmer surface waters can stimulate blooms of harmful algae in both lakes and coastal oceans,[9] which may include toxic cyanobacteria that are favored at higher temperatures.[31] Harmful algal blooms, which are caused by many factors, including climate change, exact a cost in freshwater degradation of approximately $2.2 billion annually in the United States alone.[32]

Water Supplies Projected to Decline

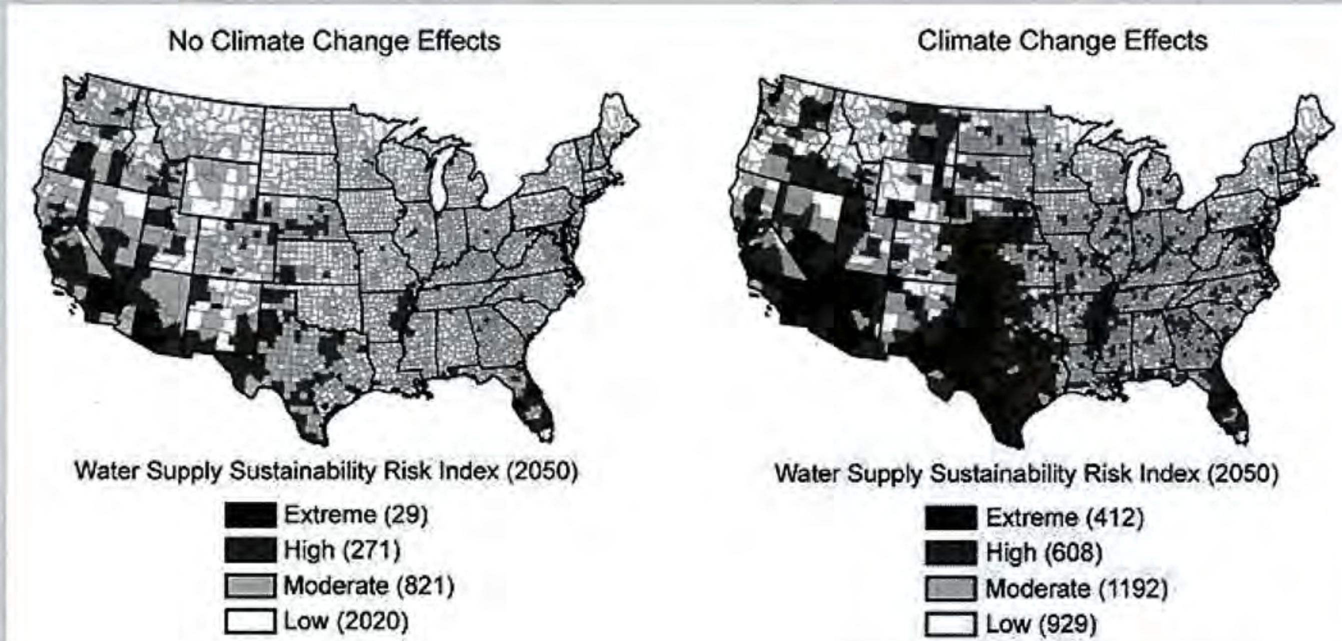

Figure 8.1. Climate change is projected to reduce the ability of ecosystems to supply water in some parts of the country. This is true in areas where precipitation is projected to decline, and even in some areas where precipitation is expected to increase. Compared to 10% of counties today, by 2050, 32% of counties will be at high or extreme risk of water shortages. Projections assume continued increases in greenhouse gas emissions through 2050 and a slow decline thereafter (A1B scenario). Numbers in parentheses indicate number of counties in each category. (Reprinted with permission from Roy et al., 2012.[27] Copyright 2012 American Chemical Society).

The Aftermath of Hurricanes

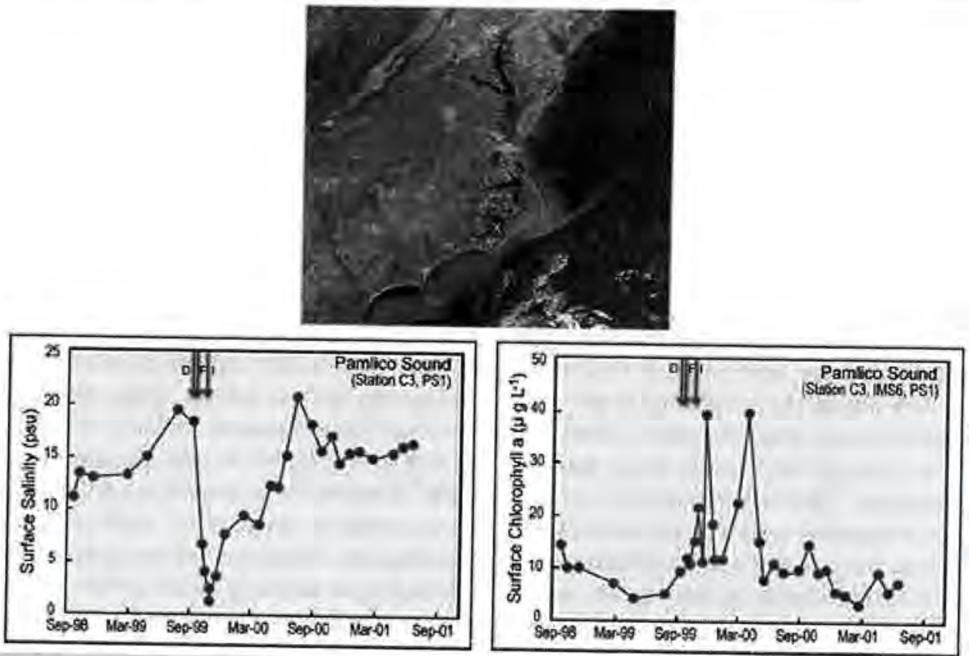

Figure 8.2. Hurricanes illustrate the links among precipitation, discharge and nutrient loading to coastal waters. Hurricanes bring intense rainfall to coastal regions, and ensuing runoff leads to blooms of algae. These blooms contribute to dead zone formation after they die and decompose. Photo above shows Pamlico Sound, North Carolina, after Hurricane Floyd. Note light green area off the coast, which is new algae growth. The graph on the left shows a steep drop in salinity of ocean water due to the large influx of freshwater from rain after a series of hurricanes. Red arrows indicate Hurricanes Dennis, Floyd, and Irene, which hit sequentially during the 1999 hurricane season. The graph on the right shows a steep rise in the amount of surface chlorophyll after these hurricanes, largely due to increased algae growth. (Figure source: (top) NASA SeaWiFS; (bottom) Paerl et al. 2003[33]).

Key Message 2: Extreme Events

Climate change, combined with other stressors, is overwhelming the capacity of ecosystems to buffer the impacts from extreme events like fires, floods, and storms.

Ecosystems play an important role in "buffering" the effects of extreme climate conditions (floods, wildfires, tornadoes, hurricanes) on the movement of materials and the flow of energy through the environment.[34] Climate change and human modifications often increase the vulnerability of ecosystems and landscapes to damage from extreme events while at the same time reducing their natural capacity to modulate the impacts of such events. Salt marshes, reefs, mangrove forests, and barrier islands provide an ecosystem service of defending coastal ecosystems and infrastructure against storm surges.[35] Losses of these natural features – from coastal development, erosion, and sea level rise – render coastal ecosystems and infrastructure more vulnerable to catastrophic damage during or after extreme events (Ch. 25: Coasts).[36] Floodplain wetlands, although greatly reduced from their historical extent, provide an ecosystem service of absorbing floodwaters and reducing the impact of high flows on river-margin lands. In the Northeast, even a small sea level rise (1.6 feet) would dramatically increase the numbers of people (47% increase) and property loss (73% increase) affected by storm surge in Long Island compared to present day storm surge impacts.[37] Extreme weather events that produce sudden increases in water flow and the materials it carries can decrease the natural capacity of ecosystems to process pollutants, both by reducing the amount of time water is in contact with reactive sites and by removing or harming the plants and microbes that remove the pollutants.[36]

Warming and, in some areas, decreased precipitation (along with past forest fire suppression practices) have increased the risk of fires exceeding historical size, resulting in unprecedented social and economic challenges. Large fires put people living in the wildland-urban interface at risk for health problems and property loss. In 2011 alone, more than 8 million acres burned in wildfires, causing 15 deaths and property losses greater than $1.9 billion.[38]

Key Message 3: Plants and Animals

Landscapes and seascapes are changing rapidly, and species, including many iconic species, may disappear from regions where they have been prevalent or become extinct, altering some regions so much that their mix of plant and animal life will become almost unrecognizable.

Vegetation model projections suggest that much of the United States will experience changes in the composition of species characteristic of specific areas. Studies applying different models for a range of future climates project biome changes for about 5% to 20% of the land area of the U.S. by 2100.[4,39] Many major changes, particularly in the western states and Alaska, will in part be driven by increases in fire frequency and severity. For example, the average time between fires in the Yellowstone National Park ecosystem is projected to decrease from 100 to 300 years to less than 30 years, potentially causing coniferous (pine, spruce, etc.) forests to be replaced by woodlands and grasslands.[40] Warming has also led to novel wildfire occurrence in ecosystems where it has been absent in recent history, such as arctic Alaska and the southwestern deserts where new fires are fueled by non-native annual grasses (Ch. 20: Southwest; Ch. 22: Alaska). Extreme weather conditions linked to sea ice decline in 2007 led to the ignition of the Anaktuvuk River Fire, which burned more than 380 square miles of arctic tundra that had not been disturbed by fire for more than 3,000 years.[41] This one fire (which burned deeply into organic peat soils) released enough carbon to the atmosphere to offset all of the carbon taken up by the entire arctic tundra biome over the past quarter-century.[42]

In addition to shifts in species assemblages, there will also be changes in species distributions. In recent decades, in both land and aquatic environments, plants and animals have moved to higher elevations at a median rate of 36 feet (0.011 kilometers) per decade, and to higher latitudes at a median rate of 10.5 miles (16.9 kilometers) per decade.[43] As the climate continues to change, models and long-term studies project even greater shifts in species ranges.[44] However, many species may not be able to keep pace with climate change for several reasons, for example because their seeds do not disperse widely or because they have limited mobility, thus leading, in some places, to local extinctions of both plants and animals. Both range shifts and local extinctions will, in many places, lead to large changes in the mix of plants and animals present in the local ecosystem, resulting in new communities that bear little resemblance to those of today.[4,8,45,46]

Some of the most obvious changes in the landscape are occurring at the boundaries between biomes. These include shifts in the latitude and elevation of the boreal (northern) forest/tundra boundary in Alaska;[47] elevation shifts of the boreal and subalpine forest/tundra boundary in the Sierra Nevada, California;[48] an elevation shift of the temperate broadleaf/conifer boundary in the Green Mountains, Vermont,[49] the shift of temperate the shrubland/conifer forest boundary in Bandelier National Monument, New Mexico,[50] and upslope shifts of the temperate mixed forest/conifer boundary in Southern California.[51] All of these are consistent with recent climatic trends and represent visible changes, like tundra switching to forest, or conifer forest switching to broadleaf forest or even to shrubland.

As temperatures rise and precipitation patterns change, many fish species (such as salmon, trout, whitefish, and char) will be lost from lower-elevation streams, including a projected loss of 47% of habitat for all trout species in the western U.S. by 2080.[8] Similarly, in the oceans, transitions from cold-water fish communities to warm-water communities have occurred in commercially important harvest areas,[52] with new industries developing in response to the arrival of new species.[53] Also, warm surface waters are driving some fish species to deeper waters.[54,55]

Warming is likely to increase the ranges of several invasive plant species in the United States,[56] increase the probability of establishment of invasive plant species in boreal forests in south-central Alaska, including the Kenai Peninsula,[57] and expand the range of the hemlock wooly adelgid, an insect that has killed many eastern hemlocks in recent years.[58] Invasive species costs to the U.S. economy are estimated at $120 billion per year,[59] including substantial impacts on ecosystem services. For instance, the yellow star-thistle, a wildland pest which is predicted to thrive with increased atmospheric CO_2,[60] currently costs California ranchers and farmers $17 million in forage and control efforts[61] and $75 million in water losses.[62] Iconic desert species such as saguaro cactus are damaged or killed by fires fueled by non-native grasses, leading to a large-scale transformation of desert shrubland into grassland in many of the familiar landscapes of the American West.[63] Bark beetles have infested extensive areas of the western United States and Canada, killing stands of temperate and boreal conifer forest across areas greater than any other outbreak in the last 125 years.[64] Climate change has been a major causal factor, with higher temperatures allowing more beetles to survive winter, complete two life cycles in a season rather than one, and to move to higher elevations and latitudes.[64,65] Bark beetle outbreaks in the Greater Yellowstone Ecosystem are occurring in habitats where outbreaks either did not previously occur or were limited in scale.[66]

It is important to realize that climate change is linked to far more dramatic changes than simply altering species' life cycles or shifting their ranges. Several species have exhibited population declines linked to climate change, with some declines so severe that species are threatened with extinction.[67] Perhaps the most striking impact of climate change is its effect on iconic species such as the polar bear, the ringed seal, and coral species (Ch. 22: Alaska; Ch. 24: Oceans). In 2008, the polar bear (*Ursus maritimus*) was listed as a threatened species, with the primary cause of its decline attributed to climate change.[68] In 2012, NOAA determined that four subspecies of the ringed seal (*Phoca hispida*) were threatened or endangered, with the primary threat being climate change.[69]

Key Message 4: Seasonal Patterns

Timing of critical biological events, such as spring bud burst, emergence from overwintering, and the start of migrations, has shifted, leading to important impacts on species and habitats.

The effect of climate change on phenology – the pattern of seasonal life cycle events in plants and animals, such as timing of leaf-out, blooming, hibernation, and migration – has been called a "globally coherent fingerprint of climate change impacts" on plants and animals.[70] Observed long-term trends towards shorter, milder winters and earlier spring thaws are altering the timing of critical spring events such as bud burst and emergence from overwintering. This can cause plants and animals to be so out of phase with their natural phenology that outbreaks of pests occur, or species cannot find food at the time they emerge.

Recent studies have documented an advance in the timing of springtime phenological events across species in response to increased temperatures.[71] Long-term observations of lilac flowering indicate that the onset of spring has advanced one day earlier per decade across the northern hemisphere in response to increased winter and spring temperatures[72] and by 1.5 days per decade earlier in the western United States.[73] Other multi-decadal studies for plant species have documented similar trends for early flowering.[74,75] In addition, plant-pollinator relationships may be disrupted by changes in nectar and pollen availability, as the timing of bloom shifts in response to temperature and precipitation.[76,77]

As spring is advancing and fall is being delayed in response to regional changes in climate,[78] the growing season is lengthening. A longer growing season will benefit some crops and natural species, but there may be a timing mismatch between the microbial activity that makes nutrients available in the soil and the readiness of plants to take up those nutrients for growth.[78,79] Where plant phenology is driven by day length, an advance in spring may exacerbate this mismatch, causing available nutrients to be leached out of the soil rather than absorbed and recycled by plants.[80] Longer growing seasons also exacerbate human allergies. For example, a longer fall allows for bigger ragweed plants that produce more pollen later into the fall (see also Ch. 9: Health).[81]

Changes in the timing of springtime bird migrations are well-recognized biological responses to warming, and have been documented in the western,[82] midwestern,[83] and eastern United States.[84,85] Some migratory birds now arrive too late for the peak of food resources at breeding grounds because temperatures at wintering grounds are changing more slowly than at spring breeding grounds.[86]

In a 34-year study of an Alaskan creek, young pink salmon (*Oncorhynchus gorbuscha*) migrated to the sea increasingly earlier over time.[87] In Alaska, warmer springs have caused earlier onset of plant emergence, and decreased spatial variation in growth and availability of forage to breeding caribou (*Rangifer tarandus*).

Key Message 5: Adaptation

Whole system management is often more effective than focusing on one species at a time, and can help reduce the harm to wildlife, natural assets, and human well-being that climate disruption might cause.

Adaptation in the context of biodiversity and natural resource management is fundamentally about managing change, which is an inherent property of natural ecosystems.[4,88,89] One strategy – adaptive management, which is a structured process of flexible decision-making under uncertainty that incorporates learning from management outcomes – has received renewed attention as a tool for helping resource managers make decisions relevant to whole systems in response to climate change.[89,90] Other strategies tinclude assessments of vulnerability and impacts,[91] and scenario planning,[92] that can be assembled into a general planning process that is flexible and iterative.

Guidance on adaptation planning for conservation has proliferated at the federal[92,93,94] and state levels,[95] and often emphasizes cooperation between scientists and managers.[94,96,97] Ecosystem-based adaptation[98,99] uses "biodiversity and ecosystem services as part of an overall adaptation strategy to help people adapt to the adverse effects of climate change."[99] An example is the explicit use of storm-buffering coastal wetlands or mangroves rather than built infrastructure like seawalls or levies to protect coastal regions (Ch. 25: Coasts).[100] An additional example is the use of wildlife corridors to connect fragmented wildlife habitat.[101]

Adaptation strategies to protect biodiversity include: 1) habitat manipulation, 2) conserving populations with higher genetic diversity or more flexible behaviors or morphologies, 3) re-planting with species or ecotypes that are better suited for future climates, 4) managed relocation (sometimes referred to as assisted migration) to help move species and populations from current locations to those areas expected to become more suitable in the future, and 5) offsite conservation such as seed banking, biobanking, and captive breeding.[92,94,96,97,102,103] Additional approaches focus on identifying and protecting features that are important for biodiversity and are less likely to be altered by climate change. The idea is to conserve the "stage" (the biophysical conditions that contribute to high levels of biodiversity) for whatever "actors" (species and populations) find those areas suitable in the future.[104]

One of the greatest challenges for adaptation in the face of climate change is the revision of management goals in fundamental ways. In particular, not only will climate change make it difficult to achieve existing conservation goals, it will demand that goals be critically examined and potentially altered in dramatic ways.[102,105] Climate changes can also severely diminish the effectiveness of current strategies and require fresh approaches. For example, whereas establishing networks of nature reserves has been a standard approach to protecting species, fixed networks of reserve do not lend themselves to adjustments for climate change.[105] Finally, migratory species and species with complex life histories cannot be simply addressed by defining preferred habitat and making vulnerability assessments. Often it could be specific life history stages that are the weak point in the species, and it is key to identify those weak links.[106]

While there is considerable uncertainty about how climate change will play out in particular locations, proactive measures can be taken to both plan for connectivity[96,107] and to identify places or habitats that may in the future become valuable habitat as a result of climate change and vegetation shifts.[108] It is important to note that when the Endangered Species Act (ESA) was passed in 1973, climate change was not a known threat or factor and was not considered in setting recovery goals or critical habitat designations.[109] However, agencies are actively working to include climate change considerations in their ESA implementation activities.

Adaptation Planning and Implementation Framework

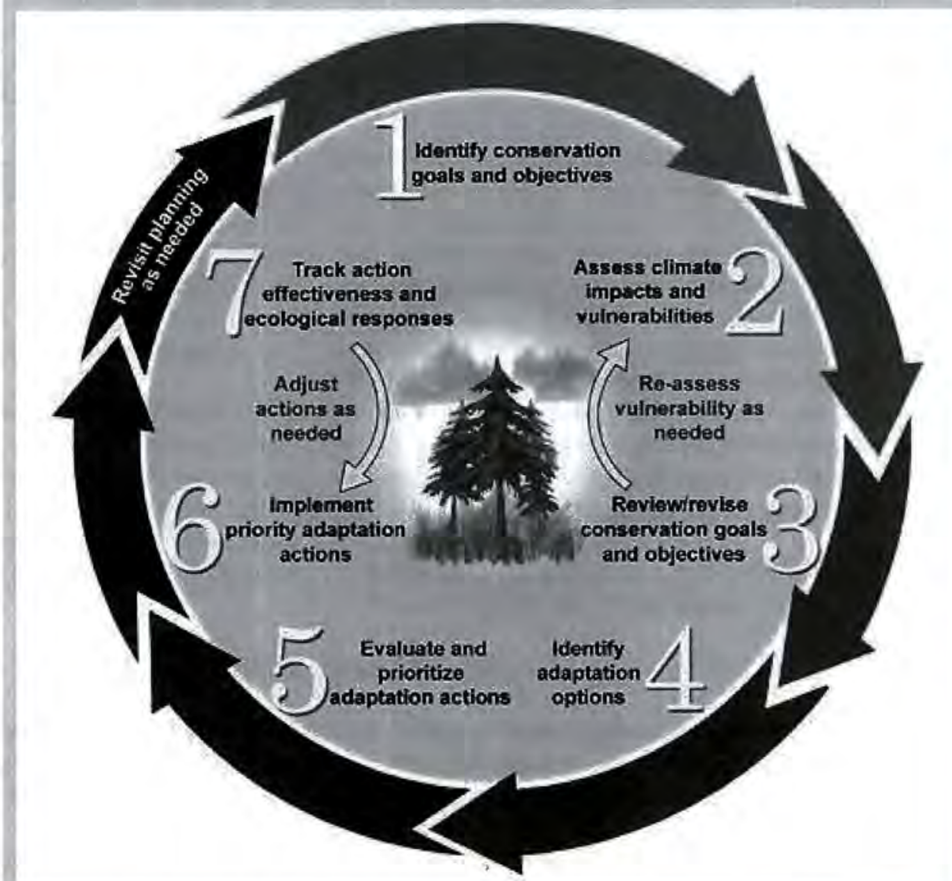

Figure 8.3. Iterative approaches to conservation planning require input and communication among many players to ensure flexibility in response to climate change. (Figure source: adapted from the National Wildlife Federation, 2013[142]).

Case Study of the 2011 Las Conchas, New Mexico Fire

In the midst of severe drought in the summer of 2011, Arizona and New Mexico suffered the largest wildfires in their recorded history, affecting more than 694,000 acres. Some rare threatened and endangered species, like the Jemez salamander, were damaged by this unusually severe fire.[110] Fires are often part of the natural disturbance regime, but if drought, poor management, and high temperatures combine, a fire can be so severe and widespread that species are damaged that otherwise might even be considered to be fire tolerant (such as spotted owls). Following the fires, heavy rainstorms led to major flooding and erosion, including at least ten debris flows. Popular recreation areas were evacuated and floods damaged the newly renovated, multi-million dollar U.S. Park Service Visitor Center at Bandelier National Monument. Sediment and ash eroded by the floods were washed downstream into the Rio Grande, which supplies 50% of the drinking water for Albuquerque, the largest city in New Mexico. Water withdrawals by the city from the Rio Grande were stopped entirely for a week and reduced for several months due to the increased cost of treatment.

These fires provide an example of how forest ecosystems, biodiversity, and ecosystem services are affected by the impacts of climate change, other environmental stresses, and past management practices. Higher temperatures, reduced snowpack, and earlier onset of springtime are leading to increases in wildfire in the western United States,[111] while extreme droughts are becoming more frequent.[112] In addition, climate change is affecting naturally occurring bark beetles: warmer winter conditions allow these pests to breed more frequently and successfully.[113,114] The dead trees left behind by bark beetles may make crown fires more likely, at least until needles fall from killed trees.[114,115] Forest management practices also have made the forests more vulnerable to catastrophic fires. In New Mexico, even-aged, second-growth forests were hit hardest because they are much denser than naturally occurring forest and consequently consume more water from the soil and increase the availability of dry above-ground fuel.

Biological Responses to Climate Change

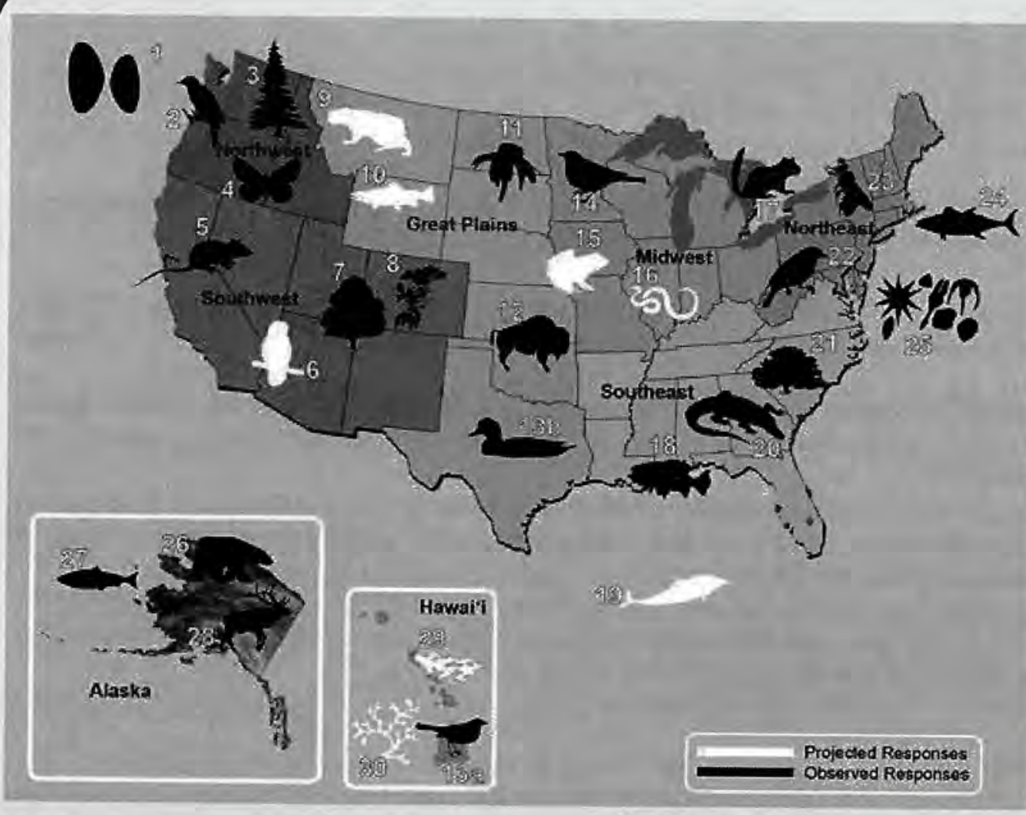

Figure 8.4. Map of selected observed and projected biological responses to climate change across the United States. Case studies listed below correspond to observed responses (black icons on map) and projected responses (white icons on map, bold italicized statements). In general, because future climatic changes are projected to exceed those experienced in the recent past, projected biological impacts tend to be of greater magnitude than recent observed changes. Because the observations and projections presented here are not paired (that is, they are not for the same species or systems), that general difference is not illustrated. (Figure source: Staudinger et al., 2012[4]).

Continued

Biological responses to climate change (continued)

1. Mussel and barnacle beds have declined or disappeared along parts of the Northwest coast due to higher temperatures and drier conditions that have compressed habitable intertidal space.[116]
2. Northern flickers arrived at breeding sites earlier in the Northwest in response to temperature changes along migration routes, and egg laying advanced by 1.15 days for every degree increase in temperature, demonstrating that this species has the capacity to adjust their phenology in response to climate change.[117]
3. Conifers in many western forests have experienced mortality rates of up to 87% from warming-induced changes in the prevalence of pests and pathogens and stress from drought.[118]
4. Butterflies that have adapted to specific oak species have not been able to colonize new tree species when climate change-induced tree migration changes local forest types, potentially hindering adaptation.[119]
5. In response to climate-related habitat change, many small mammal species have altered their elevation ranges, with lower-elevation species expanding their ranges and higher-elevation species contracting their ranges.[120]
6. ***Northern spotted owl populations in Arizona and New Mexico are projected to decline during the next century and are at high risk for extinction due to hotter, drier conditions, while the southern California population is not projected to be sensitive to future climatic changes.***[121]
7. Quaking aspen-dominated systems are experiencing declines in the western U.S. after stress due to climate-induced drought conditions during the last decade.[122]
8. Warmer and drier conditions during the early growing season in high-elevation habitats in Colorado are disrupting the timing of various flowering patterns, with potential impacts on many important plant-pollinator relationships.[77]
9. ***Population fragmentation of wolverines in the northern Cascades and Rocky Mountains is expected to increase as spring snow cover retreats over the coming century.***[123]
10. ***Cutthroat trout populations in the western U.S. are projected to decline by up to 58%, and total trout habitat in the same region is projected to decline by 47%, due to increasing temperatures, seasonal shifts in precipitation, and negative interactions with non-native species.***[8]
11. Comparisons of historical and recent first flowering dates for 178 plant species from North Dakota showed significant shifts occurred in over 40% of species examined, with the greatest changes observed during the two warmest years of the study.[75]
12. Variation in the timing and magnitude of precipitation due to climate change was found to decrease the nutritional quality of grasses, and consequently reduce weight gain of bison in the Konza Prairie in Kansas and the Tallgrass Prairie Preserve in Oklahoma.[124] Results provide insight into how climate change will affect grazer population dynamics in the future.
13. (a and b) Climatic fluctuations were found to influence mate selection and increase the probability of infidelity in birds that are normally socially monogamous, increasing the gene exchange and the likelihood of offspring survival.[125]
14. Migratory birds monitored in Minnesota over a 40-year period showed significantly earlier arrival dates, particularly in short-distance migrants, indicating that some species are capable of responding to increasing winter temperatures better than others.[126]
15. ***Up to 50% turnover in amphibian species is projected in the eastern U.S. by 2100, including the northern leopard frog, which is projected to experience poleward and elevational range shifts in response to climatic changes in the latter quarter of the century.***[127]
16. ***Studies of black ratsnake (Elaphe obsoleta) populations at different latitudes in Canada, Illinois, and Texas suggest that snake populations, particularly in the northern part of their range, could benefit from rising temperatures if there are no negative impacts on their habitat and prey.***[128]
17. Warming-induced hybridization was detected between southern and northern flying squirrels in the Great Lakes region of Ontario, Canada, and in Pennsylvania after a series of warm winters created more overlap in their habitat range, potentially acting to increase population persistence under climate change.[129]

Continued

Biological responses to climate change (continued)

18. Some warm-water fishes have moved northwards, and some tropical and subtropical fishes in the northern Gulf of Mexico have increased in temperate ocean habitat.[130] Similar shifts and invasions have been documented in Long Island Sound and Narragansett Bay in the Atlantic.[131]
19. ***Global marine mammal diversity is projected to decline at lower latitudes and increase at higher latitudes due to changes in temperatures and sea ice, with complete loss of optimal habitat for as many as 11 species by mid-century; seal populations living in tropical and temperate waters are particularly at risk to future declines.***[132]
20. Higher nighttime temperatures and cumulative seasonal rainfalls were correlated with changes in the arrival times of amphibians to wetland breeding sites in South Carolina over a 30-year time period (1978-2008).[133]
21. Seedling survival of nearly 20 resident and migrant tree species decreased during years of lower rainfall in the Southern Appalachians and the Piedmont areas, indicating that reductions in native species and limited replacement by invading species were likely under climate change.[134]
22. Widespread declines in body size of resident and migrant birds at a bird-banding station in western Pennsylvania were documented over a 40-year period; body sizes of breeding adults were negatively correlated with mean regional temperatures from the preceding year.[85]
23. Over the last 130 years (1880-2010), native bees have advanced their spring arrival in the northeastern U.S. by an average of 10 days, primarily due to increased warming. Plants have also showed a trend of earlier blooming, thus helping preserve the synchrony in timing between plants and pollinators.[135]
24. In the Northwest Atlantic, 24 out of 36 commercially exploited fish stocks showed significant range (latitudinal and depth) shifts between 1968 and 2007 in response to increased sea surface and bottom temperatures.[55]
25. Increases in maximum, and decreases in the annual variability of, sea surface temperatures in the North Atlantic Ocean have promoted growth of small phytoplankton and led to a reorganization in the species composition of primary (phytoplankton) and secondary (zooplankton) producers.[136]
26. Changes in female polar bear reproductive success (decreased litter mass and numbers of yearlings) along the north Alaska coast have been linked to changes in body size and/or body condition following years with lower availability of optimal sea ice habitat.[137]
27. Water temperature data and observations of migration behaviors over a 34-year time period showed that adult pink salmon migrated earlier into Alaskan creeks, and fry advanced the timing of migration out to sea. Shifts in migration timing may increase the potential for a mismatch in optimal environmental conditions for early life stages, and continued warming trends will likely increase pre-spawning mortality and egg mortality rates.[87]
28. Warmer springs in Alaska have caused earlier onset of plant emergence, and decreased spatial variation in growth and availability of forage to breeding caribou. This ultimately reduced calving success in caribou populations.[138]
29. ***Many Hawaiian mountain vegetation types were found to vary in their sensitivity to changes in moisture availability; consequently, climate change will likely influence elevation-related vegetation patterns in this region.***[139]
30. ***Sea level is predicted to rise by 1.6 to 3.3 feet in Hawaiian waters by 2100, consistent with global projections of 1 to 4 feet of sea level rise (see Ch. 2: Our Changing Climate, Key Message 10). This is projected to increase wave heights, the duration of turbidity, and the amount of re-suspended sediment in the water; consequently, this will create potentially stressful conditions for coral reef communities.***[140]

8: ECOSYSTEMS, BIODIVERSITY, AND ECOSYSTEM SERVICES

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SUPPLEMENTAL MATERIAL

TRACEABLE ACCOUNTS

Process for Developing Key Messages

The key messages and supporting chapter text summarize extensive evidence documented in the Ecosystems Technical Input Report, *Impacts of Climate Change on Biodiversity, Ecosystems, and Ecosystem Services: Technical Input to the 2013 National Climate Assessment.*[4] This foundational report evolved from a technical workshop held at the Gordon and Betty Moore Foundation in Palo Alto, CA, in January 2012 and attended by approximately 65 scientists. Technical inputs (127) on a wide range of topics related to ecosystems were also received and reviewed as part of the Federal Register Notice solicitation for public input.

Key message #1 Traceable Account

Climate change impacts on ecosystems reduce their ability to improve water quality and regulate water flows.

Description of evidence base

The author team digested the contents of more than 125 technical input reports on a wide array of topics to arrive at this key message. The foundational Technical Input Report[4] was the primary source used.

Studies have shown that increasing precipitation is already resulting in declining water quality in many regions of the country, particularly by increasing nitrogen loading.[10,11,12,13,14] This is because the increases in flow can pick up and carry greater loads of nutrients like nitrogen to rivers.[11,12,13,14]

One model for the Mississippi River Basin, based on a doubling of CO_2, projects that increasing discharge and nitrogen loading will lead to larger algal blooms in the Gulf of Mexico and a larger dead zone.[28] The Gulf of Mexico is the recipient system for the Mississippi Basin, receiving all of the nitrogen that is carried downriver but not removed by river processes, wetlands, or other ecosystems.

Several models project that declining streamflow, due to the combined effects of climate change and water withdrawals, will cause local extinctions of fish and other aquatic organisms,[7] particularly trout in the interior western U.S. (composite of 10 models, A1B scenario).[8] The trout study[8] is one of the few studies of impacts on fish that uses an emissions scenario and a combination of climate models. The researchers studied four different trout species. Although there were variations among species, their overall conclusion was robust across species for the composite model.

Water quality can also be negatively affected by increasing temperatures. There is widespread evidence that warmer lakes can promote the growth of harmful algal blooms, which produce toxins.[31]

New information and remaining uncertainties

Recent research has improved understanding of the relative importance of the effects of climate and human actions (for example, fertilization) on nitrogen losses from watersheds,[10,12] and how the interactions between climate and human actions (for example, water withdrawals) will affect fish populations in the west.[7,8] However, few studies have projected the impacts of future climate change on water quality. Given the tight link between river discharge and pollutants, only areas of the U.S. that are projected to see increases in precipitation will see increases in pollutant transport to rivers. It is also important to note that pollutant loading – for example, nitrogen fertilizer use – is often more important as a driver of water pollution than climate.[10,12]

Assessment of confidence based on evidence

Given the evidence base and uncertainties, there is **high** confidence that climate change impacts on ecosystems reduce their ability to improve water quality and regulate water flows.

It is well established that precipitation and associated river discharge are major drivers of water pollution in the form of excess nutrients, sediment, and dissolved organic carbon (DOC) transport into rivers. Increases in precipitation in many regions of the country are therefore contributing to declines in water quality in those areas. However, those areas of the country that will see reduced precipitation may experience water-quality improvement; thus, any lack of agreement on future water-quality impacts of climate change may be due to locational differences.

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

Climate change, combined with other stressors, is overwhelming the capacity of ecosystems to buffer the impacts from extreme events like fires, floods, and storms.

Description of evidence base

The author team digested the contents of more than 125 technical input reports on a wide array of topics to arrive at this key message. The foundational Technical Input Report[4] was the primary source used.

Fires: Climate change has increased the potential for extremely large fires with novel social, economic, and environmental impacts. In 2011, more than 8 million acres burned, with significant human mortality and property damage ($1.9 billion).[38] Warming and decreased precipitation have made fire-prone ecosystems more vulnerable to "mega-fires" – large fires that are unprecedented in their social, economic, and environmental impacts. Large fires put people living in the urban-wildland interface at risk for health problems and property loss.

Floods: Natural ecosystems such as salt marshes, reefs, mangrove forests, and barrier islands defend coastal ecosystems and infrastructure against flooding due to storm surges. The loss of these natural features due to coastal development, erosion, and sea level rise render coastal ecosystems and infrastructure more vulnerable to catastrophic damage during or after extreme events (see Ch. 25: Coasts).[36] Floodplain wetlands, which are also vulnerable to loss by inundation, absorb floodwaters and reduce the impact of high flows on river-margin lands. In the Northeast, a sea level rise of 1.6 feet (within the range of 1 to 4 feet projected for 2100; Ch. 2: Our Changing Climate, Key Message 9) will dramatically increase impacts of storm surge on people (47% increase) and property loss (73% increase) in Long Island.[37]

Storms: Natural ecosystems have a capacity to buffer extreme weather events that produce sudden increases in water flow and materials. These events reduce the amount of time water is in contact with sites that support the plants and microbes that remove pollutants (Chapter 25: Coasts).[36]

New information and remaining uncertainties

A new analytical framework was recently developed to generate insights into the interactions among the initial state of ecosystems, the type and magnitude of disturbance, and effects of disturbance.[34] Progress in understanding these relationships is critical for predicting how human activities and climate change, including extreme events like droughts, floods, and storms, will interact to affect ecosystems.

Uncertainties: The ability of ecosystems to buffer extreme events is extremely difficult to assess and quantify, as it requires understanding of complex ecosystem responses to very rare events. However, it is clear that the loss of this buffering ecosystem service is having important effects on coastal and fire-prone ecosystems across the United States.

Assessment of confidence based on evidence

Given the evidence base and uncertainties, there is **high** confidence that climate change, combined with other stressors, is overwhelming the capacity of ecosystems to buffer the impacts from extreme events like droughts, floods, and storms.

Ecosystem responses to climate change will vary regionally. For example, whether salt marshes and mangroves will be able to accrue sediment at rates sufficient to keep ahead of sea level rise and maintain their protective function will vary by region.

Climate has been the dominant factor controlling burned area during the 20th century, even during periods of fire suppression by forest management,[40,111] and the area burned annually has increased steadily over the last 20 years concurrent with warming and/or drying climate. Warming and decreased precipitation have also made fire-prone ecosystems more vulnerable to "mega-fires" – large fires that are unprecedented in their social, economic, and environmental impacts. Large fires put people living in the urban-wildland interface at risk for health problems and property loss. In 2011 alone, 8.3 million acres burned in wildfires, causing 15 deaths and property losses greater than $1.9 billion.[38]

Key message #3 Traceable Account

Landscapes and seascapes are changing rapidly, and species, including many iconic species, may disappear from regions where they have been prevalent or become extinct, altering some regions so much that their mix of plant and animal life will become almost unrecognizable.

Description of evidence base

The analysis for the Technical Input Report applied a range of future climate scenarios and projected biome changes across 5% to about 20% of the land area in the U.S. by 2100.[4] Other analyses support these projections.[39] Studies predict that wildfire will be a major driver of change in some areas, including Yellowstone National Park[40] and the Arctic.[41] These biome shifts will be associated with changes in species distributions.[43]

Evidence indicates that the most obvious changes will occur at the boundaries between ecosystems.[47,48,49,51] Plants and animals are already moving to higher elevations and latitudes in response to climate change,[43] with models projecting greater range shifts[8,46] and local extinctions in the future, leading to new plant and animal communities that may be unrecognizable in some regions.[4,45,46] One study on fish[8] used global climate models (GCMs) simulating conditions in the 2040s and 2080s under the A1B emissions scenario, with the choice of models reflecting predictions of high and low climate warming as well as an ensemble of ten models. Their models additionally accounted for biotic interactions. In a second study, a 30-year baseline (1971-2000) and output from two GCMs under the A2 scenario (continued increases in global emissions) were used to develop climate variables that effectively predict present and future species ranges.[46] Empirical data from the Sonoran Desert (n=39 plots) were used to evaluate species responses to past climate variability.

Iconic species: Wildfire is expected to damage and kill iconic desert species, including saguaro cactus.[63] Bark beetle outbreaks, which have been exacerbated by climate change, are damaging extensive areas of temperate and boreal conifer forests that are characteristic of the western United States.[64]

New information and remaining uncertainties

In addition to the Technical Input Report, more than 20 new studies of observed and predicted effects of climate change on biomes and species distribution were incorporated in the assessment.

While changes in ecosystem structure and biodiversity, including the distribution of iconic species, are occurring and are highly likely to continue, the impact of these changes on ecosystem services is unclear, that is, there is uncertainty about the impact that loss of familiar landscapes will have on people.

Assessment of confidence based on evidence

Based on the evidence base and uncertainties, confidence is **high** that familiar landscapes are changing so rapidly that iconic species may disappear from regions where they have been prevalent, altering some regions so much that their mix of plant and animal life will become almost unrecognizable. Many changes in species distribution have already occurred and will inevitably continue, resulting in the loss of familiar landscapes and the production of novel species assemblages.

Key message #4 Traceable Account

Timing of critical biological events, such as spring bud burst, emergence from overwintering, and the start of migrations, has shifted, leading to important impacts on species and habitats.

Description of evidence base

The key message and supporting text summarizes extensive evidence documented in the Ecosystems Technical Input, *Phenology as a bio-indicator of climate change impacts on people and ecosystems: Towards an integrated national assessment approach.*[71] An additional 127 input reports, on a wide range of topics related to ecosystems, were also received and reviewed as part of the Federal Register Notice solicitation for public input.

Many studies have documented an advance in springtime phenological events of species in response to climate warming. For example, long-term observations of lilac flowering indicate that the onset of spring has advanced one day earlier per decade across the northern hemisphere in response to increased winter and spring temperatures, and by 1.5 days per decade earlier in the western United States.[72,73] Other multi-decadal studies for plant species have documented similar trends for early flowering.[74,75] Evidence suggests that insect emergence from overwintering may become out of sync with pollen sources,[77] and that the beginning of bird and fish migrations are shifting.[82,83,84,85,86,87]

New information and remaining uncertainties

In addition to the Ecosystems Technical Input[71] many new studies have been conducted since the previous National Climate Assessment,[141] contributing to our understanding of the impacts of climate change on phenological events. Many studies, in many areas, have shown significant changes in phenology, including spring bud burst, emergence from overwintering, and migration shifts.

A key uncertainty is "phase effects" where organisms are so out of phase with their natural phenology that outbreaks of pests occur, species emerge and cannot find food, or pollination is disrupted. This will vary with specific species and is therefore very difficult to predict.[70]

Assessment of confidence based on evidence

Given the evidence base and uncertainties, there is very high confidence that the timing of critical events, such as spring bud burst, emergence from overwintering, and the start of migrations, has shifted, leading to important impacts on species and habitats.

Key message #5 Traceable Account

Whole system management is often more effective than focusing on one species at a time, and can help reduce the harm to wildlife, natural assets, and human well-being that climate disruption might cause.

Description of evidence base

Adaptation planning for conservation at federal[92,93,94] and state levels,[95] is focused on cooperation between scientists and managers.[34,94,96,97] Development of ecosystem-based whole system management[98] utilizes concepts about "biodiversity and ecosystem services to help people adapt to climate change."[99] An example is the use of coastal wetlands or mangroves rather than built infrastructure like seawalls or levees to protect coastal regions from storms (Chapter 25: Coasts).[100]

New information and remaining uncertainties

Adaptation strategies to protect biodiversity include: 1) habitat manipulations, 2) conserving populations with higher genetic diversity or more plastic behaviors or morphologies, 3) changing seed sources for re-planting to introduce species or ecotypes that are better suited for future climates, 4) managed relocation (sometimes referred to as assisted migration) to help move species and populations from current locations to those areas expected to become more suitable in the future, and 5) ex-situ conservation such as seed banking and captive breeding.[92,94,96,97,102] Alternative approaches focus on identifying and protecting features that are important for biodiversity and are projected to be less altered by climate change. The idea is to conserve the physical conditions that contribute to high levels of biodiversity so that species and populations can find suitable areas in the future.[104]

Assessment of confidence based on evidence

Given the evidence and remaining uncertainties, there is **very high** confidence that ecosystem-based management approaches are increasingly prevalent, and provide options for reducing the harm to biodiversity, ecosystems, and the services they provide to society. The effectiveness of these actions is much less certain, however.

Climate Change Impacts in the United States

CHAPTER 9
HUMAN HEALTH

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

9 HUMAN HEALTH

Key Messages

1. **Climate change threatens human health and well-being in many ways, including impacts from increased extreme weather events, wildfire, decreased air quality, threats to mental health, and illnesses transmitted by food, water, and disease-carriers such as mosquitoes and ticks. Some of these health impacts are already underway in the United States.**
2. **Climate change will, absent other changes, amplify some of the existing health threats the nation now faces. Certain people and communities are especially vulnerable, including children, the elderly, the sick, the poor, and some communities of color.**
3. **Public health actions, especially preparedness and prevention, can do much to protect people from some of the impacts of climate change. Early action provides the largest health benefits. As threats increase, our ability to adapt to future changes may be limited.**
4. **Responding to climate change provides opportunities to improve human health and well-being across many sectors, including energy, agriculture, and transportation. Many of these strategies offer a variety of benefits, protecting people while combating climate change and providing other societal benefits.**

Climate change, together with other natural and human-made health stressors, influences human health and disease in numerous ways. Some existing health threats will intensify and new health threats will emerge. Not everyone is equally at risk. Important considerations include age, economic resources, and location. Preventive and adaptive actions, such as setting up extreme weather early warning systems and improving water infrastructure, can reduce the severity of these impacts, but there are limits to the effectiveness of such actions in the face of some projected climate change threats.

Climate change presents a global public health problem, with serious health impacts predicted to manifest in varying ways in different parts of the world. Public health in the U.S. can be affected by disruptions of physical, biological, and ecological systems, including disturbances originating in the U.S. and elsewhere. Health effects of these disruptions include increased respiratory and cardiovascular disease, injuries and premature deaths related to extreme weather events, changes in the prevalence and geographical distribution of food- and waterborne illnesses and other infectious diseases, and threats to mental health.

Key weather and climate drivers of health impacts include increasingly frequent, intense, and longer-lasting extreme heat, which worsens drought, wildfire, and air pollution risks; increasingly frequent extreme precipitation, intense storms, and changes in precipitation patterns that lead to drought and ecosystem changes (Ch. 2: Our Changing Climate); and rising sea levels that intensify coastal flooding and storm surge (Ch. 25: Coasts). Key drivers of vulnerability include the attributes of certain groups (age, socioeconomic status, race, current level of health – see Ch. 12: Indigenous Peoples for examples of health impacts on vulnerable populations) and of place (floodplains, coastal zones, and urban areas), as well as the resilience of critical public health infrastructure. Multi-stressor situations, such as impacts on vulnerable populations following natural disasters that also damage the social and physical infrastructure necessary for resilience and emergency response, are particularly important to consider when preparing for the impacts of climate change on human health.

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Key Message 1: Wide-ranging Health Impacts

Climate change threatens human health and well-being in many ways, including impacts from increased extreme weather events, wildfire, decreased air quality, threats to mental health, and illnesses transmitted by food, water, and disease-carriers such as mosquitoes and ticks. Some of these health impacts are already underway in the United States.

Air Pollution

Climate change is projected to harm human health by increasing ground-level ozone and/or particulate matter air pollution in some locations. Ground-level ozone (a key component of smog) is associated with many health problems, such as diminished lung function, increased hospital admissions and emergency room visits for asthma, and increases in premature deaths.[1,2,3] Factors that affect ozone formation include heat, concentrations of precursor chemicals, and methane emissions, while particulate matter concentrations are affected by wildfire emissions and air stagnation episodes, among other factors.[4,5] By increasing these different factors, climate change is projected to lead to increased concentration of ozone and particulate matter in some regions.[6,7,8,9] Increases in global temperatures could cause associated increases in premature deaths related to worsened ozone and particle pollution. Estimates made assuming no change in regulatory controls or population characteristics have ranged from 1,000 to 4,300 additional premature deaths nationally per year by 2050 from combined ozone and particle health effects.[10,11] There is less certainty in the responses of airborne particles to climate change than there is about the response of ozone. Health-related costs of the current effects of ozone air pollution exceeding national standards have been estimated at $6.5 billion (in 2008 U.S. dollars) nationwide, based on a U.S. assessment of health impacts from ozone levels during 2000 to 2002.[12,13]

Climate Change Projected to Worsen Asthma

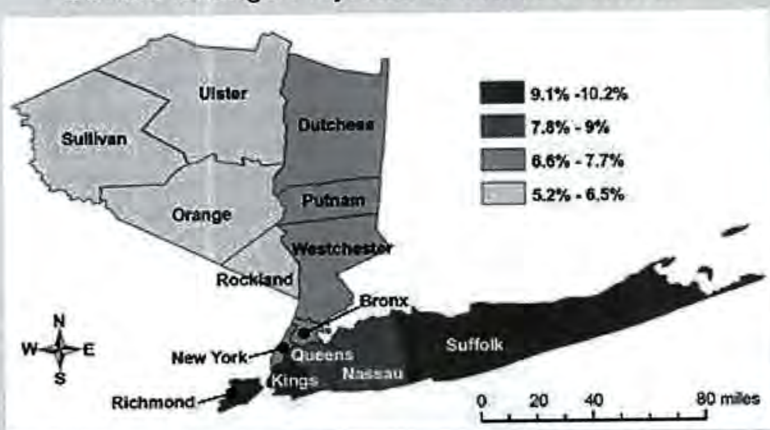

Figure 9.1. Projected increases in temperature, changes in wind patterns, and ecosystem changes will all affect future ground-level ozone concentrations. Climate projections using an increasing emissions scenario (A2) suggest that ozone concentrations in the New York metropolitan region will increase because of future climate change. This figure shows the estimated increase in ozone-related emergency room visits for children in New York in the 2020s (compared to the mid-1990s) resulting from climate change related increases in ozone concentrations. The results from this modeling exercise are shown as a percent change in visits specifically attributed to ozone exposure. For example, the 10.2% increase in Suffolk County represents five additional emergency room visits that could be attributed to increased ozone exposure over the baseline of 46 ozone-related visits from the mid-1990s. In 2010, an estimated 25.7 million Americans had asthma, which has become a problem in every state. (Figure source: Sheffield et al. 2011[14]).

Allergens

Climate change, resulting in more frost-free days and warmer seasonal air temperatures, can contribute to shifts in flowering time and pollen initiation from allergenic plant species, and increased CO_2 by itself can elevate production of plant-based allergens.[14,15,16,17,18,19] Higher pollen concentrations and longer pollen seasons can increase allergic sensitizations and asthma episodes,[20,21,22] and diminish productive work and school days.[19,22,23] Simultaneous exposure to toxic air pollutants can worsen allergic responses.[24,25,26] Extreme rainfall and rising temperatures can also foster indoor air quality problems, including the growth of indoor fungi and molds, with increases in respiratory and asthma-related conditions.[27] Asthma prevalence (the percentage of people who have ever been diagnosed with asthma and still have asthma) increased nationwide from 7.3% in 2001 to 8.4% in 2010. Asthma visits in primary care settings, emergency room visits, and hospitalizations were all stable from 2001 to 2009, and asthma death rates per 1,000 persons with asthma declined from 2001 to 2009.[28] To the extent that increased pollen exposures occur, patients and their physicians will face increased challenges in maintaining adequate asthma control.

Ragweed Pollen Season Lengthens

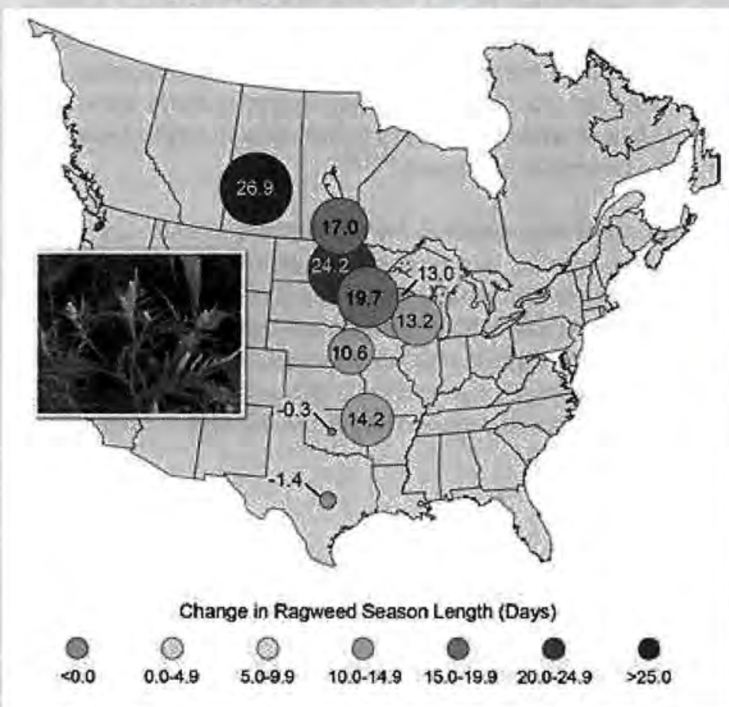

Figure 9.2. Ragweed pollen season length has increased in central North America between 1995 and 2011 by as much as 11 to 27 days in parts of the U.S. and Canada in response to rising temperatures. Increases in the length of this allergenic pollen season are correlated with increases in the number of days before the first frost. As shown in the figure, the largest increases have been observed in northern cities. (Data updated from Ziska et al. 2011[19]; Photo credit: Lewis Ziska, USDA).

Wildfires

Climate change is currently increasing the vulnerability of many forests to wildfire. Climate change is projected to increase the frequency of wildfire in certain regions of the United States (Ch. 7: Forests).[17,29] Long periods of record high temperatures are associated with droughts that contribute to dry conditions and drive wildfires in some areas.[30] Wildfire smoke contains particulate matter, carbon monoxide, nitrogen oxides, and various volatile organic compounds (which are ozone precursors)[31] and can significantly reduce air quality, both locally and in areas downwind of fires.[32,33] Smoke exposure increases respiratory and cardiovascular hospitalizations, emergency department visits, and medication dispensations for asthma, bronchitis, chest pain, chronic obstructive pulmonary disease (commonly known by its acronym, COPD), respiratory infections, and medical visits for lung illnesses.[32,34,35] It has been associated with hundreds of thousands of deaths annually, in an assessment of the global health risks from landscape fire smoke.[32,34,36,37] Future climate change is projected to increase wildfire risks and associated emissions, with harmful impacts on health.[17,38,39,40]

Wildfire Smoke has Widespread Health Effects

Figure 9.3. Wildfires, which are projected to increase in some regions due to climate change, have health impacts that can extend hundreds of miles. Shown here, forest fires in Quebec, Canada, during July 2002 (red circles) resulted in up to a 30-fold increase in airborne fine particle concentrations in Baltimore, Maryland, a city nearly a thousand miles downwind. These fine particles, which are extremely harmful to human health, not only affect outdoor air quality, but also penetrate indoors, increasing the long-distance effects of fires on health.[41] An average of 6.4 million acres burned in U.S. wildfires each year between 2000 and 2010, with 9.5 and 9.1 million acres burned in 2006 and 2012, respectively.[42] Total global deaths from the effects of landscape fire smoke have been estimated at 260,000 to 600,000 annually between the years 1997 and 2006.[37] (Figure source: Moderate Resolution Imaging Spectroradiometer (MODIS) instrument on the Terra satellite, Land Rapid Response Team, NASA/GSFC).

Temperature Extremes

Extreme heat events have long threatened public health in the United States.[43,44,45] Many cities, including St. Louis, Philadelphia, Chicago, and Cincinnati, have suffered dramatic increases in death rates during heat waves. Deaths result from heat stroke and related conditions,[44,45,46] but also from cardiovascular disease, respiratory disease, and cerebrovascular disease.[47,48] Heat waves are also associated with increased hospital admissions for cardiovascular, kidney, and respiratory disorders.[48,49,50] Extreme summer heat is increasing in the United States (Ch. 2: Our Changing Climate, Key Message 7),[51] and climate projections indicate that extreme heat events will be more frequent and intense in coming decades (Ch. 2: Our Changing Climate, Key Message 7).[2,52,53,54]

Some of the risks of heat-related sickness and death have diminished in recent decades, possibly due to better forecasting, heat-health early warning systems, and/or increased access to air conditioning for the U.S. population.[55] However, extreme heat events remain a cause of preventable death nationwide. Urban heat islands, combined with an aging population and increased urbanization, are projected to increase the vulnerability of urban populations to heat-related health impacts in the future (Ch. 11: Urban).[56,57,58]

Milder winters resulting from a warming climate can reduce illness, injuries, and deaths associated with cold and snow. Vulnerability to winter weather depends on many non-climate factors, including housing, age, and baseline health.[59] While deaths and injuries related to extreme cold events are projected to decline due to climate change, these reductions are not expected to compensate for the increase in heat-related deaths.[60,61]

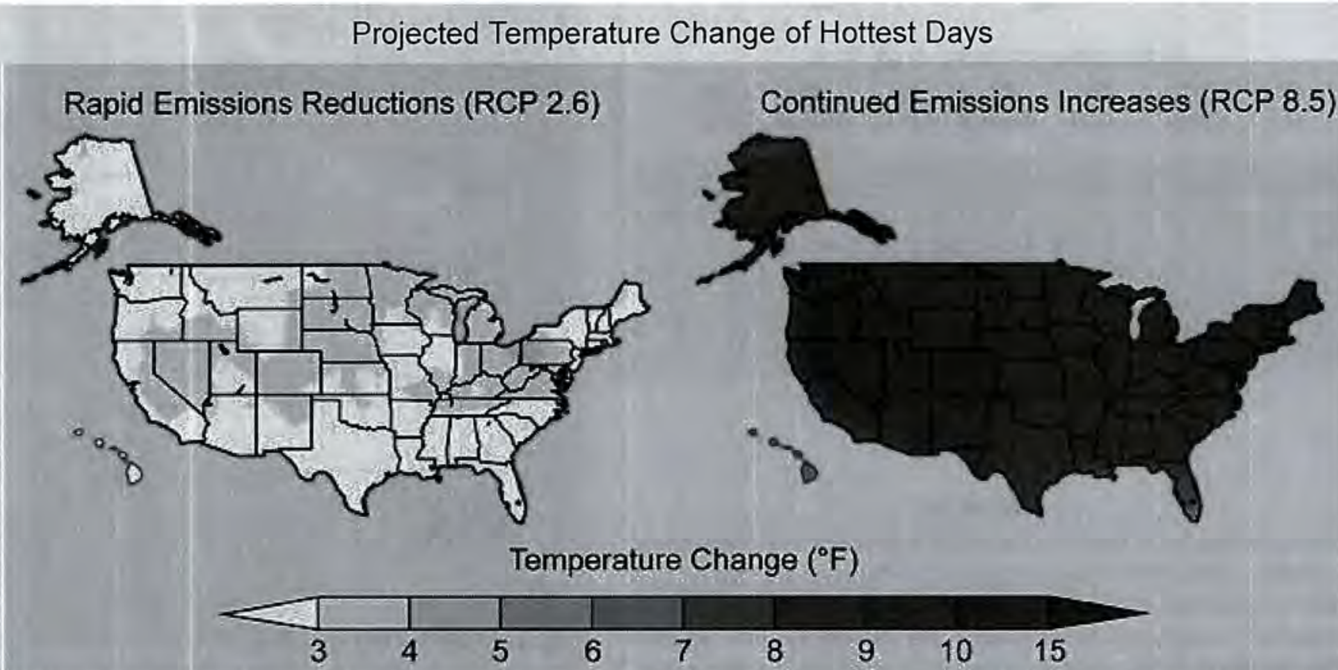

Figure 9.4. The maps show projected increases in the average temperature on the hottest days by late this century (2081-2100) relative to 1986-2005 under a scenario that assumes a rapid reduction in heat-trapping gases (RCP 2.6) and a scenario that assumes continued increases in these gases (RCP 8.5). The hottest days are those so hot they occur only once in 20 years. Across most of the continental United States, those days will be about 10°F to 15°F hotter in the future under the higher emissions scenario. (Figure source: NOAA NCDC / CICS-NC).

Precipitation Extremes: Heavy Rainfall, Flooding, and Droughts

The frequency of heavy precipitation events has already increased for the nation as a whole, and is projected to increase in all U.S. regions (Ch. 2: Our Changing Climate).[54,62] Increases in both extreme precipitation and total precipitation have contributed to increases in severe flooding events in certain regions (see Ch. 2: Our Changing Climate, Figure 2.21). Floods are the second deadliest of all weather-related hazards in the United States, accounting for approximately 98 deaths per year,[63] most due to drowning.[64] Flash floods (see Ch. 3: Water, "Flood Factors and Flood Types") and flooding associated with tropical storms result in the highest number of deaths.[63]

In addition to the immediate health hazards associated with extreme precipitation events when flooding occurs, other hazards can often appear once a storm event has passed. Elevated waterborne disease outbreaks have been reported in the weeks following heavy rainfall,[65] although other variables may affect these associations.[66] Water intrusion into buildings can result in mold contamination that manifests later, leading to indoor air quality problems. Buildings damaged during hurricanes are especially susceptible to water intrusion. Populations living in damp indoor environments experience increased prevalence of asthma and other upper respiratory tract symptoms, such as coughing and wheezing[67] as well as lower respiratory tract infections such as pneumonia, Respiratory Syncytial Virus (RSV), and RSV pneumonia (see Figure 9.7).[68]

At the opposite end of precipitation extremes, drought also poses risks to public health and safety.[69] Drought conditions may increase the environmental exposure to a broad set of health hazards including wildfires, dust storms, extreme heat events, flash flooding, degraded water quality, and reduced water quantity. Dust storms associated with drought conditions contribute to degraded air quality due to particulates and have been associated with increased incidence of Coccidioidomycosis (Valley fever), a fungal pathogen, in Arizona and California.[70]

Disease Carried by Vectors

Climate is one of the factors that influence the distribution of diseases borne by vectors (such as fleas, ticks, and mosquitoes, which spread pathogens that cause illness).[71,72,73,74,75,76,77,78] The geographic and seasonal distribution of vector populations, and the diseases they can carry, depend not only on climate but also on land use, socioeconomic and cultural factors, pest control, access to health care, and human responses to disease risk, among other factors.[72,73,79,80,81] Daily, seasonal, or year-to-year climate variability can sometimes result in vector/pathogen adaptation and shifts or expansions in their geographic ranges.[73,74,81] Such shifts can alter disease incidence depending on vector-host interaction, host immunity, and pathogen evolution.[71] North Americans are currently at risk from numerous vector-borne diseases, including Lyme,[75,82,83,84] dengue fever,[85] West Nile virus,[86] Rocky Mountain spotted fever,[87] plague, and tularemia.[88] Vector-borne pathogens not currently found in the United States, such as chikungunya, Chagas disease, and Rift Valley fever viruses, are also threats. Climate change effects on the geographical distribution and incidence of vector-borne diseases in other countries where these diseases are already found can also affect North Americans, especially as a result of increasing trade with, and travel to, tropical and subtropical areas.[74,81] Whether climate change in the U.S. will increase the chances of domestically acquiring diseases such as dengue fever is uncertain, due to vector-control efforts and lifestyle factors, such as time spent indoors, that reduce human-insect contact.

Infectious disease transmission is sensitive to local, small-scale differences in weather, human modification of the landscape, the diversity of animal hosts,[83] and human behavior that affects vector-human contact, among other factors. There is a need for finer-scale, long-term studies to help quantify the relationships among weather variables, vector range, and vector-borne pathogen occurrence, the consequences of shifting distributions of vectors and pathogens, and the impacts on human behavior. Enhanced vector surveillance and human disease tracking are needed to address these concerns.

The *Culex tarsalis* mosquito is a vector that transmits West Nile Virus.

Transmission Cycle of Lyme Disease

The development and survival of blacklegged ticks, their animal hosts, and the Lyme disease bacterium, *Borrelia burgdorferi*, are strongly influenced by climatic factors, especially temperature, precipitation, and humidity. Potential impacts of climate change on the transmission of Lyme disease include: 1) changes in the geographic distribution of the disease due to the increase in favorable habitat for ticks to survive off their hosts;[89] 2) a lengthened transmission season due to earlier onset of higher temperatures in the spring and later onset of cold and frost; 3) higher tick densities leading to greater risk in areas where the disease is currently observed, due to milder winters and potentially larger rodent host populations; and 4) changes in human behaviors, including increased time outdoors, which may increase the risk of exposure to infected ticks.

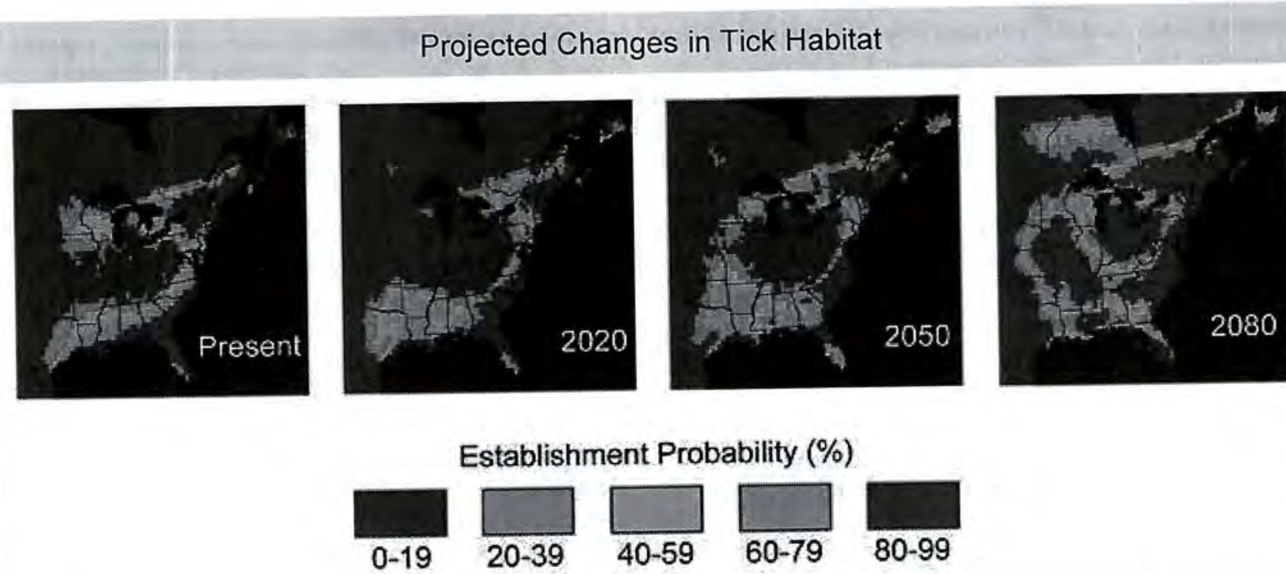

Figure 9.5. The maps show the current and projected probability of establishment of tick populations (*Ixodes scapularis*) that transmit Lyme disease. Projections are shown for 2020, 2050, and 2080. The projected expansion of tick habitat includes much of the eastern half of the country by 2080. For some areas around the Gulf Coast, the probability of tick population establishment is projected to decrease by 2080. (Figure source: adapted from Brownstein et al. 2005[90]).

Food- and Waterborne Diarrheal Disease

Diarrheal disease is a major public health issue in developing countries and, while not generally increasing in the United States, remains a persistent concern nonetheless. Exposure to a variety of pathogens in water and food causes diarrheal disease. Air and water temperatures, precipitation patterns, extreme rainfall events, and seasonal variations are all known to affect disease transmission.[65,91,92] In the United States, children and the elderly are most vulnerable to serious outcomes, and those exposed to inadequately or untreated groundwater will be among those most affected.

In general, diarrheal diseases including Salmonellosis and Campylobacteriosis are more common when temperatures are higher,[93,94] though patterns differ by place and pathogen. Diarrheal diseases have also been found to occur more frequently in conjunction with both unusually high and low precipitation.[95] Sporadic increases in streamflow rates, often preceded by rapid snowmelt[96] and changes in water treatment,[97] have also been shown to precede outbreaks. Risks of waterborne illness and beach closures resulting from changes in the magnitude of recent precipitation (within the past 24 hours) and in lake temperature are expected to increase in the Great Lakes region due to projected climate change.[98,99]

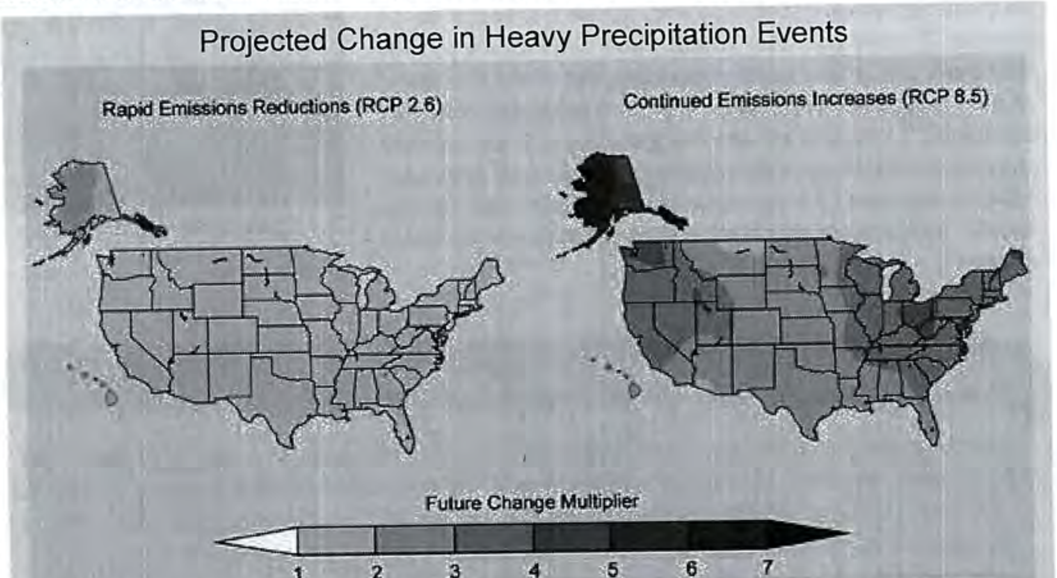

Figure 9.6. Maps show the increase in frequency of extreme daily precipitation events (a daily amount that now occurs just once in 20 years) by the later part of this century (2081-2100) compared to the latter part of the last century (1981-2000). Such extreme events are projected to occur more frequently everywhere in the United States. Under a rapid emissions reduction scenario (RCP 2.6), these events would occur nearly twice as often. For a scenario assuming continued increases in emissions (RCP 8.5), these events would occur up to five times as often. (Figure source: NOAA NCDC / CICS-NC).

Heavy Downpours are Increasing Exposure to Disease

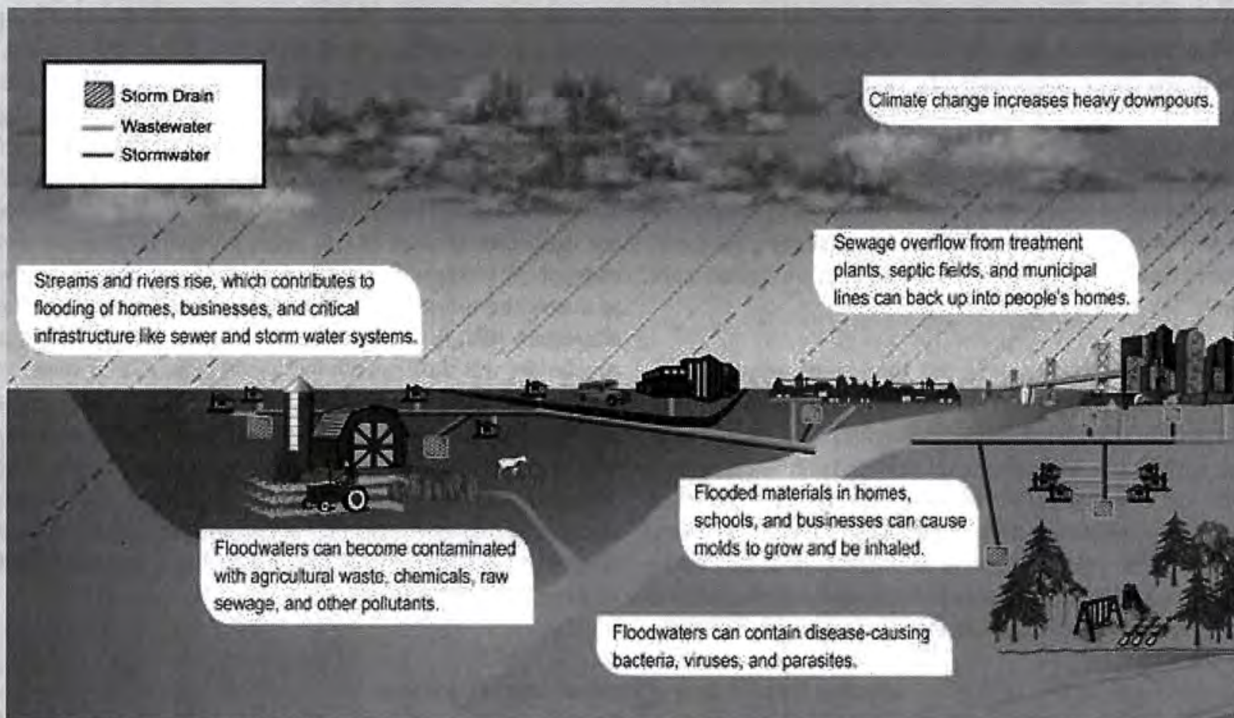

Figure 9.7. Heavy downpours, which are increasing in the United States, have contributed to increases in heavy flood events (Ch. 2: Our Changing Climate, Key Message 6). The figure above illustrates how people can become exposed to waterborne diseases. Human exposures to waterborne diseases can occur via drinking water, as well as recreational waters.[100,101,102,103] (Figure source: NOAA NCDC / CICS-NC).

Harmful Bloom of Algae

Figure 9.8. Remote sensing color image of harmful algal bloom in Lake Erie on October 9, 2011. The bright green areas have high concentrations of algae, which can be harmful to human health. The frequency and range of harmful blooms of algae are increasing.[102,103] Because algal blooms are closely related to climate factors, projected changes in climate could affect algal blooms and lead to increases in water- and food-borne exposures and subsequent cases of illness.[103] Other factors related to increases in harmful algal blooms include shifts in ocean conditions such as excess nutrient inputs.[101,102,103] (Figure source: NASA Earth Observatory[104]).

Food Security

Globally, climate change is expected to threaten food production and certain aspects of food quality, as well as food prices and distribution systems. Many crop yields are predicted to decline due to the combined effects of changes in rainfall, severe weather events, and increasing competition from weeds and pests on crop plants (Ch. 6: Agriculture, Key Message 6).[105,106] Livestock and fish production is also projected to decline.[107] Prices are expected to rise in response to declining food production and associated trends such as increasingly expensive petroleum (used for agricultural inputs such as pesticides and fertilizers).[108]

While the U.S. will be less affected than some other countries,[109,110] the nation will not be immune. Health can be affected in several ways. First, Americans with particular dietary patterns, such as Alaska Natives, will confront shortages of key foods (Ch. 12: Indigenous Peoples, Key Message 1).[111] Second, food insecurity increases with rising food prices.[112] In such situations, people cope by turning to nutrient-poor but calorie-rich foods, and/or they endure hunger, with consequences ranging from micronutrient malnutrition to obesity.[113] Third, the nutritional value of some foods is projected to decline. Elevated atmospheric CO_2 is associated with decreased plant nitrogen concentration, and therefore decreased protein, in many crops, such as barley, sorghum, and soy.[114] The nutrient content of crops is also projected to decline if soil nitrogen levels are suboptimal, with reduced levels of nutrients such as calcium, iron, zinc, vitamins, and sugars, although this effect is alleviated if sufficient nitrogen is supplied.[115] Fourth, farmers are expected to need to use more herbicides and pesticides because of increased growth of pests[116] and weeds[117] as well as decreased effectiveness[118] and duration[119] of some of these chemicals (Ch. 6: Agriculture). Farmers, farmworkers, and consumers will thus sustain increased exposure to these substances and their residues, which can be toxic. These climate change impacts on the nutritional value of food exist within a larger context in which other factors, such as agricultural practices, food distribution systems, and consumer food choices, also play key roles. Adaptation activities can reduce the health-related impacts of some of the anticipated food security challenges (Ch. 6: Agriculture).

Mental Health and Stress-related Disorders

Mental illness is one of the major causes of suffering in the United States, and extreme weather events can affect mental health in several ways.[120,121,122,123] First, following disasters, mental health problems increase, both among people with no history of mental illness, and those at risk – a phenomenon known as "common reactions to abnormal events." These reactions may be short-lived or, in some cases, long-lasting.[124] For example, research demonstrated high levels of anxiety and post-traumatic stress disorder among people affected by Hurricane Katrina,[125] and similar observations have followed floods[126] and heat waves.[127] Some evidence suggests wildfires have similar effects.[128] All of these events are increasingly fueled by climate change (see Ch. 2: Our Changing Climate). Other health consequences of intensely stressful exposures are also a concern, such as adverse birth outcomes including pre-term birth, low birth weight, and maternal complications.[129]

Second, some patients with mental illness are especially susceptible to heat.[130] Suicide rates vary with weather,[131] rising with high temperatures,[132] suggesting potential climate change impacts on depression and other mental illnesses. Dementia is a risk factor for hospitalization and death during heat waves.[127,133] Patients with severe mental illness such as schizophrenia are at risk during hot weather because their medications may interfere with temperature regulation or even directly cause hyperthermia.[134] Additional potential mental health impacts, less well understood, include the possible distress associated with environmental degradation[135] and displacement,[136] and the anxiety and despair that knowledge of climate change might elicit in some people (Ch. 12: Indigenous Peoples, Key Message 5).[122]

Key Message 2: Most Vulnerable at Most Risk

Climate change will, absent other changes, amplify some of the existing health threats the nation now faces. Certain people and communities are especially vulnerable, including children, the elderly, the sick, the poor, and some communities of color.

Climate change will increase the risk of climate-related illness and death for a number of vulnerable groups in the United States, as when Hurricane Katrina devastated New Orleans in 2005. Children, primarily because of physiological and developmental factors, will disproportionately suffer from the effects of heat waves,[47] air pollution, infectious illness, and trauma resulting from extreme weather events.[14,16,18,22,138,139,140,141]

The country's older population also could be harmed more as the climate changes. Older people are at much higher risk of dying during extreme heat events.[45,47,139,142] Pre-existing health conditions also make older adults susceptible to cardiac and respiratory impacts of air pollution[26] and to more severe consequences from infectious diseases;[143] limited mobility among older adults can also increase flood-related health risks.[144] Limited resources and an already high burden of chronic health conditions, including heart disease, obesity, and diabetes, will place the poor at higher risk of health impacts from climate change than higher income groups.[26,47] Potential increases in food cost and limited availability of some foods will exacerbate current dietary inequalities and have significant health ramifications for the poorer segments of our population (Ch. 12: Indigenous Peoples, Key Message 1).[110,145]

Climate change will disproportionately affect low-income communities and some communities of color (Ch. 12: Indigenous Peoples, Key Message 2),[139,149,151,152,153,154,155,156,157] raising environmental justice concerns. Existing health disparities[153,158,159] and other inequities[160,161] increase vulnerability. Climate change related issues that have an equity component include heat waves, air quality, and extreme weather and climate events. For example, Hurricane Katrina demonstrated how vulnerable certain groups of people were to extreme weather events, because many low-income and of-color New Orleans residents were killed, injured, or had difficulty evacuating and recovering from the storm.[154,155,156,161,162,163,164]

Elements of Vulnerability to Climate Change

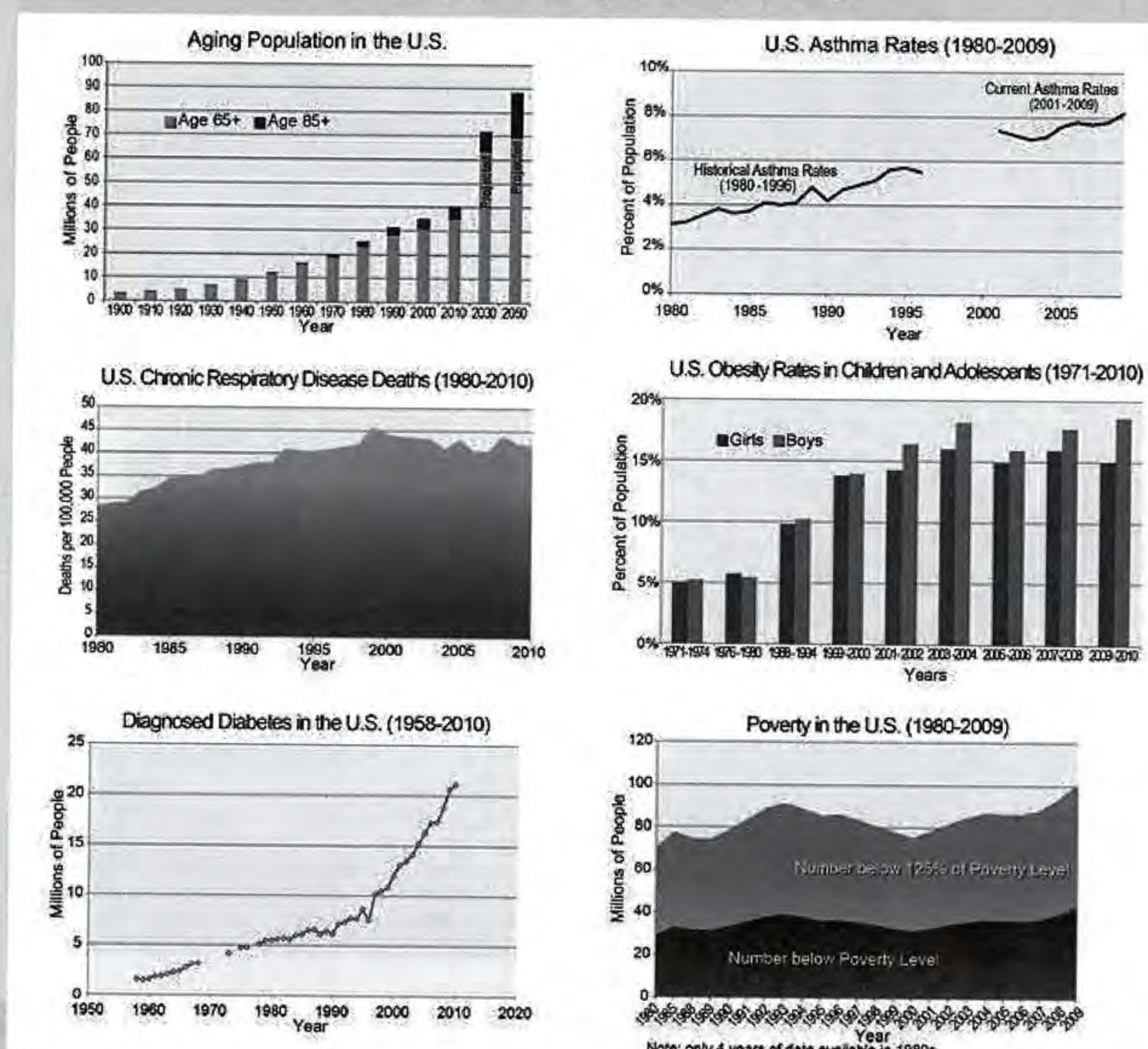

Figure 9.9. A variety of factors can increase the vulnerability of a specific demographic group to health effects due to climate change. For example, older adults are more vulnerable to heat stress because their bodies are less able to regulate their temperature. Overall population growth is projected to continue to at least 2050, with older adults comprising an increasing proportion of the population. Similarly, there are an increasing number of people who are obese and have diabetes, heart disease, or asthma, which makes them more vulnerable to a range of climate-related health impacts. Their numbers are also rising. The poor are less able to afford the kinds of measures that can protect them from and treat them for various health impacts. (Data from CDC; Health E-Stat; U.S. Census Bureau 2010, 2012; and Akinbami et al. 2011[137]).

Societal system failures during extreme events

We have already seen multiple system failures during an extreme weather event in the United States, as when Hurricane Katrina struck New Orleans.[146] Infrastructure and evacuation failures and collapse of critical response services during a storm is one example of multiple system failures. Another example is a loss of electrical power during a heat wave or wildfires, which can reduce food and water safety.[147] Air conditioning has helped reduce illness and death due to extreme heat,[148] but if power is lost, everyone is vulnerable. By their nature, such events can exceed our capacity to respond.[79] In succession, these events severely deplete our resources needed to respond, from the individual to the national scale, but disproportionately affect the most vulnerable populations.[149]

Figure 9.10. This map illustrates the national scope of the dispersion of displaced people from Hurricane Katrina. It shows the location by zip code of the 800,000 displaced Louisiana residents who requested federal emergency assistance. The evacuees ended up dispersed across the entire nation, illustrating the wide-ranging impacts that can flow from extreme weather events, such as those that are projected to increase in frequency and/or intensity as climate continues to change (Ch. 2: Our Changing Climate, Key Message 8). (Figure source: Kent 2006[150]).

Multiple climate stressors and health

Climate change impacts add to the *cumulative* stresses currently faced by vulnerable populations including children, the elderly, the poor, some communities of color, and people with chronic illnesses. These populations, and others living in certain places such as cities, floodplains, and coastlines, are more vulnerable not only to extreme events but also to ongoing, persistent climate-related threats. These threats include poor air quality, heat, drought, flooding, and mental health stress. Over time, the accumulation of these stresses will be increasingly harmful to these populations.

the strongest climate-health preparedness programs possible.[153] One survey highlighted opportunities to address climate change preparedness activities and climate-health research[181] before needs become more widespread. *America's Climate Choices: Adapting to the Impacts of Climate Choices* (Table 3.5) provides examples of health adaptation options.[187]

Key Message 4: Responses Have Multiple Benefits

Responding to climate change provides opportunities to improve human health and well-being across many sectors, including energy, agriculture, and transportation. Many of these strategies offer a variety of benefits, protecting people while combating climate change and providing other societal benefits.

Policies and other strategies intended to reduce carbon pollution and mitigate climate change can often have independent influences on human health. For example, reducing CO_2 emissions through renewable electrical power generation can reduce air pollutants like particles and sulfur dioxide. Efforts to improve the resiliency of communities and human infrastructure to climate change impacts can also improve human health. There is a growing recognition that the magnitude of health "co-benefits," like reducing both pollution and cardiovascular disease, could be significant, both from a public health and an economic standpoint.[176,188,189] Some climate change resilience efforts will benefit health, but potential co-harms should be considered when implementing these strategies. For example, although there are numerous benefits to urban greening, such as reducing the urban heat island effect while simultaneously promoting an active healthy lifestyle,[159,190,191] the urban planting of certain allergenic pollen producing species[22] could increase human pollen exposure and allergic illness. Increased pollen exposure has been linked to increased emergency department visits related to asthma and wheezing[192] in addition to respiratory allergic illnesses such as allergic rhinitis or hay fever.[193] The selective use of low to moderate pollen-producing species can decrease pollen exposure.[194]

Much of the focus of health co-benefits has been on reducing health-harming air pollution.[6,174,175,195,196] One study projects that replacing 50% of short motor vehicle trips with bicycle use and the other 50% with other forms of transportation like walking or public transit would avoid nearly 1,300 deaths in 11 midwestern metropolitan areas and create up to $8 billion in health benefits annually for the upper Midwest region.[188] Such multiple-benefit actions can reduce heat-trapping gas emissions that lead to climate change, improve air quality by reducing vehicle pollutant emissions, and improve fitness and health through increased physical activity.[99,197,198,199,200]

Innovative urban design could create increased access to active transport.[99] The compact geographical area found in cities presents opportunities to reduce energy use and emissions of heat-trapping gases and other air pollutants through active transit, improved building construction, provision of services, and infrastructure creation, such as bike paths and sidewalks.[197,201] Urban planning strategies designed to reduce the urban heat island effect, such as green/cool roofs, increased green space, parkland and urban canopy, could reduce indoor temperatures, improve indoor air quality, and could produce additional societal co-benefits by promoting social interaction and prioritizing vulnerable urban populations.[191,197]

Patterns of change related to improving health can also have co-benefits in terms of reducing carbon pollution and mitigating climate change. Current U.S. dietary guidelines and many health professionals have recommended diets higher in fruits and vegetables and lower in red meat as a means of helping

Key Message 3: Prevention Provides Protection

Public health actions, especially preparedness and prevention, can do much to protect people from some of the impacts of climate change. Early action provides the largest health benefits. As threats increase, our ability to adapt to future changes may be limited.

Prevention is a central tenet of public health. Many conditions that are difficult and costly to treat when a patient gets to the doctor could be prevented before they occur at a fraction of the cost. Similarly, many of the larger health impacts associated with climate change can be prevented through early action at significantly lower cost than dealing with them after they occur.[153,165] Early preventive interventions, such as early warnings for extreme weather, can be particularly cost-effective.[166,167,168] As with many illnesses,[169] once impacts are apparent, even the best adaptive efforts can be overwhelmed, and damage control becomes the priority.[62]

Activities that reduce carbon pollution often also provide co-benefits in the form of preventive health measures. For example, reliance on cleaner energy sources for electricity production[174] and more efficient and active transport, like biking or walking,[175] can have immediate public health benefits, through improved air quality and lowered rates of obesity, diabetes, and heart disease.[176] Reducing carbon pollution also reduces long-term adverse climate-health impacts, thus producing cost savings in the near and longer term.[176] Preventing exposures to other climate-sensitive impacts already apparent can similarly result in cost savings. For instance, heat wave early warning systems protect vulnerable groups very effectively and are much less expensive than treating and coping with heat illnesses. Systems that monitor for early outbreaks of disease are also typically much less expensive than treating communities once outbreaks take hold.[12,49,177]

Effective communication is a fundamental part of prevention. The public must understand risk in order to endorse proactive risk management. The public is familiar with the health risks of smoking, but not so for climate change. When asked about climate change impacts, Americans do not mention health impacts,[178] and when asked about health impacts specifically, most believe it will affect people in a different time or place.[179] But diverse groups of Americans find information on health impacts to be helpful once received, particularly information about the health benefits of mitigation (reducing carbon emissions) and adaptation.[180]

Determining which types of prevention to invest in (such as monitoring, early warning systems, and land-use changes that reduce the impact of heat and floods) depends on several factors, including health problems common to that particular area, vulnerable populations, the preventive health systems already in place, and the expected impacts of climate change.[181] Local capacity to adapt is very important; unfortunately the most vulnerable populations also frequently have limited resources for managing climate-health risks.

Overall, the capacity of the American public health and health care delivery systems faces many challenges.[182] The cost of dealing with current health problems is diverting resources from preventing them in the first place. This makes the U.S. population more vulnerable.[183,184] Without careful consideration of how to prevent future impacts, similar patterns could emerge regarding the health impacts from climate change. However, efforts to quantify and map vulnerability factors at the community level are underway.[151,164,185]

There are public health programs in some locations that address climate-sensitive health issues, and integrating such programs into the mainstream public health toolkit as adaptation needs increase would improve public health resilience to climate change.[79,186,187] Given that these programs have demonstrated efficacy against current threats that are expected to worsen with climate change, it is prudent to invest in creating

Large-Scale Environmental Change Favors Disease Emergence

Climate change is causing large-scale changes in the environment, increasing the likelihood of the emergence or reemergence of unfamiliar disease threats.[170] Factors include shifting ranges of disease-carrying pests, lack of immunity and preparedness, inadequate disease monitoring, and increasing global travel. Diseases including Lyme disease and dengue fever pose increasing health threats to the U.S. population; the number of U.S. patients hospitalized with dengue fever more than tripled from 2000 to 2007.[171] Although most cases of dengue fever during that time period were acquired outside the contiguous United States, the introduction of infected people into areas where the dengue virus vector is established increases the risk of locally acquired cases. The public health system is not fully prepared to monitor or respond to these growing disease risks. The introduction of new diseases into non-immune populations has been and continues to be a major challenge in public health. There are concerns that climate change may provide opportunities for pathogens to expand or shift their geographic ranges.[172,173]

to reduce the risk of cardiovascular disease and some cancers.[199,202,203] These changes in food consumption, and related changes to food production, could have co-benefits in terms of reducing greenhouse gas emissions. While the greenhouse gas footprint of the production of other foods, compared to sources such as livestock, is highly dependent on a number of factors, production of livestock currently accounts for about 30% of the U.S. total emissions of methane.[199,203,204] This amount of methane can be reduced somewhat by recovery methods such as the use of biogas digesters, but future changes in dietary practices, including those motivated by considerations other than climate change mitigation, could also have an effect on the amount of methane emitted to the atmosphere.[205]

In addition to producing health co-benefits,[206] climate change prevention and preparedness measures could also yield positive equity impacts. For example, several studies have found that communities of color and poor communities experience disproportionately high exposures to air pollution.[207,208] Climate change mitigation policies that improve local air quality thus have the potential to strongly benefit health in these communities.

An area where adaptation policy could produce more equitable health outcomes is with respect to extreme weather events. As discussed earlier, Hurricane Katrina demonstrated that communities of color, poor communities, and certain other vulnerable populations (like new immigrant communities) are at a higher risk to the adverse effects of extreme weather events.[152,155] These vulnerable populations could benefit from urban planning policies that ensure that new buildings, including homes, are constructed to resist extreme weather events.[197]

9: HUMAN HEALTH

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PHOTO CREDITS

Introduction to chapter; tourists walking close to misters keeping cool during heat wave in Las Vegas, Nevada, as shown in top banner: ©Julie Jacobson/AP/Corbis

SUPPLEMENTAL MATERIAL
TRACEABLE ACCOUNTS

Process for Developing Key Messages

The key messages were developed during technical discussions and expert deliberation at a two-day meeting of the eight chapter Lead Authors, plus Susan Hassol and Daniel Glick, held in Boulder, Colorado May 8-9, 2012; through multiple technical discussions via six teleconferences from January through June 2012, and an author team call to finalize the Traceable Account draft language on Oct 12, 2012; and through other various communications on points of detail and issues of expert judgment in the interim. The author team also engaged in targeted consultations during multiple exchanges with Contributing Authors, who provided additional expertise on subsets of the key message. These discussions were held after a review of the technical inputs and associated literature pertaining to human health, including a literature review,[209] workshop reports for the Northwest and Southeast United States, and additional technical inputs on a variety of topics.

Key message #1 Traceable Account

Climate change threatens human health and well-being in many ways, including impacts from increased extreme weather events, wildfire, decreased air quality, threats to mental health, and illnesses transmitted by food, water, and diseases-carriers such as mosquitoes and ticks. Some of these health impacts are already underway in the United States.

Description of evidence base

The key message and supporting text summarizes extensive evidence documented in several foundational technical inputs prepared for this chapter, including a literature review[209] and workshop reports for the Northwest and Southeast United States. Nearly 60 additional technical inputs related to human health were received and reviewed as part of the Federal Register Notice solicitation for public input.

Air Pollution:

The effects of decreased ozone air quality on human health have been well documented concerning projected increases in ozone,[6,7,9,11,39] even with uncertainties in projections owing to the complex formation chemistry of ozone and climate change, precursor chemical inventories, wildfire emission, stagnation episodes, methane emissions, regulatory controls, and population characteristics.[4] Ozone exposure leads to a number of health impacts.[1,2]

Allergens:

The effects of increased temperatures and atmospheric CO_2 concentration have been documented concerning shifts in flowering time and pollen initiation from allergenic plants, elevated production of plant-based allergens, and health effects of increased pollen concentrations and longer pollen seasons.[15,16,17,18,20,22,23,24,26,106] Additional studies have shown extreme rainfall and higher temperatures can lead to increased indoor air quality issues such as fungi and mold health concerns.[27]

Wildfire:

The effects of wildfire on human health have been well documented with increase in wildfire frequency[17,29,39,40] leading to decreased air quality[31,32,33] and negative health impacts.[32,34,36]

Temperature Extremes:

The effects of temperature extremes on human health have been well documented for increased heat waves,[51,53,54] which cause more deaths,[47,48] hospital admissions[50] and population vulnerability.[56,57]

Precipitation Extremes - Heavy Rainfall, Flooding, and Droughts:

The effects of weather extremes on human health have been well documented, particularly for increased heavy precipitation, which has contributed to increases in severe flooding events in certain regions. Floods are the second deadliest of all weather-related hazards in the United States.[63,64] Elevated waterborne disease outbreaks have been reported in the weeks following heavy rainfall,[65] although other variables may affect these associations.[66] Populations living in damp indoor environments experience increased prevalence of asthma and other upper respiratory tract symptoms.[67]

Disease Carried by Vectors:

Climate is one of the factors that influence the range of disease vectors; [73,74,76] a shift in the current range may increase interactions with people and affect human health.[71] North Americans are currently at risk from a number of vector-borne diseases.[75,82,83,85,86,87] There are some ambiguities on the relative role and contribution of climate change among the range of factors that affect disease transmission dynamics.[71,72,73,74,75,76] However, observational studies are already underway and confidence is high based on scientific literature that climate change has contributed to the expanded range of certain disease vectors, including *Ixodes* ticks which are vectors for Lyme disease in the United States.[78,84,89]

Food- and Waterborne Diarrheal Disease:

There has been extensive research concerning the effects of climate change on water- and food-borne disease transmission.[92,93,95,96,97] The current evidence base strongly supports waterborne diarrheal disease being both seasonal and sensitive to climate variability. There are also multiple studies associating extreme precipitation events with waterborne disease outbreaks.[65] This evidence of responsiveness of waterborne disease to weather and climate, combined with evidence strongly suggesting that temperatures will increase and extreme precipitation events will increase in frequency and severity (Ch. 2: Our Changing Climate), provides a strong argument for climate change impacts on waterborne disease by analogy. There are multiple studies associating extreme precipitation events with waterborne disease outbreaks and strong climatological evidence for increasing frequency and intensity of extreme precipitation events in the future. The scientific literature modeling the projected impacts of climate change on waterborne disease is somewhat limited, however. Combined, we therefore have overall medium confidence in the impact of climate change on waterborne and food-borne disease.

Harmful Algal Blooms:

Because algal blooms are closely related to climate factors, projected changes in climate could affect algal blooms and lead to increases in food- and waterborne exposures and subsequent cases of illness.[96,97,98,99,103] Harmful algal blooms have multiple exposure routes.[100]

Food Security:

Climate change is expected to have global impacts on both food production and certain aspects of food quality. The impact of temperature extremes, changes in precipitation and elevated atmospheric CO_2, and increasing competition from weeds and pests on crop plants are areas of active research (Ch. 6: Agriculture, Key Message 6).[105,106] The U.S. as a whole will be less affected than some other countries. However, the most vulnerable, including those dependent on subsistence lifestyles, especially Alaska Natives and low-income populations, will confront shortages of key foods.

Mental Health and Stress-Related Disorders:

The effects of extreme weather on mental health have been extensively studied.[120,122,123] Studies have shown the impacts of mental health problems after disasters,[124] with extreme events like Hurricane Katrina,[125] floods,[126] heat waves,[127] and wildfires[128] having led to mental health problems. Further work has shown that some people with mental illnesses are especially vulnerable to heat. Suicide rates vary with weather,[131,132] dementia is a risk factor for hospitalization and death during heat waves,[127,133] and medications for schizophrenia may interfere with temperature regulation or even directly cause hyperthermia.[134] Additional potential mental health impacts include distress associated with environmental degradation, displacement, and the knowledge of climate change.[122,123,136]

New information and remaining uncertainties

Important new evidence on heat-health effects[44,45] confirmed many of the findings from a prior literature review. Uncertainties in the magnitude of projections of future climate-related morbidity and mortality can result from differences in climate model projections of the frequency and intensity of extreme weather events such as heat waves and other climate parameters such as precipitation.

Efforts to improve the information base should address the coordinated monitoring of climate and improved surveillance of health effects.

Assessment of confidence based on evidence

Overall: **Very High** confidence. There is considerable consensus and a high quality of evidence in the published peer-reviewed literature that a wide range of health effects will be exacerbated by climate change in the United States. There is less agreement on the magnitude of these effects because of the exposures in question and the multi-factorial nature of climate-health vulnerability, with regional and local differences in underlying health susceptibilities and adaptive capacity. Other uncertainties include how much effort and resources will be put into improving the adap-

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

tive capacity of public health systems to prepare in advance for the health effects of climate change, prevent harm to individual and community health, and limit associated health burdens and societal costs.

Increased Ozone Exposure: **Very High** confidence.
Allergens: **High** confidence.
Wildfires: **Very High** confidence.
Thermal Extremes: **Very High** confidence.
Extreme Weather Events: **Very High** confidence.
Vector-borne Infectious Diseases: **High** or **Very High** confidence for shift in range of disease-carrying vectors. **Medium** confidence for whether human disease transmission will follow.
Food- and Waterborne disease: **Medium** confidence.
Harmful Algal Blooms: **Medium** confidence.
Food Security: **Medium** confidence for food quality; **High** confidence for food security.

Threats to Mental Health: **Very High** confidence for post-disaster impacts; **Medium** confidence for climate-induced stress.

KEY MESSAGE #2 TRACEABLE ACCOUNT

Climate change will, absent other changes, amplify some of the existing health threats the nation now faces. Certain people and communities are especially vulnerable, including children, the elderly, the sick, the poor, and some communities of color.

Description of evidence base

The key message and supporting text summarizes extensive evidence documented in several foundational technical inputs prepared for this chapter, including a literature review[209] and workshop reports for the Northwest and Southeast regions.[210] Nearly 60 additional technical inputs related to human health were received and reviewed as part of the Federal Register Notice solicitation for public input.

Current epidemiological evidence on climate-sensitive health outcomes in the U.S. indicates that health impacts will differ substantially by location, pathway of exposure, underlying susceptibility, and adaptive capacity. These disparities in health impacts will largely result from differences in the distribution of individual attributes in a population that confers vulnerability (age, socioeconomic status, and race), attributes of place that reduce or amplify exposure (floodplain, coastal zone, and urban heat island), and the resilience of critical public health infrastructure.

Amplification of existing health threats: The effects of extreme heat and heat waves, projected worsening air pollution and asthma, extreme rainfall and flooding, and displacement and injuries associated with extreme weather events, fueled by climate change, are already substantial public health issues. Trends projected under a changing climate are projected to exacerbate these health effects in the future.[62]

Children: The effects of climate change increase vulnerability of children to extreme heat, and increased health damage (morbidity, mortality) resulting from heat waves has been well documented.[16,22,51,53,140] Extreme heat also causes more pediatric deaths,[47,48] and more emergency room visits and hospital admissions.[49,50] Adverse effects from increased heavy precipitation can lead to more pediatric deaths, waterborne diseases,[66] and illness.[141]

The elderly: Heat stress is especially damaging to the health of older people,[45,49,60,133,142,209] as are climate-sensitive increases in air pollution.

The sick: People and communities lacking the resources to adapt or to enhance mobility and escape health-sensitive situations are at relatively high risk.[164]

The poor: People and communities lacking the resources to adapt or to move and escape health-sensitive situations are at relatively high risk.[164]

Some communities of color: There are racial disparities in climate-sensitive exposures to extreme heat in urban areas, and in access to means of adaptation – for example air conditioning use.[149,151,157,211] There are also racial disparities in withstanding, and recovering from, extreme weather events.[155,162]

Climate change will disproportionately impact low-income communities and some communities of color, raising environmental justice concerns.[139,149,151,154,155,157,161,164] Existing health disparities[153,158,159] and other inequities[161] increase vulnerability. For example, Hurricane Katrina demonstrated how vulnerable these populations were to extreme weather events because many low-income and of-color New Orleans residents were killed, injured, or had difficulty evacuating and recovering from the storm.[155,162] Other climate change related issues that have an equity component include heat waves and air quality.[139,149,154,164]

New information and remaining uncertainties

Important new evidence[45] confirmed findings from a prior literature review.[139]

The potential for specific climate-vulnerable communities to experience highly harmful health effects is not entirely clear in specific regions and on specific time frames due to uncertainties in rates of adaptation and uncertainties about the outcome of public health interventions currently being implemented that aim to address underlying health disparities and determinants of health.[206] The public health community has not routinely conducted evaluations of the overall success of adaptation interventions or of particular elements of those interventions.

Assessment of confidence based on evidence

Given the evidence base and remaining uncertainties, confidence that climate change will amplify existing health threats: **Very High**.
Among those especially vulnerable are:
Children: **Very High**.
The elderly: **Very High**.
The sick: **Very High**.
The poor: **Very High**.
Some communities of color: **High**.

KEY MESSAGE #3 TRACEABLE ACCOUNT

Public health actions, especially preparedness and prevention, can do much to protect people from some of the impacts of climate change. Early action provides the largest health benefits. As threats increase, our ability to adapt to future changes may be limited.

Description of evidence base

The key message and supporting text summarizes extensive evidence documented in several foundational technical inputs prepared for this chapter, including a literature review[209] and workshop reports for the Northwest and Southeast United States. Nearly 60 additional technical inputs related to human health were received and reviewed as part of the Federal Register Notice solicitation for public input.

A number of studies have demonstrated that prevention activities that reduce carbon pollution, like using alternative energy sources[174] and using active transportation like biking or walking,[188] can lead to significant public health benefits, which can save costs in the near and long term.[176] Health impacts associated with climate change can be prevented through early action at significantly lower cost than dealing with them after they occur. For example, heat wave early warning systems are much less expensive than treating heat-related illnesses.[165] Existing adaptation programs have improved public health resilience.[9,153] One survey highlighted opportunities to address climate change preparedness activities and climate-health research[181] before needs become more widespread.

Considering U.S. public health in general, the cost-effectiveness of many prevention activities is well established.[183] Some preventive actions are cost-saving, while others are deemed cost-effective based on a pre-determined threshold. Early preventive interventions, such as early warnings for extreme weather, can be particularly cost-effective.[166] However, there is less information on the cost-effectiveness of specific prevention interventions relevant to climate sensitive health threats (for example, heat early warning systems). Overall, we have high confidence that public health actions can do much to protect people from some of the impacts of climate change, and that early action provides the largest health benefits.

The inverse relationship between the magnitude of an impact and a community's ability to adapt is well established and understood. Two extreme events, Hurricane Katrina and the European heat wave of 2003, illustrate this relationship well.[167] Extreme events interact with social vulnerability to produce extreme impacts, and the increasing frequency of extreme events associated with climate change is prompting concern for impacts that may overwhelm adaptive capacity.[62,173] This is equally true of the public health sector, specifically, leading to very high confidence that as threats increase, our ability to adapt to future changes may be limited.

New information and remaining uncertainties

A key issue (uncertainty) is the extent to which the nation, states, communities and individuals will be able to adapt to climate change because this depends on the levels of local exposure to climate-health threats, underlying susceptibilities, and the capacities to adapt that are available at each scale. Overall, the capacity of the American public health and health care delivery systems faces many challenges.[182] The cost of dealing with current health problems is diverting resources from preventing them in the first place. This makes the U.S. population more vulnerable.[56,183]

Steps for improving the information base on adaptation include undertaking a more comprehensive evaluation of existing climate-health preparedness programs and their effectiveness in various jurisdictions (cities, counties, states, nationally).

Assessment of confidence based on evidence

Overall, given the evidence base and remaining uncertainties: **High**.
High: Public health actions, especially preparedness and prevention, can do much to protect people from some of the impacts of climate change. Prevention provides the most protection; but we do not as yet have a lot of post-implementation information with which to evaluate preparedness plans.
High: Early action provides the largest health benefits. There is evidence that heat-health early warning systems have saved lives and money in U.S. cities like Philadelphia, PA.[165]
Very High: Our ability to adapt to future changes may be limited.

KEY MESSAGE #4 TRACEABLE ACCOUNT

Responding to climate change provides opportunities to improve human health and well-being across many sectors, including energy, agriculture, and transportation. Many of these strategies offer a variety of benefits, protecting people while combating climate change and providing other societal benefits.

Description of evidence base

The key message and supporting text summarizes extensive evidence documented in several foundational technical inputs prepared for this chapter, including a literature review[209] and workshop reports for the Northwest and Southeast U.S. regions.[210] Nearly 60 additional technical inputs related to human health were received and reviewed as part of the Federal Register Notice solicitation for public input.

A number of studies have explored the opportunities available to improve health and well-being as a result of adapting to climate change,[176] with many recent publications illustrating the benefit of reduced air pollution.[6,174,175,195] Additionally, some studies have looked at the co-benefits to climate change and health of applying innovative urban design practices which reduce energy consumption and pollution while increasing public health,[99,188,197,198] decrease vulnerability of communities to extreme events[152,197] and reduce the disparity between different societal groups.[206,207,212]

New information and remaining uncertainties

More studies are needed to fully evaluate both the intended and unintended health consequences of efforts to improve the resiliency of communities and human infrastructure to climate change impacts. There is a growing recognition that the magnitude of these health co-benefits or co-harms could be significant, both from a public health and an economic standpoint. [176,188,189]

Assessment of confidence based on evidence

Given the evidence base and remaining uncertainties, confidence is **Very High**.