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

10 Agriculture and Rural Communities

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

10 Agriculture and Rural Communities

Tyringham, Massachusetts

Key Message 1

Reduced Agricultural Productivity

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

Key Message 2

Degradation of Soil and Water Resources

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

Key Message 3

Health Challenges to Rural Populations and Livestock

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

Key Message 4

Vulnerability and Adaptive Capacity of Rural Communities

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

Executive Summary

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

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

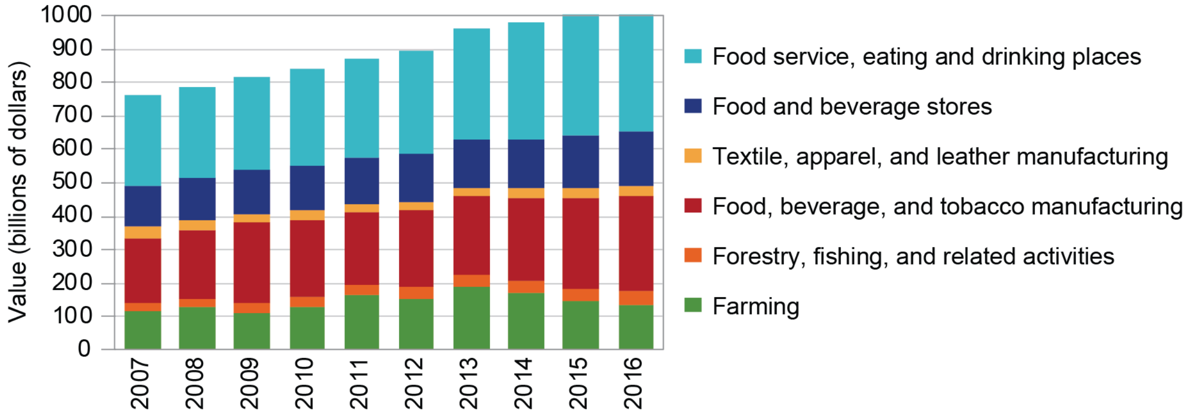
Climate change has the potential to adversely impact agricultural productivity at local, regional, and continental scales through alterations in rainfall patterns, more frequent occurrences of climate extremes (including high temperatures or drought), and altered patterns of pest pressure. Risks associated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

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

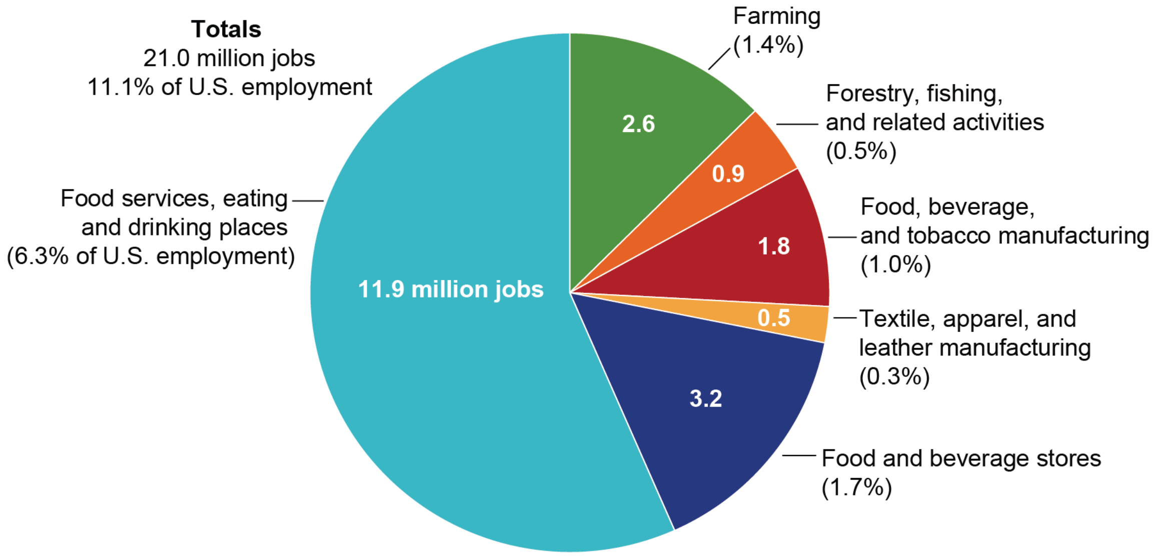
Climate change impacts, such as changes in extreme weather conditions, have a complex influence on human and livestock health. The consequences of climate change on the incidence of drought also impact the frequency and intensity of wildfires, and this holds implications for agriculture and rural communities.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

Agricultural Jobs and Revenue

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

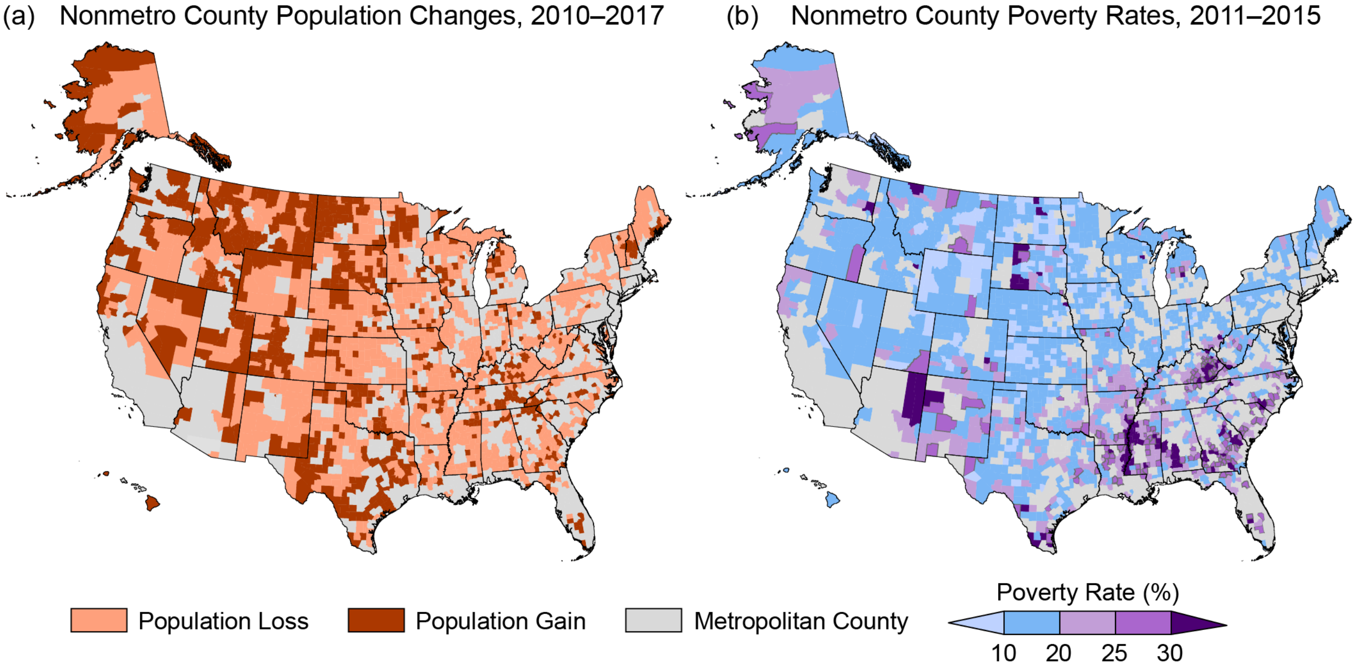


(b) Employment in Agriculture, Food, and Related Industries, 2015



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

Population Changes and Poverty Rates in Rural Counties


(a) Nonmetro County Population Changes, 2010–2017

(b) Nonmetro County Poverty Rates, 2011–2015

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

State of the Agriculture and Rural Communities Sectors

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

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

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

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

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

Agricultural Jobs and Revenue

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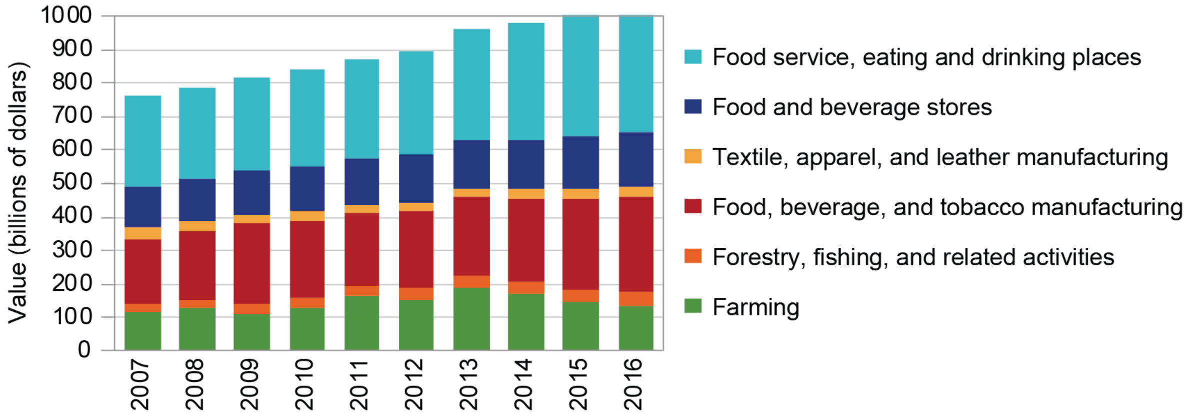

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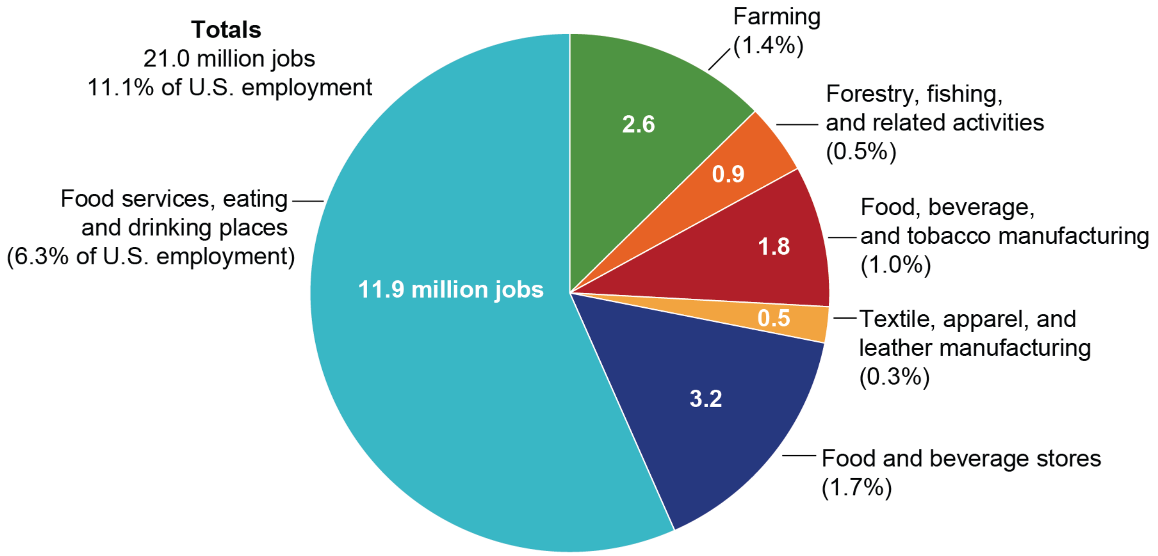

Figure 10.1: The figure shows (a) the contribution of agriculture and related sectors to the U.S. economy and (b) employment figures in agriculture and related sectors (as of 2015). Agriculture and other food-related value-added sectors account for 21 million full- and part-time jobs and contribute about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

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

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

Population Changes and Poverty Rates in Rural Counties

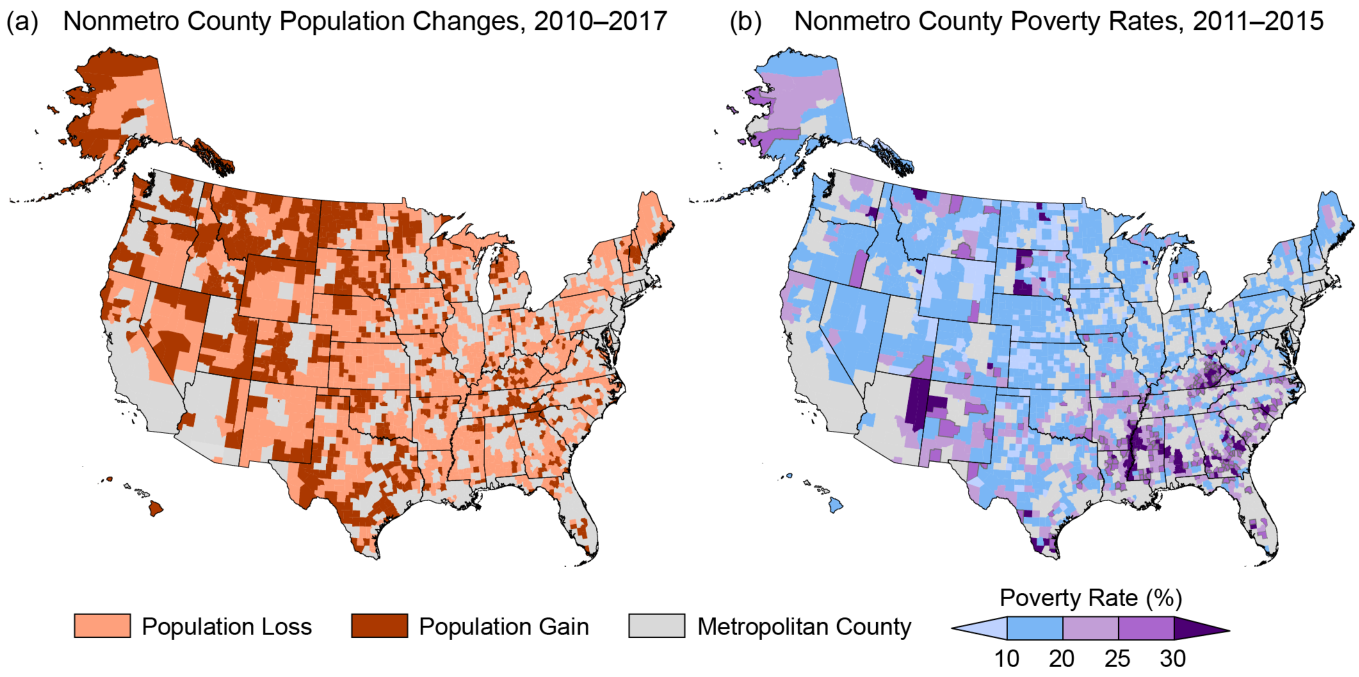
(a) Nonmetro County Population Changes, 2010–2017

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

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

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

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

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

Key Message 1

Reduced Agricultural Productivity

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

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

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

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

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

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

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

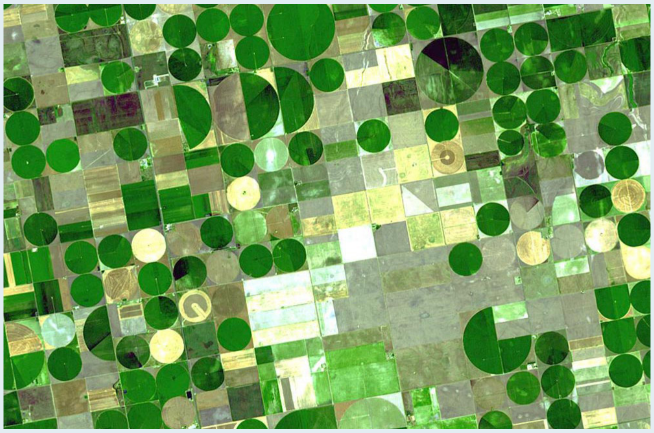
The same aspects of climate change that affect the incidence of drought also affect the frequency and intensity of wildfires, which pose major risks to agriculture and rural communities. Grassland, rangeland, and forest ecosystems, which support ruminant livestock production, represent more than half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

Case Study: Groundwater Depletion in the Ogallala Aquifer Region

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

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

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



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

Case Study: Groundwater Depletion in the Ogallala Aquifer Region, continued

Changes in the Ogallala Aquifer

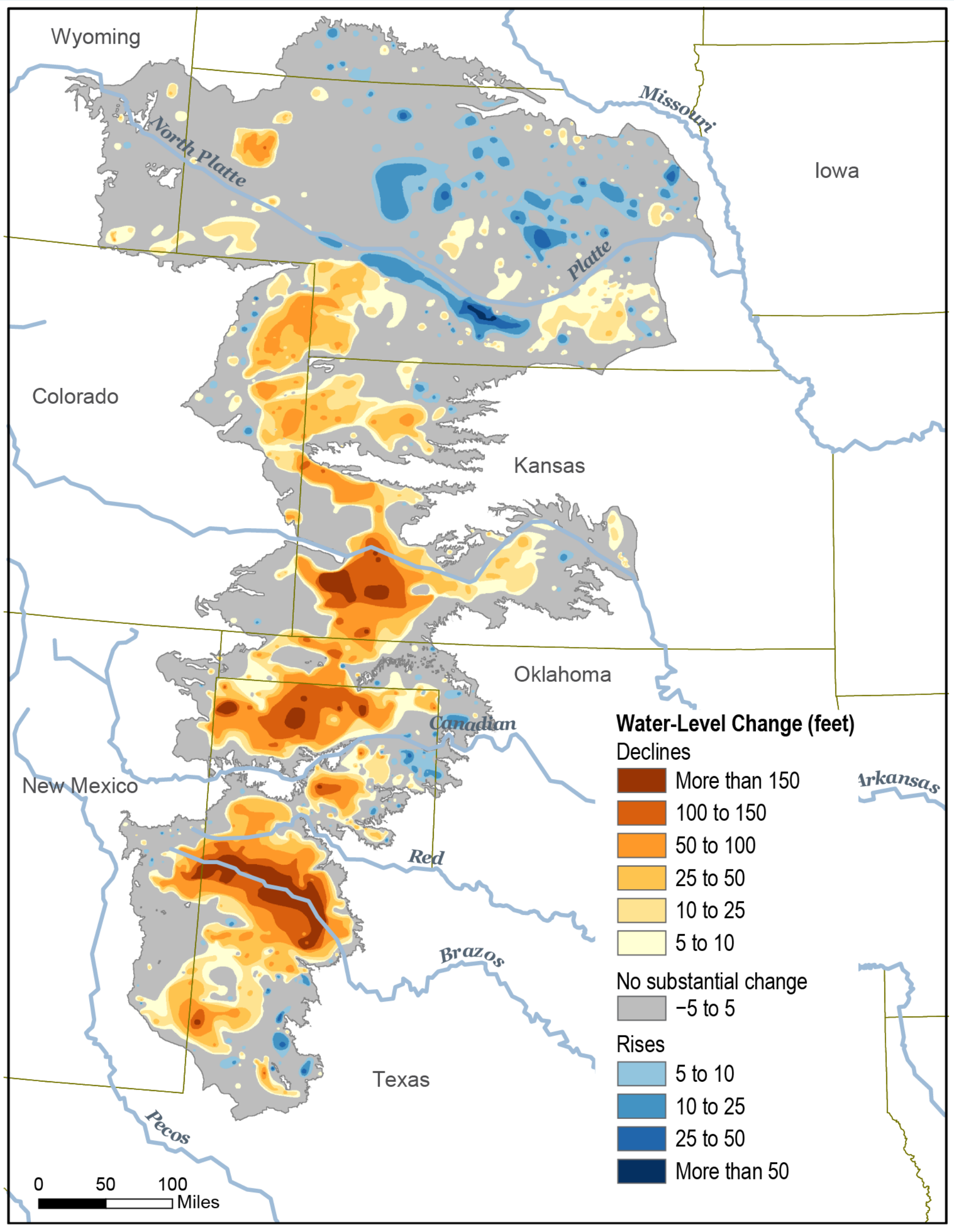


Figure 10.3: The figure shows changes in groundwater levels in the Ogallala Aquifer from predevelopment to 2015. Source: adapted from McGuire 2017.[163]

Key Message 2

Degradation of Soil and Water Resources

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

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

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

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

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

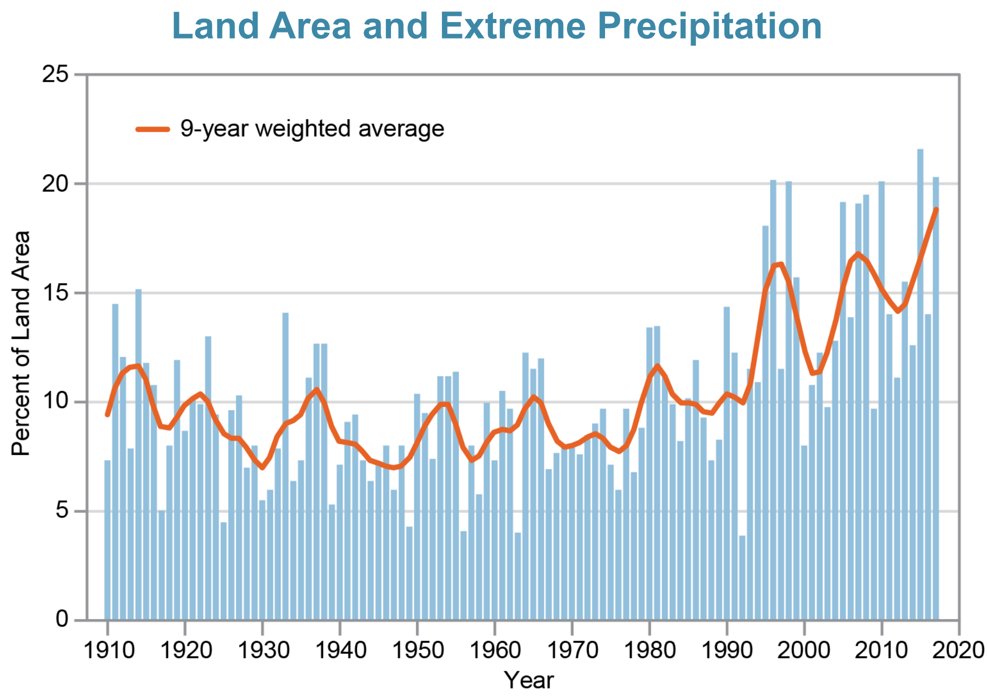


Figure 10.4: The figure shows the percent of land area in the contiguous 48 states experiencing extreme one-day precipitation events between 1910 and 2017. These extreme events pose erosion and water quality risks that have increased in recent decades. The bars represent individual years, and the orange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

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

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

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

Key Message 3

Health Challenges to Rural Populations and Livestock

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

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

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

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

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

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

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

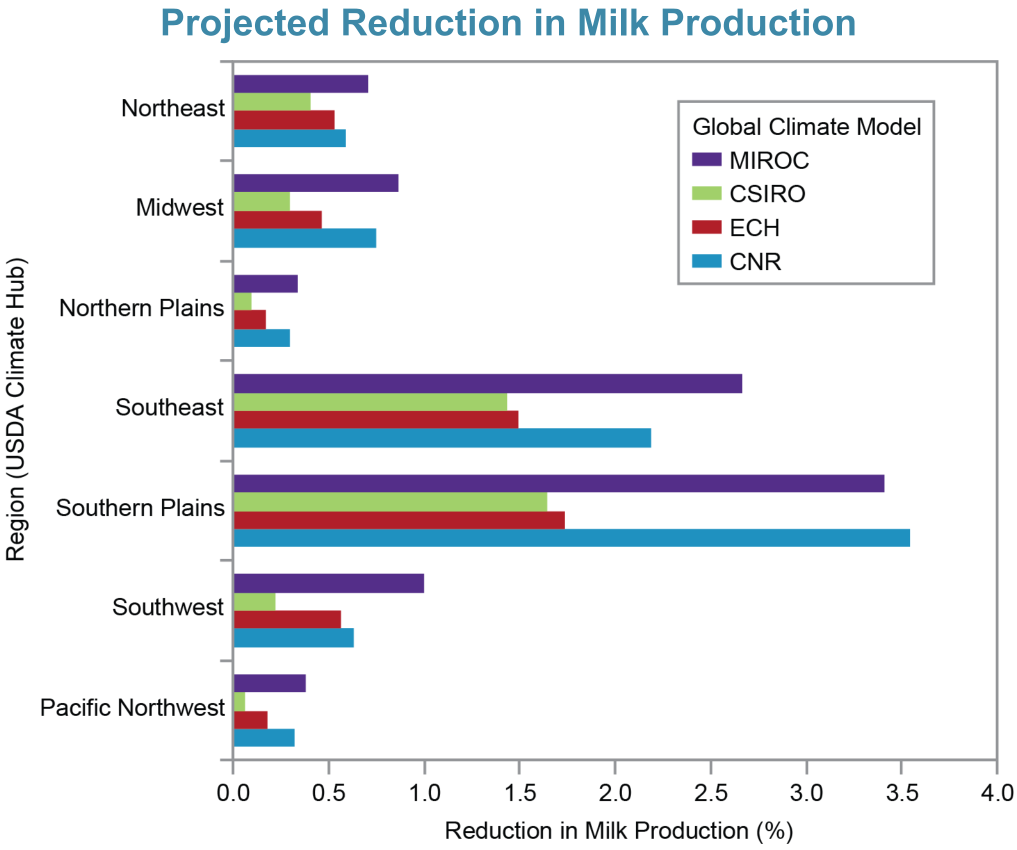


Figure 10.5: The figure shows the predicted reduction in annual milk production in 2030 compared to 2010 in climate change-induced heat stress. The regions are grouped according to USDA regional Climate Hubs (https://www.climatehubs.oce.usda.gov), and the colored bars show the four global climate models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

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

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

Key Message 4

Vulnerability and Adaptive Capacity of Rural Communities

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

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

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

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

Emerging Issues and Research Gaps

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

- Considerable private- and public-sector research is focused on the genetic improvement of crops to enhance resilience under climate stress. However, most of the research has focused on a few major species, with minimal public resources invested in genetic improvement of specialty crops. Additionally, these efforts have focused largely on yield and much less on quality improvements that have significant nutritional and economic implications.
- Additional research would improve our understanding of the interactive effects of CO_2 concentration levels in the atmosphere, temperature, and water availability on plant physiological responses, particularly in highly dynamic field environments.
- Field-scale research has been conducted on the potential of cellulosic bioenergy crops, including grasses, fast-growing woody species, and corn residue harvest. However, the cascading effects of land-use change (from food to bioenergy crops) on rural economies, labor, and the environment remain uncertain.
- Scientific understanding of climate change impacts on beneficial and pest insects, pathogens and beneficial microorganisms, and weeds is limited, as is knowledge about the interactions of these organisms within complex agricultural landscapes.
- The Agricultural Model Intercomparison and Improvement Project (AgMIP) applies state-of-the art climate, crop/livestock, and agricultural economic models, along with stakeholder input, to coordinate multi-model regional and global assessments of climate impacts and adaptation. AgMIP is developing a rigorous process to evaluate agricultural models and thus is promoting continuous model improvement as well as supporting data sharing and the identification of adaptation technologies and policies. Currently, there is no comparable modeling framework to address animal agriculture or to evaluate the cascading effects of production on the broader food systems and food security issues.

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

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

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

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Traceable Accounts

Process Description

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

Key Message 1

Reduced Agricultural Productivity

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

Description of evidence base

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

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

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

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

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

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

Major uncertainties

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

Description of confidence and likelihood

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

Key Message 2

Degradation of Soil and Water Resources

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

Description of evidence base

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

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

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

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

Major uncertainties

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

Description of confidence and likelihood

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

Key Message 3

Health Challenges to Rural Populations and Livestock

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

Description of evidence base

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

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

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

Major uncertainties

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

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

Description of confidence and likelihood

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

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

Key Message 4

Vulnerability and Adaptive Capacity of Rural Communities

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

Description of evidence base

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

Major uncertainties

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

Description of confidence and likelihood

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

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