10 Agriculture and Rural Communities

Federal Coordinating Lead Author
Carolyn Olson
U.S. Department of Agriculture

Chapter Leads
Prasanna Gowda
USDA Agricultural Research Service

Jean L. Steiner
USDA Agricultural Research Service

Chapter Authors
Tracey Farrigan
USDA Economic Research Service

Michael A. Grusak
USDA Agricultural Research Service

Mark Boggess
USDA Agricultural Research Service

Review Editor
Georgine Yorgey
Washington State University

Recommended Citation for Chapter

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

On the Web: https://nca2018.globalchange.gov/chapter/agriculture-rural

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.

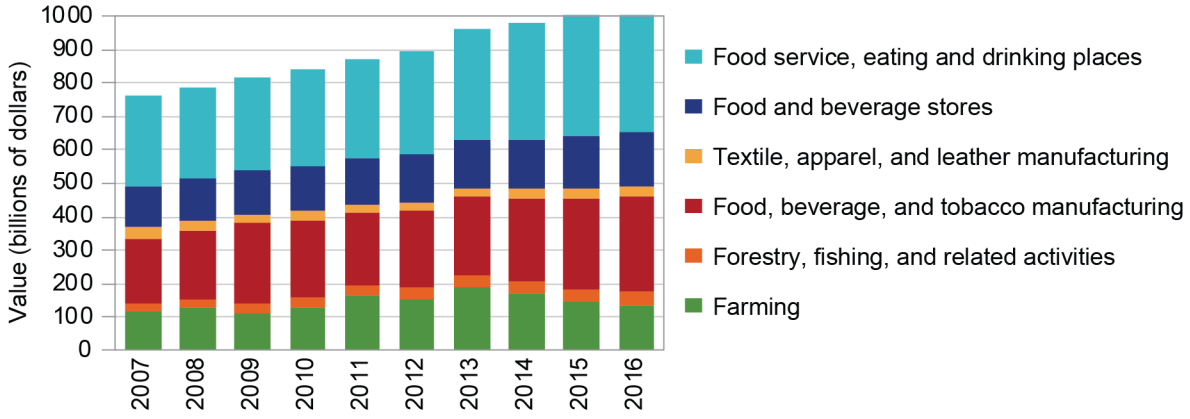
Climate change has the potential to adversely impact agricultural productivity at local, regional, and continental scales through alterations in rainfall patterns, more frequent occurrences of climate extremes (including high temperatures or drought), and altered patterns of pest pressure. Risks associated 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.

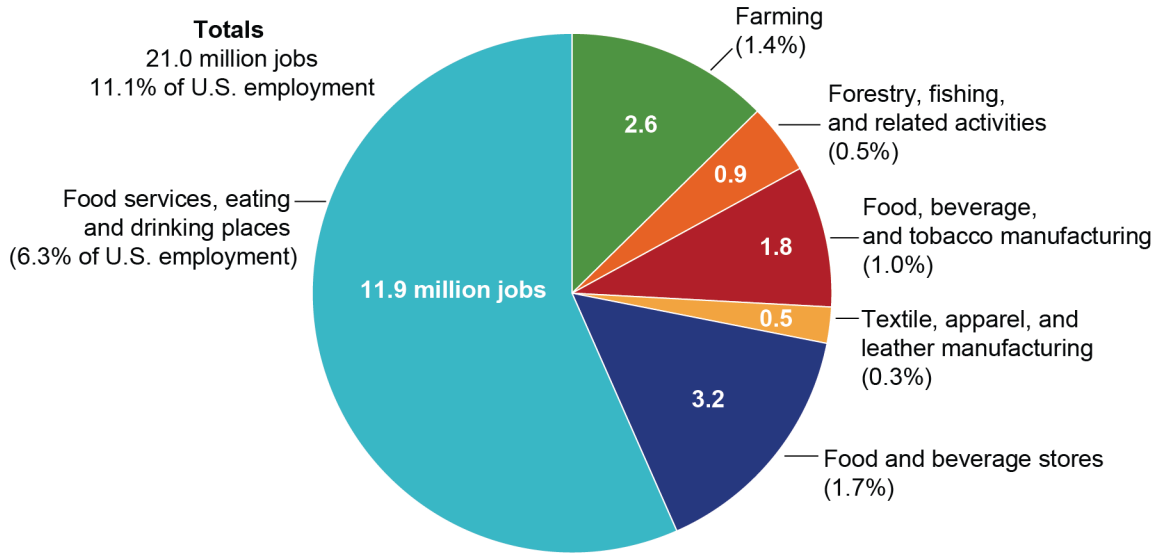
Climate change impacts, such as changes in extreme weather conditions, have a complex influence on human and livestock health. The consequences of climate change on the incidence of drought also impact the frequency and intensity of wildfires, and this holds implications for agriculture and rural communities. 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

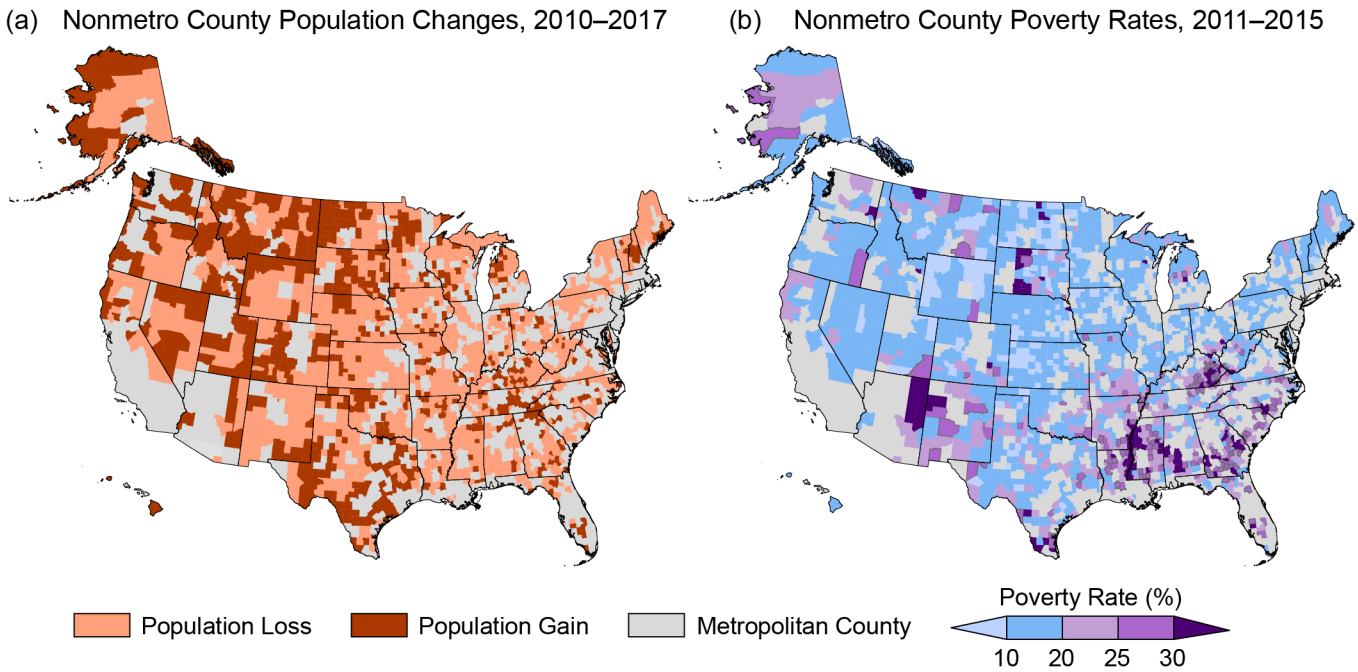


(b) Employment in Agriculture, Food, and Related Industries, 2015



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



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

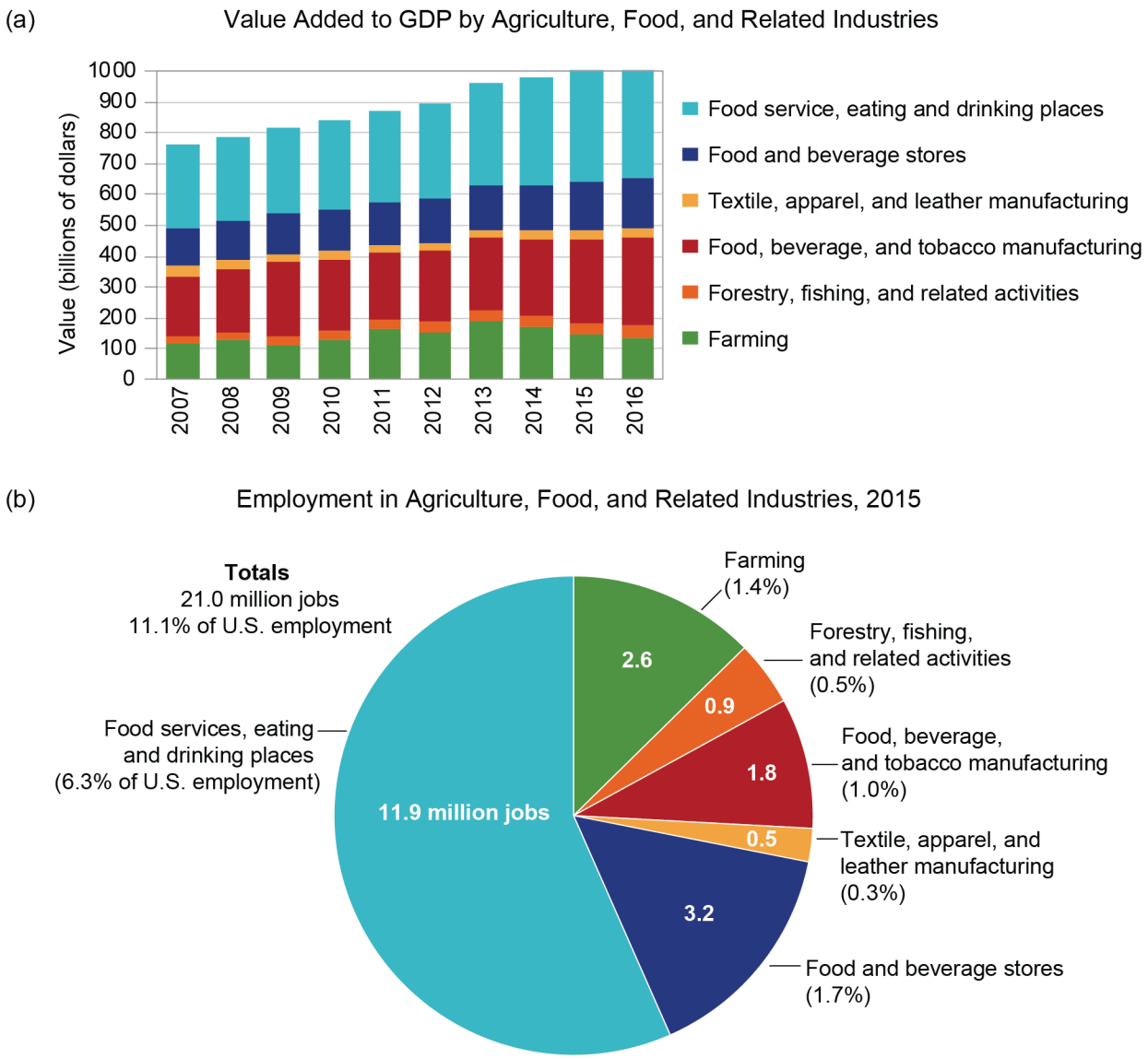


Figure 10.1: The figure shows (a) the contribution of agriculture and related sectors to the U.S. economy and (b) employment figures in agriculture and related sectors (as of 2015). Agriculture and other food-related value-added sectors account for 21 million full- and part-time jobs and contribute about $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

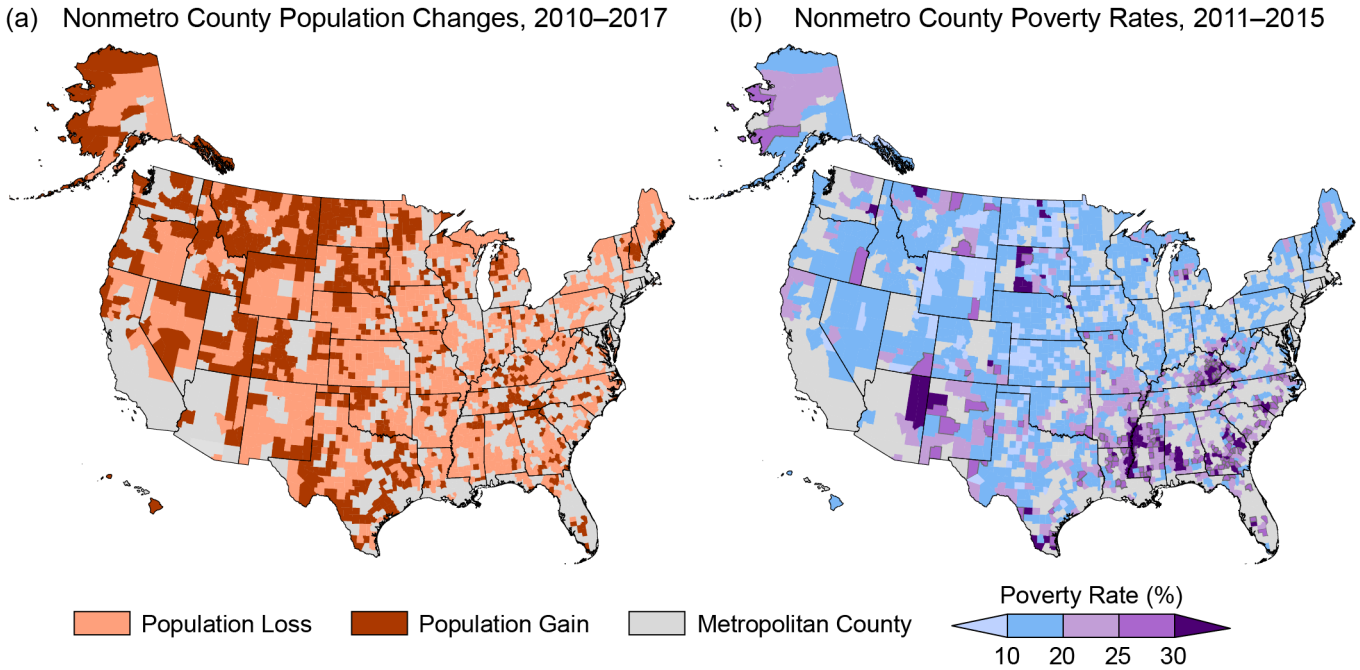


Figure 10.2: The figure shows county-level (a) population changes for 2010–2017 and (b) poverty rates for 2011–2015 in rural U.S. communities. Rural populations are migrating to urban regions due to relatively slow employment growth and high rates of poverty. Data for the U.S. Caribbean region were not 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

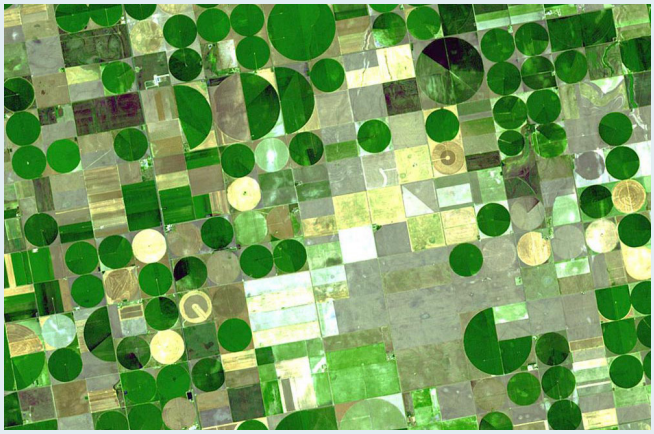
controls.[150] On average, the United States spends about $1 billion annually to fight wildfires, but it spent more than $2.9 billion in 2017 due to extreme drought conditions in some regions.[151] States, local governments, and the private sector also absorbed additional costs of firefighting and recovery. (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

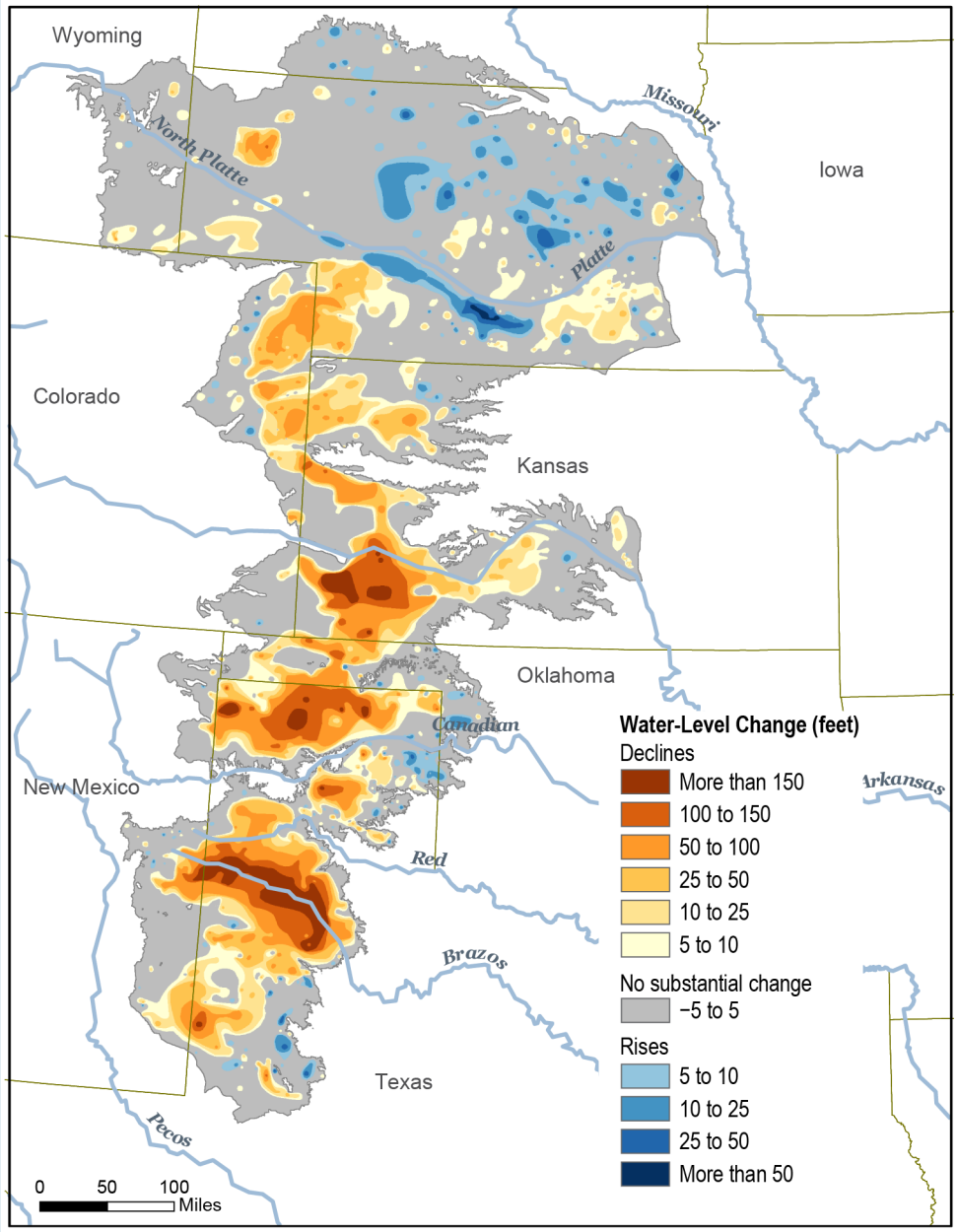


Figure 10.3: The figure shows changes in groundwater levels in the Ogallala Aquifer from predevelopment to 2015. Source: adapted from McGuire 2017.[163]

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

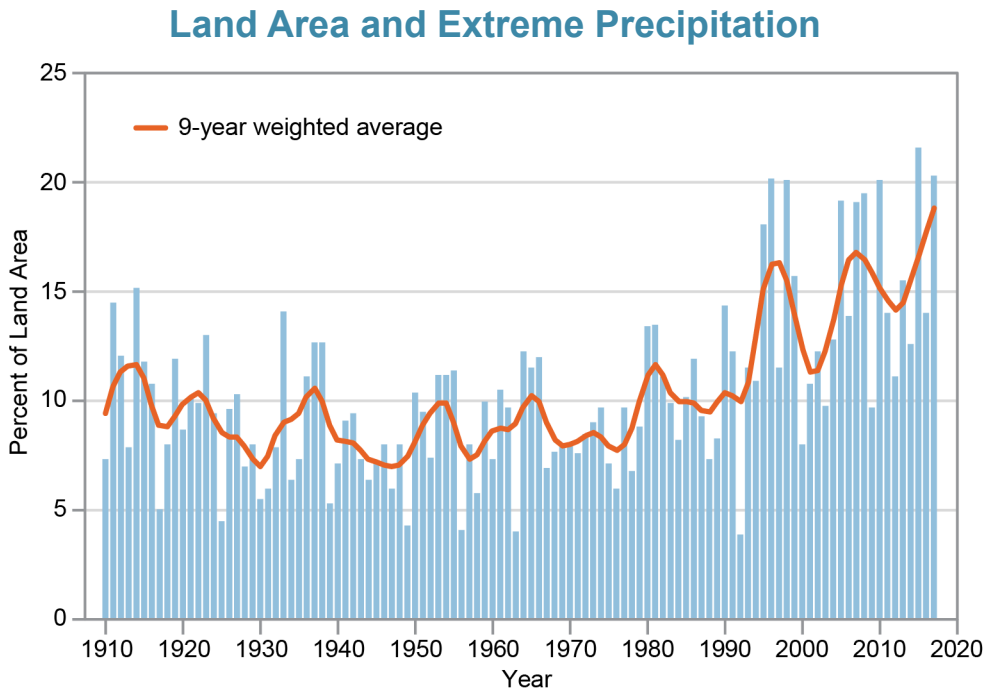


Figure 10.4: The figure shows the percent of land area in the contiguous 48 states experiencing extreme one-day precipitation events between 1910 and 2017. These extreme events pose erosion and water quality risks that have increased in recent decades. The bars represent individual years, and the orange 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

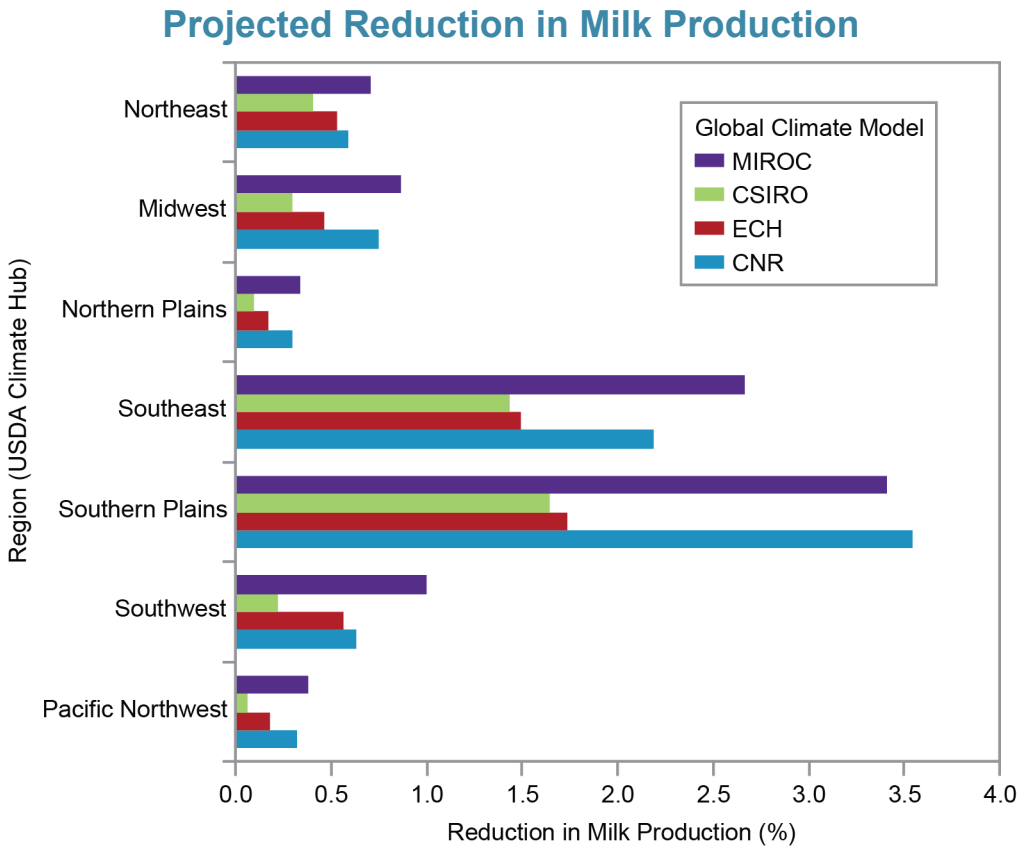


Figure 10.5: The figure shows the predicted reduction in annual milk production in 2030 compared to 2010 in climate change-induced heat stress. The regions are grouped according to USDA regional Climate Hubs (https://www.climatehubs.oce.usda.gov), and the colored bars show the four global climate models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

Acknowledgments

USGCRP Coordinators

Susan Aragon-Long
Senior Scientist

Allyza Lustig
Program Coordinator

Opening Image Credit
Tyringham, Massachusetts: © DenisTangneyJr/E+/ Getty Images.

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.

References

1. Kassel, K., A. Melton, and R.M. Morrison, 2017: Selected Charts from *Ag and Food Statistics: Charting the Essentials*. AP-078. USDA Economic Research Service, Washington, DC, 27 pp. https://www.ers.usda.gov/webdocs/publications/85463/ap-078.pdf?v=43025

2. ERS, 2018: Nonmetro Population Change, 2010-17 [chart]. USDA Economic Research Service (ERS), Washington, DC. https://www.ers.usda.gov/data-products/chart-gallery/gallery/chart-detail/?chartId=60121

3. ERS, 2017: Nonmetro County Poverty Rates, 2011-2015 Average [chart]. USDA Economic Research Service (ERS), Washington, DC. https://www.ers.usda.gov/data-products/chart-gallery/gallery/chart-detail/?chartId=82280

4. ERS, 2017: County Economic Types, 2015 Edition [website]. USDA Economic Research Service (ERS), Washington, DC. https://www.ers.usda.gov/data-products/county-typology-codes/descriptions-and-maps/

5. Farrigan, T., 2014: Poverty and deep poverty increasing in rural America. *Amber Waves*. https://www.ers.usda.gov/amber-waves/2014/march/poverty-and-deep-poverty-increasing-in-rural-america

6. Farrigan, T. and T. Parker, 2012: The concentration of poverty is a growing rural problem. *Amber Waves*. https://www.ers.usda.gov/amber-waves/2012/december/concentration-of-poverty

7. Hertz, T. and T. Farrigan, 2016: Understanding the Rise in Rural Child Poverty, 2003-2014. Economic Research Report No. (ERR-208) USDA Economic Research Service, Washington, DC, 27 pp. https://www.ers.usda.gov/publications/pub-details/?pubid=45543

8. Glaser, L., K. Kassel, and R.M. Morrison, 2013: A visual primer for the food and agricultural sectors. *Amber Waves*. https://www.ers.usda.gov/amber-waves/2013/december/a-visual-primer-for-the-food-and-agricultural-sectors/

9. USDA, 2014: 2012 Census of Agriculture. U.S. Department of Agriculture, National Agricultural Statistics Service, Washington, DC, 695 pp. http://www.agcensus.usda.gov/Publications/2012/

10. Brown, M.E., J.M. Antle, P. Backlund, E.R. Carr, W.E. Easterling, M.K. Walsh, C. Ammann, W. Attavanich, C.B. Barrett, M.F. Bellemare, V. Dancheck, C. Funk, K. Grace, J.S.I. Ingram, H. Jiang, H. Maletta, T. Mata, A. Murray, M. Ngugi, D. Ojima, B. O'Neill, and C. Tebaldi, 2015: Climate Change, Global Food Security, and the U.S. Food System. U.S. Global Change Research Program, Washington, DC, 146 pp. http://dx.doi.org/10.7930/J0862DC7

11. Brown, J.F. and M.S. Pervez, 2014: Merging remote sensing data and national agricultural statistics to model change in irrigated agriculture. *Agricultural Systems*, **127**, 28-40. http://dx.doi.org/10.1016/j.agsy.2014.01.004

12. Pugh, T.A.M., C. Müller, J. Elliott, D. Deryng, C. Folberth, S. Olin, E. Schmid, and A. Arneth, 2016: Climate analogues suggest limited potential for intensification of production on current croplands under climate change. *Nature Communications*, **7**, 12608. http://dx.doi.org/10.1038/ncomms12608

13. Tilman, D., 1999: Global environmental impacts of agricultural expansion: The need for sustainable and efficient practices. *Proceedings of the National Academy of Sciences of the United States of America*, **96** (11), 5995-6000. http://dx.doi.org/10.1073/pnas.96.11.5995

14. FAO, 2011: The State of the World's Land and Water Resources for Food and Agriculture: Managing Systems at Risk. Food and Agriculture Organization of the United Nations (FAO) and Earthscan, Rome and London, 285 pp. http://www.fao.org/docrep/017/i1688e/i1688e00.htm

15. USDA, 2010: Strategic Plan: FY 2010-2015. U.S. Department of Agriculture (USDA), Washington, DC, 50 pp. https://www.ocfo.usda.gov/usdasp/sp2010/sp2010.pdf

16. USDA, 2010: USDA Climate Change Science Plan. U.S. Department of Agriculture (USDA), Washington, DC, 21 pp. http://www.usda.gov/oce/climate_change/science_plan2010/USDA_CCSPlan_120810.pdf

17. Anderson, W.F., G. Sarath, S. Edme, M.D. Casler, R.B. Mitchell, C.M. Tobias, A.L. Hale, S.E. Sattler, and J.E. Knoll, 2016: Dedicated herbaceous biomass feedstock genetics and development. *BioEnergy Research*, **9** (2), 399-411. http://dx.doi.org/10.1007/s12155-015-9709-8

18. Blanco-Canqui, H., R.B. Mitchell, V.L. Jin, M.R. Schmer, and K.M. Eskridge, 2017: Perennial warm-season grasses for producing biofuel and enhancing soil properties: An alternative to corn residue removal. *GCB Bioenergy*, **9** (9), 1510-1521. http://dx.doi.org/10.1111/gcbb.12436

19. Brosse, N., A. Dufour, X. Meng, Q. Sun, and A. Ragauskas, 2012: *Miscanthus*: A fast-growing crop for biofuels and chemicals production. *Biofuels, Bioproducts and Biorefining*, **6** (5), 580-598. http://dx.doi.org/10.1002/bbb.1353

20. Ilut, DC, P.L. Sanchez, T.A. Coffelt, J.M. Dyer, M.A. Jenks, and M.A. Gore, 2017: A century of guayule: Comprehensive genetic characterization of the guayule (*Parthenium argentatum* A. Gray) USDA germplasm collection. *bioRxiv*. http://dx.doi.org/10.1101/147256

21. Long, D.S., F.L. Young, W.F. Schillinger, C.L. Reardon, J.D. Williams, B.L. Allen, W.L. Pan, and D.J. Wysocki, 2016: Development of dryland oilseed production systems in northwestern region of the USA. *BioEnergy Research*, **9** (2), 412-429. http://dx.doi.org/10.1007/s12155-016-9719-1

22. Mitchell, R.B., M.R. Schmer, W.F. Anderson, V. Jin, K.S. Balkcom, J. Kiniry, A. Coffin, and P. White, 2016: Dedicated energy crops and crop residues for bioenergy feedstocks in the central and eastern USA. *BioEnergy Research*, **9** (2), 384-398. http://dx.doi.org/10.1007/s12155-016-9734-2

23. USGCRP, 2018: Second State of the Carbon Cycle Report (SOCCR2): A Sustained Assessment Report. Cavallaro, N., G. Shrestha, R. Birdsey, M. Mayes, R. Najjar, S. Reed, P. Romero-Lankao, and Z. Zhu, Eds. U.S. Global Change Research Program, Washington, DC, 877 pp. https://doi.org/10.7930/SOCCR2.2018

24. Karlen, D.L., S.J. Birrell, J.M.F. Johnson, S.L. Osborne, T.E. Schumacher, G.E. Varvel, R.B. Ferguson, J.M. Novak, J.R. Fredrick, J.M. Baker, J.A. Lamb, P.R. Adler, G.W. Roth, and E.D. Nafziger, 2014: Multilocation corn stover harvest effects on crop yields and nutrient removal. *BioEnergy Research*, **7** (2), 528-539. http://dx.doi.org/10.1007/s12155-014-9419-7

25. Johnson, J.M.F., J.M. Novak, G.E. Varvel, D.E. Stott, S.L. Osborne, D.L. Karlen, J.A. Lamb, J. Baker, and P.R. Adler, 2014: Crop residue mass needed to maintain soil organic carbon levels: Can it be determined? *BioEnergy Research*, **7** (2), 481-490. http://dx.doi.org/10.1007/s12155-013-9402-8

26. Johnson, J.M.F. and N.W. Barbour, 2016: Nitrous oxide emission and soil carbon sequestration from herbaceous perennial biofuel feedstocks. *Soil Science Society of America Journal*, **80** (4), 1057-1070. http://dx.doi.org/10.2136/sssaj2015.12.0436

27. Novak, J.M., W.J. Busscher, D.W. Watts, J.E. Amonette, J.A. Ippolito, I.M. Lima, J. Gaskin, K.C. Das, C. Steiner, M. Ahmedna, D. Rehrah, and H. Schomberg, 2012: Biochars impact on soil-moisture storage in an Ultisol and two Aridisols. *Soil Science*, **177** (5), 310-320. http://dx.doi.org/10.1097/SS.0b013e31824e5593

28. Spokas, K.A., K.B. Cantrell, J.M. Novak, D.W. Archer, J.A. Ippolito, H.P. Collins, A.A. Boateng, I.M. Lima, M.C. Lamb, A.J. McAloon, R.D. Lentz, and K.A. Nichols, 2012: Biochar: A synthesis of its agronomic impact beyond carbon sequestration. *Journal of Environmental Quality*, **41** (4), 973-989. http://dx.doi.org/10.2134/jeq2011.0069

29. Bracmort, K., 2010: Biochar: Examination of an Emerging Concept to Mitigate Climate Change. CRS R40186. Congressional Research Service Washington, DC, 9 pp. https://fas.org/sgp/crs/misc/R40186.pdf

30. Adler, P.R., J.G. Mitchell, G. Pourhashem, S. Spatari, S.J. Del Grosso, and W.J. Parton, 2015: Integrating biorefinery and farm biogeochemical cycles offsets fossil energy and mitigates soil carbon losses. *Ecological Applications*, **25** (4), 1142-1156. http://dx.doi.org/10.1890/13-1694.1

31. Field, J.L., E. Marx, M. Easter, P.R. Adler, and K. Paustian, 2016: Ecosystem model parameterization and adaptation for sustainable cellulosic biofuel landscape design. *GCB Bioenergy*, **8** (6), 1106-1123. http://dx.doi.org/10.1111/gcbb.12316

32. Karlen, D.L., L.W. Beeler, R.G. Ong, and B.E. Dale, 2015: Balancing energy, conservation, and soil health requirements for plant biomass. *Journal of Soil and Water Conservation*, **70** (5), 279-287. http://dx.doi.org/10.2489/jswc.70.5.279

33. Hu, F., Y. Gan, H. Cui, C. Zhao, F. Feng, W. Yin, and Q. Chai, 2016: Intercropping maize and wheat with conservation agriculture principles improves water harvesting and reduces carbon emissions in dry areas. *European Journal of Agronomy*, **74**, 9-17. http://dx.doi.org/10.1016/j.eja.2015.11.019

34. Ruisi, P., S. Saia, G. Badagliacca, G. Amato, A.S. Frenda, D. Giambalvo, and G. Di Miceli, 2016: Long-term effects of no tillage treatment on soil N availability, N uptake, and ^{15}N-fertilizer recovery of durum wheat differ in relation to crop sequence. *Field Crops Research*, **189**, 51-58. http://dx.doi.org/10.1016/j.fcr.2016.02.009

35. Wiebe, K., 2003: Linking Land Quality, Agricultural Productivity, and Food Security. Agricultural Economic Report No. AER-823. USDA Economic Research Service, Washington, DC, 60 pp. https://www.ers.usda.gov/publications/pub-details/?pubid=41575

36. Godfray, H.C.J., J.R. Beddington, I.R. Crute, L. Haddad, D. Lawrence, J.F. Muir, J. Pretty, S. Robinson, S.M. Thomas, and C. Toulmin, 2010: Food security: The challenge of feeding 9 billion people. *Science*, **327** (5967), 812-818. http://dx.doi.org/10.1126/science.1185383

37. EPA, 2018: Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990–2016. EPA 430-P-18-001. U.S. Environmental Protection Agency (EPA), Washington, DC, various pp. https://www.epa.gov/sites/production/files/2018-01/documents/2018_complete_report.pdf

38. Walthall, C., P. Backlund, J. Hatfield, L. Lengnick, E. Marshall, M. Walsh, S. Adkins, M. Aillery, E.A. Ainsworth, C. Amman, C.J. Anderson, I. Bartomeus, L.H. Baumgard, F. Booker, B. Bradley, D.M. Blumenthal, J. Bunce, K. Burkey, S.M. Dabney, J.A. Delgado, J. Dukes, A. Funk, K. Garrett, M. Glenn, D.A. Grantz, D. Goodrich, S. Hu, R.C. Izaurralde, R.A.C. Jones, S.-H. Kim, A.D.B. Leaky, K. Lewers, T.L. Mader, A. McClung, J. Morgan, D.J. Muth, M. Nearing, D.M. Oosterhuis, D. Ort, C. Parmesan, W.T. Pettigrew, W. Polley, R. Rader, C. Rice, M. Rivington, E. Rosskopf, W.A. Salas, L.E. Sollenberger, R. Srygley, C. Stöckle, E.S. Takle, D. Timlin, J.W. White, R. Winfree, L. Wright-Morton, and L.H. Ziska, 2012: Climate Change and Agriculture in the United States: Effects and Adaptation. USDA Technical Bulletin 1935. U.S. Department of Agriculture, Washington, DC, 186 pp. http://www.usda.gov/oce/climate_change/effects_2012/CC%20and%20Agriculture%20Report%20(02-04-2013)b.pdf

39. Hatfield, J., G. Takle, R. Grotjahn, P. Holden, R.C. Izaurralde, T. Mader, E. Marshall, and D. Liverman, 2014: Ch. 6: Agriculture. *Climate Change Impacts in the United States: The Third National Climate Assessment*. Melillo, J.M., Terese (T.C.) Richmond, and G.W. Yohe, Eds. U.S. Global Change Research Program, Washington, DC, 150-174. http://dx.doi.org/10.7930/J02Z13FR

40. FAO, 2016: 2016 The State of Food and Agriculture: Climate Change, Agriculture and Food Security. Food and Agriculture Organization (FAO) of the United Nations, Rome, Italy, xvii, 173 pp. http://www.fao.org/3/a-i6030e.pdf

41. Hatfield, J.L., K.J. Boote, B.A. Kimball, L.H. Ziska, R.C. Izaurralde, D. Ort, A.M. Thomson, and D. Wolfe, 2011: Climate impacts on agriculture: Implications for crop production. *Agronomy Journal*, **103** (2), 351-370. http://dx.doi.org/10.2134/agronj2010.0303

42. Walsh, J., D. Wuebbles, K. Hayhoe, J. Kossin, K. Kunkel, G. Stephens, P. Thorne, R. Vose, M. Wehner, J. Willis, D. Anderson, S. Doney, R. Feely, P. Hennon, V. Kharin, T. Knutson, F. Landerer, T. Lenton, J. Kennedy, and R. Somerville, 2014: Ch. 2: Our changing climate. *Climate Change Impacts in the United States: The Third National Climate Assessment*. Melillo, J.M., T.C. Richmond, and G.W. Yohe, Eds. U.S. Global Change Research Program, Washington, DC, 19-67. http://dx.doi.org/10.7930/J0KW5CXT

43. Fischer, E.M. and R. Knutti, 2016: Observed heavy precipitation increase confirms theory and early models. *Nature Climate Change*, **6** (11), 986-991. http://dx.doi.org/10.1038/nclimate3110

44. Hatfield, J., C. Swanston, M. Janowiak, R.F. Steele, J. Hempel, J. Bochicchio, W. Hall, M. Cole, S. Hestvik, and J. Whitaker, 2015: USDA Midwest and Northern Forests Regional Climate Hub: Assessment of Climate Change Vulnerability and Adaptation and Mitigation Strategies. Anderson, T., Ed., U.S. Department of Agriculture, 55 pp. https://www.climatehubs.oce.usda.gov/content/usda-midwest-and-northern-forests-regional-climate-hub-assessment-climate-change

45. Malcolm, S., E. Marshall, M. Aillery, P. Heisey, M. Livingston, and K. Day-Rubenstein, 2012: Agricultural Adaptation to a Changing Climate: Economic and Environmental Implications Vary by U.S. Region. USDA-ERS Economic Research Report 136. U.S. Department of Agriculture Economic Research Service, Washington, DC. http://dx.doi.org/10.2139/ssrn.2112045

46. Takle, E.S.T., D. Gustafson, R. Beachy, G.C. Nelson, D. Mason-D'Croz, and A. Palazzo, 2013: US food security and climate change: Agricultural futures. *Economics: The Open-Access, Open-Assessment E-Journal*, **7** (2013-34), 1-41. http://dx.doi.org/10.5018/economics-ejournal.ja.2013-34

47. ERS, 2018: U.S. Agricultural Trade at a Glance [web site]. USDA Economic Research Service (ERS), Washington, DC. https://www.ers.usda.gov/topics/international-markets-us-trade/us-agricultural-trade/us-agricultural-trade-at-a-glance/

48. Glantz, M.H., R. Gommes, and S. Ramasamy, 2009: Coping with a Changing Climate: Considerations for Adaptation and Mitigation in Agriculture. FAO Environment And Natural Resources Series 15. Food and Agriculture Organization of the United Nations (FAO), Rome, 100 pp. http://www.fao.org/docrep/012/i1315e/i1315e00.htm

49. Coleman-Jensen, A., M.P. Rabbitt, C.A. Gregory, and A. Singh, 2016: Household Food Security in the United States in 2015. Economic Research Report (ERR) 215. U.S. Department of Agriculture, Economic Research Service, Washington, DC, 36 pp. https://www.ers.usda.gov/publications/pub-details/?pubid=79760

50. Hallström, E., A. Carlsson-Kanyama, and P. Börjesson, 2015: Environmental impact of dietary change: A systematic review. *Journal of Cleaner Production*, **91**, 1-11. http://dx.doi.org/10.1016/j.jclepro.2014.12.008

51. Harwatt, H., J. Sabaté, G. Eshel, S. Soret, and W. Ripple, 2017: Substituting beans for beef as a contribution toward US climate change targets. *Climatic Change*, **143** (1), 261-270. http://dx.doi.org/10.1007/s10584-017-1969-1

52. U.N. Department of Economic and Social Affairs Population Division, 2017: World Population Prospects: The 2017 Revision. Key Findings and Advance Tables U.N. Department of Economic and Social Affairs, New York, NY, 46 pp. https://esa.un.org/unpd/wpp/Publications/Files/WPP2017_KeyFindings.pdf

53. Woodson, R., 2016: The Role of U.S. Research Universities in Meeting the Global Food Security Challenge. 2016 AAAS Charles Valentine Riley Memorial Lecture. American Association for the Advancement of Science, Washington, DC, 19 pp. https://mcmprodaaas.s3.amazonaws.com/s3fs-public/2016%20AAAS%20Riley%20Lecture%20Proceedings.pdf

54. Rojas-Downing, M.M., A.P. Nejadhashemi, T. Harrigan, and S.A. Woznicki, 2017: Climate change and livestock: Impacts, adaptation, and mitigation. *Climate Risk Management*, **16**, 145-163. http://dx.doi.org/10.1016/j.crm.2017.02.001

55. Yorgey, G.G., S.A. Hall, E.R. Allen, E.M. Whitefield, N.M. Embertson, V.P. Jones, B.R. Saari, K. Rajagopalan, G.E. Roesch-McNally, B. Van Horne, J.T. Abatzoglou, H.P. Collins, L.L. Houston, T.W. Ewing, and C.E. Kruger, 2017: Northwest U.S. agriculture in a changing climate: Collaboratively defined research and extension priorities. *Frontiers in Environmental Science*, **5**, 52. http://dx.doi.org/10.3389/fenvs.2017.00052

56. Delgado, J.A. and C.J. Gantzer, 2015: The 4Rs for cover crops and other advances in cover crop management for environmental quality. *Journal of Soil and Water Conservation*, **70** (6), 142A-145A. http://dx.doi.org/10.2489/jswc.70.6.142A

57. Malcolm, S., E. Marshall, P. Heisey, and M. Livingston, 2013: Adaptation can help U.S. crop producers confront climate change. *Amber Waves*. https://www.ers.usda.gov/amber-waves/2013/february/adaptation-can-help-us-crop-producers-confront-climate-change/

58. Pitesky, M., A. Gunasekara, C. Cook, and F. Mitloehner, 2014: Adaptation of agricultural and food systems to a changing climate and increasing urbanization. *Current Sustainable/Renewable Energy Reports*, **1** (2), 43-50. http://dx.doi.org/10.1007/s40518-014-0006-5

59. Abberton, M., J. Batley, A. Bentley, J. Bryant, H. Cai, J. Cockram, A. Costa de Oliveira, L.J. Cseke, H. Dempewolf, C. De Pace, D. Edwards, P. Gepts, A. Greenland, A.E. Hall, R. Henry, K. Hori, G.T. Howe, S. Hughes, M. Humphreys, D. Lightfoot, A. Marshall, S. Mayes, H.T. Nguyen, F.C. Ogbonnaya, R. Ortiz, A.H. Paterson, R. Tuberosa, B. Valliyodan, R.K. Varshney, and M. Yano, 2016: Global agricultural intensification during climate change: A role for genomics. *Plant Biotechnology Journal*, **14** (4), 1095-1098. http://dx.doi.org/10.1111/pbi.12467

60. Araya, A., I. Kisekka, X. Lin, P.V. Vara Prasad, P.H. Gowda, C. Rice, and A. Andales, 2017: Evaluating the impact of future climate change on irrigated maize production in Kansas. *Climate Risk Management*, **17**, 139-154. http://dx.doi.org/10.1016/j.crm.2017.08.001

61. Kisekka, I., A. Schlegel, L. Ma, P.H. Gowda, and P.V.V. Prasad, 2017: Optimizing preplant irrigation for maize under limited water in the High Plains. *Agricultural Water Management*, **187**, 154-163. http://dx.doi.org/10.1016/j.agwat.2017.03.023

62. Kaye, J.P. and M. Quemada, 2017: Using cover crops to mitigate and adapt to climate change. A review. *Agronomy for Sustainable Development*, **37** (1), 4. http://dx.doi.org/10.1007/s13593-016-0410-x

63. Hammac, W.A., D.E. Stott, D.L. Karlen, and C.A. Cambardella, 2016: Crop, tillage, and landscape effects on near-surface soil quality indices in Indiana. *Soil Science Society of America Journal*, **80** (6), 1638-1652. http://dx.doi.org/10.2136/sssaj2016.09.0282

64. Mader, T.L., S.M. Holt, G.L. Hahn, M.S. Davis, and D.E. Spiers, 2002: Feeding strategies for managing heat load in feedlot cattle. *Journal of Animal Science*, **80** (9), 2373-2382. http://dx.doi.org/10.2527/2002.8092373x

65. Holt, S.M., J.B. Gaughan, and T.L. Mader, 2004: Feeding strategies for grain-fed cattle in a hot environment. *Australian Journal of Agricultural Research*, **55** (7), 719-725. http://dx.doi.org/10.1071/AR03261

66. Howden, S.M., J.-F. Soussana, F.N. Tubiello, N. Chhetri, M. Dunlop, and H. Meinke, 2007: Adapting agriculture to climate change. *Proceedings of the National Academy of Sciences of the United States of America*, **104** (50), 19691-19696. http://dx.doi.org/10.1073/pnas.0701890104

67. Keown, J.F., P.J. Kononoff, and R.J. Grant, 2016: How to Reduce Heat Stress in Dairy Cattle. NebGuide G1582. University of Nebraska–Lincoln Extension, Institute of Agriculture and Natural Resources, Lincoln, NE, 2 pp. http://extensionpublications.unl.edu/assets/pdf/g1582.pdf

68. Havlík, P., H. Valin, A. Mosnier, M. Obersteiner, J.S. Baker, M. Herrero, M.C. Rufino, and E. Schmid, 2013: Crop productivity and the global livestock sector: Implications for land use change and greenhouse gas emissions. *American Journal of Agricultural Economics*, **95** (2), 442-448. http://dx.doi.org/10.1093/ajae/aas085

69. Mader, T.L. and D. Griffin, 2015: Management of cattle exposed to adverse environmental conditions. *Veterinary Clinics: Food Animal Practice*, **31** (2), 247-258. http://dx.doi.org/10.1016/j.cvfa.2015.03.006

70. De Rensis, F., I. Garcia-Ispierto, and F. López-Gatius, 2015: Seasonal heat stress: Clinical implications and hormone treatments for the fertility of dairy cows. *Theriogenology*, **84** (5), 659-666. http://dx.doi.org/10.1016/j.theriogenology.2015.04.021

71. Urdaz, J.H., M.W. Overton, D.A. Moore, and J.E.P. Santos, 2006: *Technical note*: Effects of adding shade and fans to a feedbunk sprinkler system for preparturient cows on health and performance. *Journal of Dairy Science*, **89** (6), 2000-2006. http://dx.doi.org/10.3168/jds.S0022-0302(06)72267-6

72. Brown-Brandl, T.M., C.G. Chitko-McKown, R.A. Eigenberg, J.J. Mayer, T.H. Welsh, J.D. Davis, and J.L. Purswell, 2017: Physiological responses of feedlot heifers provided access to different levels of shade. *Animal*, **11** (8), 1344-1353. http://dx.doi.org/10.1017/S1751731116002664

73. Scasta, J.D., D.L. Lalman, and L. Henderson, 2016: Drought mitigation for grazing operations: Matching the animal to the environment. *Rangelands*, **38** (4), 204-210. http://dx.doi.org/10.1016/j.rala.2016.06.006

74. Derner, J.D. and D.J. Augustine, 2016: Adaptive management for drought on rangelands. *Rangelands*, **38** (4), 211-215. http://dx.doi.org/10.1016/j.rala.2016.05.002

75. Derner, J.D., C. Stanley, and C. Ellis, 2016: Usable science: Soil health. *Rangelands*, **38** (2), 64-67. http://dx.doi.org/10.1016/j.rala.2015.10.010

76. Renaudeau, D., A. Collin, S. Yahav, V. de Basilio, J.L. Gourdine, and R.J. Collier, 2011: Adaptation to hot climate and strategies to alleviate heat stress in livestock production. *Animal*, **6** (5), 707-728. http://dx.doi.org/10.1017/S1751731111002448

77. Garner, J.B., M.L. Douglas, S.R.O. Williams, W.J. Wales, L.C. Marett, T.T.T. Nguyen, C.M. Reich, and B.J. Hayes, 2016: Genomic selection improves heat tolerance in dairy cattle. *Scientific Reports*, **6**, 34114. http://dx.doi.org/10.1038/srep34114

78. Luck, J., M. Spackman, A. Freeman, P. Tre¸bicki, W. Griffiths, K. Finlay, and S. Chakraborty, 2011: Climate change and diseases of food crops. *Plant Pathology*, **60** (1), 113-121. http://dx.doi.org/10.1111/j.1365-3059.2010.02414.x

79. Chakraborty, S. and A.C. Newton, 2011: Climate change, plant diseases and food security: An overview. *Plant Pathology*, **60** (1), 2-14. http://dx.doi.org/10.1111/j.1365-3059.2010.02411.x

80. Hewitt, C., V.B.S. Silva, N. Golding, R. Gao, C.A.S. Coelho, R. Duell, J. Pollock, K. Onogi, and W. Secretariat, 2015: Managing risk with climate prediction products and services. *WMO Bulletin*, **64**. https://public.wmo.int/en/resources/bulletin/managing-risk-climate-prediction-products-and-services

81. Falco, S.D., F. Adinolfi, M. Bozzola, and F. Capitanio, 2014: Crop insurance as a strategy for adapting to climate change. *Journal of Agricultural Economics*, **65** (2), 485-504. http://dx.doi.org/10.1111/1477-9552.12053

82. Mase, A.S., B.M. Gramig, and L.S. Prokopy, 2017: Climate change beliefs, risk perceptions, and adaptation behavior among midwestern U.S. crop farmers. *Climate Risk Management*, **15**, 8-17. http://dx.doi.org/10.1016/j.crm.2016.11.004

83. Key, N., S. Sneeringer, and D. Marquardt, 2014: Climate Change, Heat Stress, and U.S. Dairy Production. Economic Research Report No. ERR-175. USDA Economic Research Service, Washington, DC, 45 pp. https://www.ers.usda.gov/publications/pub-details/?pubid=45282

84. USGCRP, 2017: Climate Science Special Report: Fourth National Climate Assessment, Volume I. Wuebbles, D.J., D.W. Fahey, K.A. Hibbard, D.J. Dokken, B.C. Stewart, and T.K. Maycock, Eds. U.S. Global Change Research Program, Washington, DC, USA, 470 pp. http://dx.doi.org/10.7930/J0J964J6

85. Auffhammer, M. and W. Schlenker, 2014: Empirical studies on agricultural impacts and adaptation. *Energy Economics*, **46**, 555-561. http://dx.doi.org/10.1016/j.eneco.2014.09.010

86. Wehner, M.F., J.R. Arnold, T. Knutson, K.E. Kunkel, and A.N. LeGrande, 2017: Droughts, floods, and wildfires. *Climate Science Special Report: Fourth National Climate Assessment, Volume I*. Wuebbles, D.J., D.W. Fahey, K.A. Hibbard, D.J. Dokken, B.C. Stewart, and T.K. Maycock, Eds. U.S. Global Change Research Program, Washington, DC, USA, 231-256. http://dx.doi.org/10.7930/J0CJ8BNN

87. Otkin, J.A., M. Svoboda, E.D. Hunt, T.W. Ford, M.C. Anderson, C. Hain, and J.B. Basara, 2018: Flash droughts: A review and assessment of the challenges imposed by rapid onset droughts in the United States. *Bulletin of the American Meteorological Society*, **99**, 911-919. http://dx.doi.org/10.1175/bams-d-17-0149.1

88. Mann, M.E. and P.H. Gleick, 2015: Climate change and California drought in the 21st century. *Proceedings of the National Academy of Sciences of the United States of America*, **112** (13), 3858-3859. http://dx.doi.org/10.1073/pnas.1503667112

89. Bita, C. and T. Gerats, 2013: Plant tolerance to high temperature in a changing environment: Scientific fundamentals and production of heat stress-tolerant crops. *Frontiers in Plant Science*, **4** (273). http://dx.doi.org/10.3389/fpls.2013.00273

90. Challinor, A.J., J. Watson, D.B. Lobell, S.M. Howden, D.R. Smith, and N. Chhetri, 2014: A meta-analysis of crop yield under climate change and adaptation. *Nature Climate Change*, **4** (4), 287-291. http://dx.doi.org/10.1038/nclimate2153

91. Zampieri, M., A. Ceglar, F. Dentener, and A. Toreti, 2017: Wheat yield loss attributable to heat waves, drought and water excess at the global, national and subnational scales. *Environmental Research Letters*, **12** (6), 064008. http://dx.doi.org/10.1088/1748-9326/aa723b

92. Zhao, C., B. Liu, S. Piao, X. Wang, D.B. Lobell, Y. Huang, M. Huang, Y. Yao, S. Bassu, P. Ciais, J.-L. Durand, J. Elliott, F. Ewert, I.A. Janssens, T. Li, E. Lin, Q. Liu, P. Martre, C. Müller, S. Peng, J. Peñuelas, A.C. Ruane, D. Wallach, T. Wang, D. Wu, Z. Liu, Y. Zhu, Z. Zhu, and S. Asseng, 2017: Temperature increase reduces global yields of major crops in four independent estimates. *Proceedings of the National Academy of Sciences of the United States of America*, **114** (35), 9326-9331. http://dx.doi.org/10.1073/pnas.1701762114

93. Climate Central, 2012: The Age of Western Wildfires. Climate Central, Princeton, NJ, 18 pp. http://www.climatecentral.org/wgts/wildfires/Wildfires2012.pdf

94. Upton, J., 2017: Breathing fire: Health is a causality of California's climate-fueled blazes. *Climate Central News*. Climate Central, Princeton, NJ. http://www.climatecentral.org/news/breathing-fire-california-air-quality-smoke-waves-21754

95. Donovan, V.M., C.L. Wonkka, and D. Twidwell, 2017: Surging wildfire activity in a grassland biome. *Geophysical Research Letters*, **44** (12), 5986-5993. http://dx.doi.org/10.1002/2017GL072901

96. Turco, M., J. von Hardenberg, A. AghaKouchak, M.C. Llasat, A. Provenzale, and R.M. Trigo, 2017: On the key role of droughts in the dynamics of summer fires in Mediterranean Europe. *Scientific Reports*, **7** (1), 81. http://dx.doi.org/10.1038/s41598-017-00116-9

97. Marshall, E., M. Aillery, S. Malcolm, and R. Williams, 2015: Climate Change, Water Scarcity, and Adaptation in the U.S. Fieldcrop Sector. Economic Research Report No. (ERR-201). USDA Economic Research Service, Washington, DC, 119 pp. https://www.ers.usda.gov/publications/pub-details/?pubid=45496

98. Scanlon, B.R., R.C. Reedy, C.C. Faunt, D. Pool, and K. Uhlman, 2016: Enhancing drought resilience with conjunctive use and managed aquifer recharge in California and Arizona. *Environmental Research Letters*, **11** (3), 035013. http://dx.doi.org/10.1088/1748-9326/11/4/049501

99. Blanc, E., K. Strzepek, A. Schlosser, H. Jacoby, A. Gueneau, C. Fant, S. Rausch, and J. Reilly, 2014: Modeling U.S. water resources under climate change. *Earth's Future*, **2** (4), 197-224. http://dx.doi.org/10.1002/2013EF000214

100. Blanc, E., J. Caron, C. Fant, and E. Monier, 2017: Is current irrigation sustainable in the United States? An integrated assessment of climate change impact on water resources and irrigated crop yields. *Earth's Future*, **5** (8), 877-892. http://dx.doi.org/10.1002/2016EF000473

101. Franzluebbers, A.J., 2002: Water infiltration and soil structure related to organic matter and its stratification with depth. *Soil and Tillage Research*, **66** (2), 197-205. http://dx.doi.org/10.1016/S0167-1987(02)00027-2

102. Farm Service Agency, 2017: Emergency Disaster Designation and Declaration Process. Disaster Assistance Fact Sheet. USDA Farm Service Agency, Washington, DC, 2 pp. https://www.fsa.usda.gov/Assets/USDA-FSA-Public/usdafiles/FactSheets/2017/emergency_disaster_designation_and_declaration_process_oct2017.pdf

103. Kimball, B.A., J.W. White, G.W. Wall, and M.J. Ottman, 2016: Wheat responses to a wide range of temperatures: The Hot Serial Cereal Experiment. *Improving Modeling Tools to Assess Climate Change Effects on Crop Response*. Hatfield, J.L. and D. Fleisher, Eds. American Society of Agronomy, Crop Science Society of America, and Soil Science Society of America, Inc., Madison, WI, 33-44. http://dx.doi.org/10.2134/advagricsystmodel7.2014.0014

104. Prager, D., C. Burns, and N. Key, 2017: Examining farm sector and farm household income. *Amber Waves*. https://www.ers.usda.gov/amber-waves/2017/august/examining-farm-sector-and-farm-household-income/

105. Rippey, B.R., 2015: The U.S. drought of 2012. *Weather and Climate Extremes*, **10**, 57-64. http://dx.doi.org/10.1016/j.wace.2015.10.004

106. RMA, 2017: The Risk Management Agency Safety Net: Market Penetration and Market Potential. USDA Risk Management Agency, Washington, DC, 58 pp. https://www.rma.usda.gov/pubs/2017/portfolio/portfolio.pdf

107. Diffenbaugh, N.S., D.L. Swain, and D. Touma, 2015: Anthropogenic warming has increased drought risk in California. *Proceedings of the National Academy of Sciences of the United States of America*, **112** (13), 3931-3936. http://dx.doi.org/10.1073/pnas.1422385112

108. Basso, B., A.D. Kendall, and D.W. Hyndman, 2013: The future of agriculture over the Ogallala Aquifer: Solutions to grow crops more efficiently with limited water. *Earth's Future*, **1** (1), 39-41. http://dx.doi.org/10.1002/2013EF000107

109. State of California, 2016: Sustainable Groundwater Management. California Department of Water Resources, Sacramento, CA. http://www.water.ca.gov/groundwater/sgm/

110. State of California, 2016: Groundwater Sustainability Plan Emergency Regulations. California Department of Water Resources, Sacramento, CA. http://www.water.ca.gov/groundwater/sgm/gsp.cfm

111. Moran, T. and A. Cravens, 2015: California's Sustainable Groundwater Management Act of 2014: Recommendations for Preventing and Resolving Groundwater Conflicts. Stanford University Water in the West, Stanford, CA, 30 pp. http://waterinthewest.stanford.edu/sites/default/files/SGMA_RecommendationsforGWConflicts_2.pdf

112. Beach, R.H., Y. Cai, A. Thomson, X. Zhang, R. Jones, B.A. McCarl, A. Crimmins, J. Martinich, J. Cole, S. Ohrel, B. DeAngelo, J. McFarland, K. Strzepek, and B. Boehlert, 2015: Climate change impacts on US agriculture and forestry: Benefits of global climate stabilization. *Environmental Research Letters*, **10** (9), 095004. http://dx.doi.org/10.1088/1748-9326/10/9/095004

113. Schauberger, B., S. Archontoulis, A. Arneth, J. Balkovic, P. Ciais, D. Deryng, J. Elliott, C. Folberth, N. Khabarov, C. Müller, T.A.M. Pugh, S. Rolinski, S. Schaphoff, E. Schmid, X. Wang, W. Schlenker, and K. Frieler, 2017: Consistent negative response of US crops to high temperatures in observations and crop models. *Nature Communications*, **8**, 13931. http://dx.doi.org/10.1038/ncomms13931

114. Swann, A.L.S., F.M. Hoffman, C.D. Koven, and J.T. Randerson, 2016: Plant responses to increasing CO_2 reduce estimates of climate impacts on drought severity. *Proceedings of the National Academy of Sciences of the United States of America*, **113** (36), 10019-10024. http://dx.doi.org/10.1073/pnas.1604581113

115. Eyshi Rezaei, E., H. Webber, T. Gaiser, J. Naab, and F. Ewert, 2015: Heat stress in cereals: Mechanisms and modelling. *European Journal of Agronomy*, **64**, 98-113. http://dx.doi.org/10.1016/j.eja.2014.10.003

116. Gourdji, S.M., A.M. Sibley, and D.B. Lobell, 2013: Global crop exposure to critical high temperatures in the reproductive period: Historical trends and future projections. *Environmental Research Letters*, **8** (2), 024041. http://dx.doi.org/10.1088/1748-9326/8/2/024041

117. Hatfield, J.L. and J.H. Prueger, 2015: Temperature extremes: Effect on plant growth and development. *Weather and Climate Extremes*, **10** (Part A), 4-10. http://dx.doi.org/10.1016/j.wace.2015.08.001

118. Kerr, A., J. Dialesandro, K. Steenwerth, N. Lopez-Brody, and E. Elias, 2017: Vulnerability of California specialty crops to projected mid-century temperature changes. *Climatic Change*. http://dx.doi.org/10.1007/s10584-017-2011-3

119. Varanasi, A., P.V.V. Prasad, and M. Jugulam, 2016: Ch. 3: Impact of climate change factors on weeds and herbicide efficacy. *Advances in Agronomy*. Sparks, D.L., Ed. Academic Press, 107-146. http://dx.doi.org/10.1016/bs.agron.2015.09.002

120. Asseng, S., F. Ewert, P. Martre, R.P. Rötter, D.B. Lobell, D. Cammarano, B.A. Kimball, M.J. Ottman, G.W. Wall, J.W. White, M.P. Reynolds, P.D. Alderman, P.V.V. Prasad, P.K. Aggarwal, J. Anothai, B. Basso, C. Biernath, A.J. Challinor, G. De Sanctis, J. Doltra, E. Fereres, M. Garcia-Vila, S. Gayler, G. Hoogenboom, L.A. Hunt, R.C. Izaurralde, M. Jabloun, C.D. Jones, K.C. Kersebaum, A.K. Koehler, C. Müller, S. Naresh Kumar, C. Nendel, G. O'Leary, J.E. Olesen, T. Palosuo, E. Priesack, E. Eyshi Rezaei, A.C. Ruane, M.A. Semenov, I. Shcherbak, C. Stöckle, P. Stratonovitch, T. Streck, I. Supit, F. Tao, P.J. Thorburn, K. Waha, E. Wang, D. Wallach, J. Wolf, Z. Zhao, and Y. Zhu, 2015: Rising temperatures reduce global wheat production. *Nature Climate Change*, **5**, 143-147. http://dx.doi.org/10.1038/nclimate2470

121. Bassu, S., N. Brisson, J.-L. Durand, K. Boote, J. Lizaso, J.W. Jones, C. Rosenzweig, A.C. Ruane, M. Adam, C. Baron, B. Basso, C. Biernath, H. Boogaard, S. Conijn, M. Corbeels, D. Deryng, G. De Sanctis, S. Gayler, P. Grassini, J. Hatfield, S. Hoek, C. Izaurralde, R. Jongschaap, A.R. Kemanian, K.C. Kersebaum, S.-H. Kim, N.S. Kumar, D. Makowski, C. Müller, C. Nendel, E. Priesack, M.V. Pravia, F. Sau, I. Shcherbak, F. Tao, E. Teixeira, D. Timlin, and K. Waha, 2014: How do various maize crop models vary in their responses to climate change factors? *Global Change Biology*, **20** (7), 2301-2320. http://dx.doi.org/10.1111/gcb.12520

122. Grafton, R.Q., J. Williams, and Q. Jiang, 2017: Possible pathways and tensions in the food and water nexus. *Earth's Future*, **5** (5), 449-462. http://dx.doi.org/10.1002/2016EF000506

123. Myers, S.S., A. Zanobetti, I. Kloog, P. Huybers, A.D.B. Leakey, A.J. Bloom, E. Carlisle, L.H. Dietterich, G. Fitzgerald, T. Hasegawa, N.M. Holbrook, R.L. Nelson, M.J. Ottman, V. Raboy, H. Sakai, K.A. Sartor, J. Schwartz, S. Seneweera, M. Tausz, and Y. Usui, 2014: Increasing CO_2 threatens human nutrition. *Nature*, **510** (7503), 139-142. http://dx.doi.org/10.1038/nature13179

124. Myers, S.S., M.R. Smith, S. Guth, C.D. Golden, B. Vaitla, N.D. Mueller, A.D. Dangour, and P. Huybers, 2017: Climate change and global food systems: Potential impacts on food security and undernutrition. *Annual Review of Public Health*, **38** (1), 259-277. http://dx.doi.org/10.1146/annurev-publhealth-031816-044356

125. Korres, N.E., J.K. Norsworthy, P. Tehranchian, T.K. Gitsopoulos, D.A. Loka, D.M. Oosterhuis, D.R. Gealy, S.R. Moss, N.R. Burgos, M.R. Miller, and M. Palhano, 2016: Cultivars to face climate change effects on crops and weeds: A review. *Agronomy for Sustainable Development*, **36** (1), 12. http://dx.doi.org/10.1007/s13593-016-0350-5

126. Hatfield, J.L. and C.L. Walthall, 2015: Meeting global food needs: Realizing the potential via genetics × environment × management interactions. *Agronomy Journal*, **107** (4), 1215-1226. http://dx.doi.org/10.2134/agronj15.0076

127. Watson, A., S. Ghosh, M.J. Williams, W.S. Cuddy, J. Simmonds, M.-D. Rey, M. Asyraf Md Hatta, A. Hinchliffe, A. Steed, D. Reynolds, N.M. Adamski, A. Breakspear, A. Korolev, T. Rayner, L.E. Dixon, A. Riaz, W. Martin, M. Ryan, D. Edwards, J. Batley, H. Raman, J. Carter, C. Rogers, C. Domoney, G. Moore, W. Harwood, P. Nicholson, M.J. Dieters, I.H. DeLacy, J. Zhou, C. Uauy, S.A. Boden, R.F. Park, B.B.H. Wulff, and L.T. Hickey, 2018: Speed breeding is a powerful tool to accelerate crop research and breeding. *Nature Plants*, **4** (1), 23-29. http://dx.doi.org/10.1038/s41477-017-0083-8

128. Kant, S., S. Seneweera, J. Rodin, M. Materne, D. Burch, S. Rothstein, and G. Spangenberg, 2012: Improving yield potential in crops under elevated CO_2: Integrating the photosynthetic and nitrogen utilization efficiencies. *Frontiers in Plant Science*, **3** (162). http://dx.doi.org/10.3389/fpls.2012.00162

129. Bevan, M.W., C. Uauy, B.B.H. Wulff, J. Zhou, K. Krasileva, and M.D. Clark, 2017: Genomic innovation for crop improvement. *Nature*, **543**, 346-354. http://dx.doi.org/10.1038/nature22011

130. Ortiz, R., K.D. Sayre, B. Govaerts, R. Gupta, G.V. Subbarao, T. Ban, D. Hodson, J.M. Dixon, J. Iván Ortiz-Monasterio, and M. Reynolds, 2008: Climate change: Can wheat beat the heat? *Agriculture, Ecosystems & Environment*, **126** (1), 46-58. http://dx.doi.org/10.1016/j.agee.2008.01.019

131. Mittler, R. and E. Blumwald, 2010: Genetic engineering for modern agriculture: Challenges and perspectives. *Annual Review of Plant Biology*, **61** (1), 443-462. http://dx.doi.org/10.1146/annurev-arplant-042809-112116

132. Chapman, S.C., S. Chakraborty, M.F. Dreccer, and S.M. Howden, 2012: Plant adaptation to climate change—Opportunities and priorities in breeding. *Crop and Pasture Science*, **63** (3), 251-268. http://dx.doi.org/10.1071/CP11303

133. Jha, U.C., A. Bohra, and N.P. Singh, 2014: Heat stress in crop plants: Its nature, impacts and integrated breeding strategies to improve heat tolerance. *Plant Breeding*, **133** (6), 679-701. http://dx.doi.org/10.1111/pbr.12217

134. Heisey, P.W. and K. Day Rubenstein, 2015: Using Crop Genetic Resources to Help Agriculture Adapt to Climate Change: Economics and Policy. Economic Information Bulletin No. EIB-139. U.S. Department of Agriculture, Economic Research Service, Washington, DC, 29 pp. https://www.ers.usda.gov/publications/pub-details/?pubid=43963

135. Board on Agriculture and Natural Resources (BANR), 2016: *Genetically Engineered Crops: Experiences and Prospects*. The National Academies Press, Washington, DC, 606 pp. http://dx.doi.org/10.17226/23395

136. Lipper, L., P. Thornton, B.M. Campbell, T. Baedeker, A. Braimoh, M. Bwalya, P. Caron, A. Cattaneo, D. Garrity, K. Henry, R. Hottle, L. Jackson, A. Jarvis, F. Kossam, W. Mann, N. McCarthy, A. Meybeck, H. Neufeldt, T. Remington, P.T. Sen, R. Sessa, R. Shula, A. Tibu, and E.F. Torquebiau, 2014: Climate-smart agriculture for food security. *Nature Climate Change*, **4**, 1068-1072. http://dx.doi.org/10.1038/nclimate2437

137. Asfaw, S. and L. Lipper, 2016: Managing Climate Risk Using Climate-Smart Agriculture. I5402E/1/04.16. Food and Agriculture Organization of the United Nations, Rome, Italy, 15 pp. http://www.fao.org/3/a-i5402e.pdf

138. Steenwerth, K.L., A.K. Hodson, A.J. Bloom, M.R. Carter, A. Cattaneo, C.J. Chartres, J.L. Hatfield, K. Henry, J.W. Hopmans, W.R. Horwath, B.M. Jenkins, E. Kebreab, R. Leemans, L. Lipper, M.N. Lubell, S. Msangi, R. Prabhu, M.P. Reynolds, S. Sandoval Solis, W.M. Sischo, M. Springborn, P. Tittonell, S.M. Wheeler, S.J. Vermeulen, E.K. Wollenberg, L.S. Jarvis, and L.E. Jackson, 2014: Climate-smart agriculture global research agenda: Scientific basis for action. *Agriculture & Food Security*, **3** (1), 11. http://dx.doi.org/10.1186/2048-7010-3-11

139. Monaghan, J.M., A. Daccache, L.H. Vickers, T.M. Hess, E.K. Weatherhead, I.G. Grove, and J.W. Knox, 2013: More "crop per drop": Constraints and opportunities for precision irrigation in European agriculture. *Journal of the Science of Food and Agriculture*, **93** (5), 977-980. http://dx.doi.org/10.1002/jsfa.6051

140. Wallander, S., M. Aillery, D. Hellerstein, and M.S. Hand, 2013: The Role of Conservation Programs in Drought Risk Adaptation. Economic Research Report ERR-148. USDA, Eonomic Research Service, Washington, DC, 68 pp. https://www.ers.usda.gov/publications/pub-details/?pubid=45067

141. Balafoutis, A., B. Beck, S. Fountas, J. Vangeyte, T. Wal, I. Soto, M. Gómez-Barbero, A. Barnes, and V. Eory, 2017: Precision agriculture technologies positively contributing to GHG emissions mitigation, farm productivity and economics. *Sustainability*, **9** (8), 1339. http://dx.doi.org/10.3390/su9081339

142. McPherson, R.A., C.A. Fiebrich, K.C. Crawford, J.R. Kilby, D.L. Grimsley, J.E. Martinez, J.B. Basara, B.G. Illston, D.A. Morris, K.A. Kloesel, A.D. Melvin, H. Shrivastava, J.M. Wolfinbarger, J.P. Bostic, D.B. Demko, R.L. Elliott, S.J. Stadler, J.D. Carlson, and A.J. Sutherland, 2007: Statewide monitoring of the mesoscale environment: A technical update on the Oklahoma Mesonet. *Journal of Atmospheric and Oceanic Technology*, **24** (3), 301-321. http://dx.doi.org/10.1175/jtech1976.1

143. Irmak, S., J.M. Rees, G.L. Zoubek, B.S. van DeWalle, W.R. Rathje, R. DeBuhr, D. Leininger, D.D. Siekman, J.W. Schneider, and A.P. Christiansen, 2010: Nebraska Agricultural Water Management Demonstration Network (NAWMDN): Integrating research and extension/outreach. *Applied Engineering in Agriculture*, **26** (4), 599-613. http://dx.doi.org/10.13031/2013.32066

144. MRLC, [2017]: National Land Cover Database 2011 (NLCD 2011) Multi-Resolution Land Characteristics (MRLC) Consortium, Sioux Falls, SD. https://www.mrlc.gov/nlcd2011.php

145. Vose, J., J.S. Clark, C. Luce, and T. Patel-Weynand, Eds., 2016: *Effects of Drought on Forests and Rangelands in the United States: A Comprehensive Science Synthesis*. Gen. Tech. Rep. WO-93b. U.S. Department of Agriculture, Forest Service, Washington Office, Washington, DC, 289 pp. http://www.treesearch.fs.fed.us/pubs/50261

146. USDA Forest Service and DOI Office of Wildland Fire, 2015: 2014 Quadrennial Fire Review: Final Report. Booz Allen Hamilton, Washington, DC, 79 pp. https://www.forestsandrangelands.gov/documents/qfr/2014QFRFinalReport.pdf

147. Liu, Z., M.C. Wimberly, A. Lamsal, T.L. Sohl, and T.J. Hawbaker, 2015: Climate change and wildfire risk in an expanding wildland–urban interface: A case study from the Colorado Front Range Corridor. *Landscape Ecology*, **30** (10), 1943-1957. http://dx.doi.org/10.1007/s10980-015-0222-4

148. Norgaard, K.M., K. Vinyeta, L. Hillman, B. Tripp, and F. Lake, 2016: Karuk Tribe Climate Vulnerability Assessment: Assessing Vulnerabilities from the Increased Frequency of High Severity Fire. Karuk Tribe, Department of Natural Resources, Happy Camp, CA, 205 pp. https://karuktribeclimatechangeprojects.wordpress.com/climate-vulnerabilty-assessment/

149. Gamble, J.L., J. Balbus, M. Berger, K. Bouye, V. Campbell, K. Chief, K. Conlon, A. Crimmins, B. Flanagan, C. Gonzalez-Maddux, E. Hallisey, S. Hutchins, L. Jantarasami, S. Khoury, M. Kiefer, J. Kolling, K. Lynn, A. Manangan, M. McDonald, R. Morello-Frosch, M.H. Redsteer, P. Sheffield, K. Thigpen Tart, J. Watson, K.P. Whyte, and A.F. Wolkin, 2016: Ch. 9: Populations of concern. *The Impacts of Climate Change on Human Health in the United States: A Scientific Assessment*. U.S. Global Change Research Program, Washington, DC, 247–286. http://dx.doi.org/10.7930/J0Q81B0T

150. FEMA, 2004: The California Fires Coordination Group. A Report to the Secretary of Homeland Security. Department of Homeland Security, Emergence Preparedness and Response, Washington, DC, 62 pp. https://www.fema.gov/pdf/library/draft_cfcg_report_0204.pdf

151. NIFC, 2017: Historical Wildland Fire Information: Suppression Costs (1985-2016). National Interagency Fire Center (NIFC), Boise, ID, 1 pp. https://www.nifc.gov/fireInfo/fireInfo_documents/SuppCosts.pdf

152. Guerrero, B., S. Amosson, and T. McCollum, 2013: The Impact of the Beef Industry in the Southern Ogallala Region. AG-001. Texas A&M AgriLife Extension Service, College Station, TX, 17 pp. http://mediad.publicbroadcasting.net/p/hppr/files/201309/Impact_of_the_Beef_Industry.pdf

153. Scanlon, B.R., C.C. Faunt, L. Longuevergne, R.C. Reedy, W.M. Alley, V.L. McGuire, and P.B. McMahon, 2012: Groundwater depletion and sustainability of irrigation in the US High Plains and Central Valley. *Proceedings of the National Academy of Sciences of the United States of America*, **109** (24), 9320-9325. http://dx.doi.org/10.1073/pnas.1200311109

154. O'Shaughnessy, S.A., S.R. Evett, A. Andrade, F. Workneh, J.A. Price, and C.M. Rush, 2016: Site-specific variable-rate irrigation as a means to enhance water use efficiency. *Transactions of the ASABE*, **59** (1), 239. http://dx.doi.org/10.13031/trans.59.11165

155. O'Shaughnessy, S.A. and P.D. Colaizzi, 2017: Performance of precision mobile drip irrigation in the Texas High Plains region. *Agronomy*, **7** (4), 68. http://dx.doi.org/10.3390/agronomy7040068

156. Chai, Q., Y. Gan, C. Zhao, H.-L. Xu, R.M. Waskom, Y. Niu, and K.H.M. Siddique, 2015: Regulated deficit irrigation for crop production under drought stress. A review. *Agronomy for Sustainable Development*, **36** (1), 3. http://dx.doi.org/10.1007/s13593-015-0338-6

157. Rudnick, D., S. Irmak, R. Ferguson, T. Shaver, K. Djaman, G. Slater, A. Bereuter, N. Ward, D. Francis, M. Schmer, B. Wienhold, and S.V. Donk, 2016: Economic return versus crop water productivity of maize for various nitrogen rates under full irrigation, limited irrigation, and rainfed settings in south central Nebraska. *Journal of Irrigation and Drainage Engineering*, **142** (6), 04016017. http://dx.doi.org/10.1061/(ASCE)IR.1943-4774.0001023

158. Trout, T.J. and K.C. DeJonge, 2017: Water productivity of maize in the US high plains. *Irrigation Science*, **35** (3), 251-266. http://dx.doi.org/10.1007/s00271-017-0540-1

159. Li, X., S. Kang, X. Zhang, F. Li, and H. Lu, 2018: Deficit irrigation provokes more pronounced responses of maize photosynthesis and water productivity to elevated CO_2. *Agricultural Water Management*, **195**, 71-83. http://dx.doi.org/10.1016/j.agwat.2017.09.017

160. Gowda, P.H., T.A. Howell, R.L. Baumhardt, D.O. Porter, T.H. Marek, and V. Nangia, 2016: A user-friendly interactive tool for estimating reference ET using ASCE standardized Penman-Monteith equation. *Applied Engineering in Agriculture*, **32** (3), 383. http://dx.doi.org/10.13031/aea.32.11673

161. Zhao, J., Q. Xue, K.E. Jessup, B. Hao, X. Hou, T.H. Marek, W. Xu, S.R. Evett, S.A. O'Shaughnessy, and D.K. Brauer, 2018: Yield and water use of drought-tolerant maize hybrids in a semiarid environment. *Field Crops Research*, **216**, 1-9. http://dx.doi.org/10.1016/j.fcr.2017.11.001

162. Brauer, D., D. Devlin, K. Wagner, M. Ballou, D. Hawkins, and R. Lascano, 2017: Ogallala Aquifer Program: A catalyst for research and education to sustain the Ogallala Aquifer on the Southern High Plains (2003–2017). *Journal of Contemporary Water Research & Education*, **162** (1), 4-17. http://dx.doi.org/10.1111/j.1936-704X.2017.03256.x

163. McGuire, V.L., 2017: Water-Level and Recoverable Water in Storage Changes, High Plains Aquifer, Predevelopment to 2015 and 2013–15. 2017-5040, Scientific Investigations Report 2017-5040. U. S. Geological Survey, Reston, VA, 24 pp. http://dx.doi.org/10.3133/sir20175040

164. Pimentel, D. and M. Burgess, 2013: Soil erosion threatens food production. *Agriculture*, **3** (3), 443-463. http://dx.doi.org/10.3390/agriculture3030443

165. Lal, R. and B.A. Stewart, Eds., 1990: *Soil Degradation*. Advances in Soil Science 11. Springer, New York, 345 pp. http://dx.doi.org/10.1007/978-1-4612-3322-0

166. Sharpley, A., 2016: Managing agricultural phosphorus to minimize water quality impacts. *Scientia Agricola*, **73**, 1-8. http://dx.doi.org/10.1590/0103-9016-2015-0107

167. Issaka, S. and M.A. Ashraf, 2017: Impact of soil erosion and degradation on water quality: A review. *Geology, Ecology, and Landscapes*, **1** (1), 1-11. http://dx.doi.org/10.1080/24749508.2017.1301053

168. Yasarer, L.M.W. and B.S.M. Sturm, 2016: Potential impacts of climate change on reservoir services and management approaches. *Lake and Reservoir Management*, **32** (1), 13-26. http://dx.doi.org/10.1080/10402381.2015.1107665

169. Frank, D., M. Reichstein, M. Bahn, K. Thonicke, D. Frank, M.D. Mahecha, P. Smith, M. van der Velde, S. Vicca, F. Babst, C. Beer, N. Buchmann, J.G. Canadell, P. Ciais, W. Cramer, A. Ibrom, F. Miglietta, B. Poulter, A. Rammig, S.I. Seneviratne, A. Walz, M. Wattenbach, M.A. Zavala, and J. Zscheischler, 2015: Effects of climate extremes on the terrestrial carbon cycle: Concepts, processes and potential future impacts. *Global Change Biology*, **21** (8), 2861-2880. http://dx.doi.org/10.1111/gcb.12916

170. Yue, Y., J. Ni, P. Ciais, S. Piao, T. Wang, M. Huang, A.G.L. Borthwick, T. Li, Y. Wang, A. Chappell, and K. Van Oost, 2016: Lateral transport of soil carbon and land–atmosphere CO_2 flux induced by water erosion in China. *Proceedings of the National Academy of Sciences of the United States of America*, **113** (24), 6617-6622. http://dx.doi.org/10.1073/pnas.1523358113

171. EPA, 2016: Climate Change Indicators: Heavy Precipitation. U.S. Environmental Protection Agency (EPA). https://www.epa.gov/climate-indicators/climate-change-indicators-heavy-precipitation

172. Garbrecht, J.D., J.L. Steiner, and C.A. Cox, 2007: The times they are changing: Soil and water conservation in the 21st century. *Hydrological Processes*, **21** (19), 2677-2679. http://dx.doi.org/10.1002/hyp.6853

173. Maresch, W., M.R. Walbridge, and D. Kugler, 2008: Enhancing conservation on agricultural landscapes: A new direction for the Conservation Effects Assessment Project. *Journal of Soil and Water Conservation*, **63** (6), 198A-203A. http://dx.doi.org/10.2489/jswc.63.6.198A

174. Xu, H., D.G. Brown, and A.L. Steiner, 2018: Sensitivity to climate change of land use and management patterns optimized for efficient mitigation of nutrient pollution. *Climatic Change*, **147** (3), 647-662. http://dx.doi.org/10.1007/s10584-018-2159-5

175. Testa, J.M., Y. Li, Y.J. Lee, M. Li, DC Brady, D.M. Di Toro, W.M. Kemp, and J.J. Fitzpatrick, 2014: Quantifying the effects of nutrient loading on dissolved O_2 cycling and hypoxia in Chesapeake Bay using a coupled hydrodynamic–biogeochemical model. *Journal of Marine Systems*, **139**, 139-158. http://dx.doi.org/10.1016/j.jmarsys.2014.05.018

176. Carpenter, S.R., E.H. Stanley, and M.J.V. Zanden, 2011: State of the world's freshwater ecosystems: Physical, chemical, and biological changes. *Annual Review of Environment and Resources*, **36** (1), 75-99. http://dx.doi.org/10.1146/annurev-environ-021810-094524

177. National Research Council, 2009: *Nutrient Control Actions for Improving Water Quality in the Mississippi River Basin and Northern Gulf of Mexico*. The National Academies Press, Washington, DC, 90 pp. http://dx.doi.org/10.17226/12544

178. Ahn, K.-H. and R.N. Palmer, 2016: Trend and variability in observed hydrological extremes in the United States. *Journal of Hydrologic Engineering*, **21** (2), 04015061. http://dx.doi.org/10.1061/(ASCE)HE.1943-5584.0001286

179. Pryor, S.C., J.A. Howe, and K.E. Kunkel, 2009: How spatially coherent and statistically robust are temporal changes in extreme precipitation in the contiguous USA? *International Journal of Climatology*, **29** (1), 31-45. http://dx.doi.org/10.1002/joc.1696

180. Groisman, P.Y., R.W. Knight, and T.R. Karl, 2001: Heavy precipitation and high streamflow in the contiguous United States: Trends in the twentieth century. *Bulletin of the American Meteorological Society*, **82** (2), 219-246. http://dx.doi.org/10.1175/1520-0477(2001)082<0219:hpahsi>2.3.co;2

181. Groisman, P.Y., R.W. Knight, D.R. Easterling, T.R. Karl, G.C. Hegerl, and V.N. Razuvaev, 2005: Trends in intense precipitation in the climate record. *Journal of Climate*, **18** (9), 1326-1350. http://dx.doi.org/10.1175/jcli3339.1

182. Altieri, A.H. and K.B. Gedan, 2015: Climate change and dead zones. *Global Change Biology*, **21** (4), 1395-1406. http://dx.doi.org/10.1111/gcb.12754

183. Bendtsen, J. and J.L.S. Hansen, 2013: Effects of global warming on hypoxia in the Baltic Sea–North Sea transition zone. *Ecological Modelling*, **264**, 17-26. http://dx.doi.org/10.1016/j.ecolmodel.2012.06.018

184. Carstensen, J., J.H. Andersen, B.G. Gustafsson, and D.J. Conley, 2014: Deoxygenation of the Baltic Sea during the last century. *Proceedings of the National Academy of Sciences of the United States of America*, **111** (15), 5628-5633. http://dx.doi.org/10.1073/pnas.1323156111

185. Hagy, J.D., W.R. Boynton, C.W. Keefe, and K.V. Wood, 2004: Hypoxia in Chesapeake Bay, 1950–2001: Long-term change in relation to nutrient loading and river flow. *Estuaries*, **27** (4), 634-658. http://dx.doi.org/10.1007/bf02907650

186. Jenny, J.P., F. Arnaud, B. Alric, J.M. Dorioz, P. Sabatier, M. Meybeck, and M.E. Perga, 2014: Inherited hypoxia: A new challenge for reoligotrophicated lakes under global warming. *Global Biogeochemical Cycles*, **28** (12), 1413-1423. http://dx.doi.org/10.1002/2014GB004932

187. Bianchi, T.S., S.F. DiMarco, J.H. Cowan, R.D. Hetland, P. Chapman, J.W. Day, and M.A. Allison, 2010: The science of hypoxia in the Northern Gulf of Mexico: A review. *Science of The Total Environment*, **408** (7), 1471-1484. http://dx.doi.org/10.1016/j.scitotenv.2009.11.047

188. Smith, D.R., K.W. King, and M.R. Williams, 2015: What is causing the harmful algal blooms in Lake Erie? *Journal of Soil and Water Conservation*, **70** (2), 27A-29A. http://dx.doi.org/10.2489/jswc.70.2.27A

189. Du, J., J. Shen, K. Park, Y.P. Wang, and X. Yu, 2018: Worsened physical condition due to climate change contributes to the increasing hypoxia in Chesapeake Bay. *Science of The Total Environment*, **630**, 707-717. http://dx.doi.org/10.1016/j.scitotenv.2018.02.265

190. Rabalais, N.N., R.J. Díaz, L.A. Levin, R.E. Turner, D. Gilbert, and J. Zhang, 2010: Dynamics and distribution of natural and human-caused hypoxia. *Biogeosciences*, **7** (2), 585-619. http://dx.doi.org/10.5194/bg-7-585-2010

191. Park, K., C.-K. Kim, and W.W. Schroeder, 2007: Temporal variability in summertime bottom hypoxia in shallow areas of Mobile Bay, Alabama. *Estuaries and Coasts*, **30** (1), 54-65. http://dx.doi.org/10.1007/bf02782967

192. Díaz, R.J. and R. Rosenberg, 2008: Spreading dead zones and consequences for marine ecosystems. *Science*, **321** (5891), 926-929. http://dx.doi.org/10.1126/science.1156401

193. NOAA Fisheries, 2016: Fisheries Economics of the United States, 2014. NOAA Technical Memorandum NMFS-F/SPO-163. NOAA, National Marine Fisheries Service (NOAA Fisheries), Silver Spring, MD, 235 pp. https://www.st.nmfs.noaa.gov/economics/publications/feus/fisheries_economics_2014/index

194. Díaz, R.J. and R. Rosenberg, 2011: Introduction to environmental and economic consequences of hypoxia. *International Journal of Water Resources Development*, **27** (1), 71-82. http://dx.doi.org/10.1080/07900627.2010.531379

195. Meier, H.E.M., H.C. Andersson, K. Eilola, B.G. Gustafsson, I. Kuznetsov, B. Müller-Karulis, T. Neumann, and O.P. Savchuk, 2011: Hypoxia in future climates: A model ensemble study for the Baltic Sea. *Geophysical Research Letters*, **38** (24). http://dx.doi.org/10.1029/2011GL049929

196. Winder, M. and U. Sommer, 2012: Phytoplankton response to a changing climate. *Hydrobiologia*, **698** (1), 5-16. http://dx.doi.org/10.1007/s10750-012-1149-2

197. Gilly, W.F., J.M. Beman, S.Y. Litvin, and B.H. Robison, 2013: Oceanographic and biological effects of shoaling of the oxygen minimum zone. *Annual Review of Marine Science*, **5** (1), 393-420. http://dx.doi.org/10.1146/annurev-marine-120710-100849

198. CENR, 2010: Scientific Assessment of Hypoxia in U.S. Coastal Waters. Interagency Working Group on Harmful Algal Blooms, Hypoxia, and Human Health of the Joint Subcommittee on Ocean Science and Technology. Committee on Environment and Natural Resources, Washington, DC, 154 pp. https://obamawhitehouse.archives.gov/sites/default/files/microsites/ostp/hypoxia-report.pdf

199. IJC, 2014: A Balanced Diet for Lake Erie: Reducing Phosphorus Loadings and Harmful Algal Blooms. International Joint Commission (IJC), Washington, DC, and Ottowa, ON, 96 pp. http://www.ijc.org/files/publications/2014%20IJC%20LEEP%20REPORT.pdf

200. Olson, K., J. Matthews, L.W. Morton, and J. Sloan, 2015: Impact of levee breaches, flooding, and land scouring on soil productivity. *Journal of Soil and Water Conservation*, **70** (1), 5A-11A. http://dx.doi.org/10.2489/jswc.70.1.5A

201. Parris, A., P. Bromirski, V. Burkett, D. Cayan, M. Culver, J. Hall, R. Horton, K. Knuuti, R. Moss, J. Obeysekera, A. Sallenger, and J. Weiss, 2012: Global Sea Level Rise Scenarios for the United States National Climate Assessment. NOAA Tech Memo OAR CPO-1. National Oceanic and Atmospheric Administration, Silver Spring, MD, 37 pp. http://scenarios.globalchange.gov/sites/default/files/NOAA_SLR_r3_0.pdf

202. Sweet, W.V., R. Horton, R.E. Kopp, A.N. LeGrande, and A. Romanou, 2017: Sea level rise. *Climate Science Special Report: Fourth National Climate Assessment, Volume I*. Wuebbles, D.J., D.W. Fahey, K.A. Hibbard, D.J. Dokken, B.C. Stewart, and T.K. Maycock, Eds. U.S. Global Change Research Program, Washington, DC, USA, 333-363. http://dx.doi.org/10.7930/J0VM49F2

203. U.S. Federal Government, 2016: U.S. Climate Resilience Toolkit: Coastal Erosion [web page]. United States Global Change Research Program, Washington, DC. https://toolkit.climate.gov/topics/coastal-flood-risk/coastal-erosion

204. Dahl, T.E. and S.-M. Stedman, 2013: Status and Trends of Wetlands in the Coastal Watersheds of the Conterminous United States 2004 to 2009. U.S. Department of the Interior, Fish and Wildlife Service and National Oceanic and Atmospheric Administration, National Marine Fisheries Service, Reston, VA, and Silver Spring, MD, 46 pp. https://www.fws.gov/wetlands/Documents/Status-and-Trends-of-Wetlands-In-the-Coastal-Watersheds-of-the-Conterminous-US-2004-to-2009.pdf

205. Storlazzi, C.D., E.P.L. Elias, and P. Berkowitz, 2015: Many atolls may be uninhabitable within decades due to climate change. *Scientific Reports*, **5**, 14546. http://dx.doi.org/10.1038/srep14546

206. Ziska, L., K. Knowlton, C. Rogers, D. Dalan, N. Tierney, M.A. Elder, W. Filley, J. Shropshire, L.B. Ford, C. Hedberg, P. Fleetwood, K.T. Hovanky, T. Kavanaugh, G. Fulford, R.F. Vrtis, J.A. Patz, J. Portnoy, F. Coates, L. Bielory, and D. Frenz, 2011: Recent warming by latitude associated with increased length of ragweed pollen season in central North America. *Proceedings of the National Academy of Sciences of the United States of America*, **108** (10), 4248-4251. http://dx.doi.org/10.1073/pnas.1014107108

207. Fann, N., T. Brennan, P. Dolwick, J.L. Gamble, V. Ilacqua, L. Kolb, C.G. Nolte, T.L. Spero, and L. Ziska, 2016: Ch. 3: Air quality impacts. *The Impacts of Climate Change on Human Health in the United States: A Scientific Assessment*. U.S. Global Change Research Program, Washington, DC, 69–98. http://dx.doi.org/10.7930/J0GQ6VP6

208. St-Pierre, N.R., B. Cobanov, and G. Schnitkey, 2003: Economic losses from heat stress by US livestock industries. *Journal of Dairy Science*, **86**, E52-E77. http://dx.doi.org/10.3168/jds.S0022-0302(03)74040-5

209. Amundson, J.L., T.L. Mader, R.J. Rasby, and Q.S. Hu, 2006: Environmental effects on pregnancy rate in beef cattle. *Journal of Animal Science*, **84** (12), 3415-3420. http://dx.doi.org/10.2527/jas.2005-611

210. Dash, S., A.K. Chakravarty, A. Singh, A. Upadhyay, M. Singh, and Y. Saleem, 2016: Effect of heat stress on reproductive performances of dairy cattle and buffaloes: A review. *Veterinary World*, **9** (3), 235-244. http://dx.doi.org/10.14202/vetworld.2016.235-244

211. Giridhar, K. and A. Samireddypalle, 2015: Impact of climate change on forage availability for livestock. *Climate Change Impact on Livestock: Adaptation and Mitigation*. Sejian, V., J. Gaughan, L. Baumgard, and C. Prasad, Eds. Springer India, New Delhi, 97-112. http://dx.doi.org/10.1007/978-81-322-2265-1_7

212. Lee, M.A., A.P. Davis, M.G.G. Chagunda, and P. Manning, 2017: Forage quality declines with rising temperatures, with implications for livestock production and methane emissions. *Biogeosciences*, **14** (6), 1403-1417. http://dx.doi.org/10.5194/bg-14-1403-2017

213. Paul, B.K., D. Che, and V.L. Tinnon, 2007: Emergency Responses for High Plains Cattle Affected by the December 28-31, 2006, Blizzard. Quick Response Report 191. Natural Hazards Center, Boulder, CO, 12 pp. http://hermes.cde.state.co.us/drupal/islandora/object/co%3A5497/datastream/OBJ/view

214. Zhorov, I., 2013: Why did South Dakota snowstorm kill so many cattle? *National Geographic*. https://news.nationalgeographic.com/news/2013/10/131022-cattle-blizzard-south-dakota-winter-storm-atlas/

215. Pragna, P., P.R. Archana, J. Aleena, V. Sejian, G. Krishnan, M. Bagath, A. Manimaran, V. Beena, E.K. Kurien, G. Varma, and R. Bhatta, 2017: Heat stress and dairy cow: Impact on both milk yield and composition. *International Journal of Dairy Science*, **12** (1), 1-11. http://dx.doi.org/10.3923/ijds.2017.1.11

216. Yano, M., H. Shimadzu, and T. Endo, 2014: Modelling temperature effects on milk production: A study on Holstein cows at a Japanese farm. *SpringerPlus*, **3** (1), 129. http://dx.doi.org/10.1186/2193-1801-3-129

217. Cowley, F.C., D.G. Barber, A.V. Houlihan, and D.P. Poppi, 2015: Immediate and residual effects of heat stress and restricted intake on milk protein and casein composition and energy metabolism. *Journal of Dairy Science*, **98** (4), 2356-2368. http://dx.doi.org/10.3168/jds.2014-8442

218. Key, N. and S. Sneeringer, 2014: Potential effects of climate change on the productivity of U.S. dairies. *American Journal of Agricultural Economics*, **96** (4), 1136-1156. http://dx.doi.org/10.1093/ajae/aau002

219. Mader, T.L., L.J. Johnson, and J.B. Gaughan, 2010: A comprehensive index for assessing environmental stress in animals. *Journal of Animal Science*, **88** (6), 2153-2165. http://dx.doi.org/10.2527/jas.2009-2586

220. Kristensen, T.N., A.A. Hoffmann, C. Pertoldi, and A.V. Stronen, 2015: What can livestock breeders learn from conservation genetics and vice versa? *Frontiers in Genetics*, **6** (38). http://dx.doi.org/10.3389/fgene.2015.00038

221. Fournel, S., V. Ouellet, and É. Charbonneau, 2017: Practices for alleviating heat stress of dairy cows in humid continental climates: A literature review. *Animals*, **7** (5), 37. http://dx.doi.org/10.3390/ani7050037

222. Thornton, P.K., 2010: Livestock production: Recent trends, future prospects. *Philosophical Transactions of the Royal Society B: Biological Sciences*, **365** (1554), 2853-2867. http://dx.doi.org/10.1098/rstb.2010.0134

223. Keller Jensen, J., 2009: Climate Change and Rural Communities in the US. Draft Briefing Paper. Rural Policy Research Institute, Iowa City, IA, 13 pp. http://www.rupri.org/Forms/Climate_Change_Brief.pdf

224. Gallopin, G.C., 2006: Linkages between vulnerability, resilience, and adaptive capacity. *Global Environmental Change*, **16** (3), 293-303. http://dx.doi.org/10.1016/j.gloenvcha.2006.02.004

225. Rosser, E., 2006: Rural housing and code enforcement: Navigating between values and housing types. *Georgetown Journal on Poverty Law & Policy*, **13** (1), 33-93. https://papers.ssrn.com/sol3/papers.cfm?abstract_id=842584

226. *Public Hearing RE: The State of Rural Infrastructure*, 2017: U.S. House of Representatives. https://agriculture.house.gov/calendar/eventsingle.aspx?EventID=3974

227. Kuttner, H., 2016: The Economic Impact of Rural Broadband. Briefing Paper. Hudson Institute, Washington, DC, 29 pp. https://www.hudson.org/research/12428-the-economic-impact-of-rural-broadband

228. Williamson, T., H. Hesseln, and M. Johnston, 2012: Adaptive capacity deficits and adaptive capacity of economic systems in climate change vulnerability assessment. *Forest Policy and Economics*, **15**, 160-166. http://dx.doi.org/10.1016/j.forpol.2010.04.003

229. Morello-Frosch, R., M. Pastor, J. Sadd, and S.B. Shonkoff, 2009: The Climate Gap: Inequalities in How Climate Change Hurts Americans & How to Close the Gap. University of California, Berkeley, and USC Program for Environmental & Regional Equity. http://dornsife.usc.edu/assets/sites/242/docs/The_Climate_Gap_Full_Report_FINAL.pdf

230. Marshall, N.A., 2010: Understanding social resilience to climate variability in primary enterprises and industries. *Global Environmental Change*, **20** (1), 36-43. http://dx.doi.org/10.1016/j.gloenvcha.2009.10.003

231. U.S. Bureau of Reclamation, 2014: Reclamation: Managing Water in the West, Climate Change Adaptation Strategy. U.S. Department of the Interior, Bureau of Reclamation, Washington, DC, 50 pp. https://www.hsdl.org/?view&did=760006

232. Pelling, M., 2010: *Adaptation to Climate Change: From Resilience to Transformation*. Routledge, Abingdon, UK, 224 pp.

233. Engle, N.L., 2011: Adaptive capacity and its assessment. *Global Environmental Change*, **21** (2), 647-656. http://dx.doi.org/10.1016/j.gloenvcha.2011.01.019

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

235. Mueller, B. and S.I. Seneviratne, 2012: Hot days induced by precipitation deficits at the global scale. *Proceedings of the National Academy of Sciences of the United States of America*, **109** (31), 12398-12403. http://dx.doi.org/10.1073/pnas.1204330109

236. Mazdiyasni, O. and A. AghaKouchak, 2015: Substantial increase in concurrent droughts and heatwaves in the United States. *Proceedings of the National Academy of Sciences of the United States of America*, **112** (37), 11484-11489. http://dx.doi.org/10.1073/pnas.1422945112

237. Young, S.L., 2017: As climate shifts, so do pests: A national forum and assessment. *Bulletin of the Ecological Society of America*, **98** (2), 165-172. http://dx.doi.org/10.1002/bes2.1315

238. Bebber, D.P., M.A.T. Ramotowski, and S.J. Gurr, 2013: Crop pests and pathogens move polewards in a warming world. *Nature Climate Change*, **3** (11), 985-988. http://dx.doi.org/10.1038/nclimate1990

239. Havstad, K.M., J.R. Brown, R. Estell, E. Elias, A. Rango, and C. Steele, 2016: Vulnerabilities of southwestern U.S. rangeland-based animal agriculture to climate change. *Climatic Change*. http://dx.doi.org/10.1007/s10584-016-1834-7

240. Liang, X.-Z., Y. Wu, R.G. Chambers, D.L. Schmoldt, W. Gao, C. Liu, Y.-A. Liu, C. Sun, and J.A. Kennedy, 2017: Determining climate effects on US total agricultural productivity. *Proceedings of the National Academy of Sciences of the United States of America*, **114** (12), E2285-E2292. http://dx.doi.org/10.1073/pnas.1615922114

241. Rosenzweig, C., J. Elliott, D. Deryng, A.C. Ruane, C. Müller, A. Arneth, K.J. Boote, C. Folberth, M. Glotter, N. Khabarov, K. Neumann, F. Piontek, T.A.M. Pugh, E. Schmid, E. Stehfest, H. Yang, and J.W. Jones, 2014: Assessing agricultural risks of climate change in the 21st century in a global gridded crop model intercomparison. *Proceedings of the National Academy of Sciences of the United States of America*, **111** (9), 3268-3273. http://dx.doi.org/10.1073/pnas.1222463110

242. Ray, D.K., J.S. Gerber, G.K. MacDonald, and P.C. West, 2015: Climate variation explains a third of global crop yield variability. *Nature Communications*, **6**, 5989. http://dx.doi.org/10.1038/ncomms6989

243. Novick, K.A., D.L. Ficklin, P.C. Stoy, C.A. Williams, G. Bohrer, A.C. Oishi, S.A. Papuga, P.D. Blanken, A. Noormets, B.N. Sulman, R.L. Scott, L. Wang, and R.P. Phillips, 2016: The increasing importance of atmospheric demand for ecosystem water and carbon fluxes. *Nature Climate Change*, **6**, 1023-1027. http://dx.doi.org/10.1038/nclimate3114

244. Lobell, D.B., W. Schlenker, and J. Costa-Roberts, 2011: Climate trends and global crop production since 1980. *Science*, **333** (6042), 616-620. http://dx.doi.org/10.1126/science.1204531

245. Hatfield, J.L., L. Wright-Morton, and B. Hall, 2017: Vulnerability of grain crops and croplands in the Midwest to climatic variability and adaptation strategies. *Climatic Change*. http://dx.doi.org/10.1007/s10584-017-1997-x

246. Kukal, M.S. and S. Irmak, 2018: Climate-driven crop yield and yield variability and climate change impacts on the U.S. Great Plains agricultural production. *Scientific Reports*, **8** (1), 3450. http://dx.doi.org/10.1038/s41598-018-21848-2

247. Tebaldi, C. and D. Lobell, 2015: Estimated impacts of emission reductions on wheat and maize crops. *Climatic Change*. http://dx.doi.org/10.1007/s10584-015-1537-5

248. Tack, J., A. Barkley, and L.L. Nalley, 2015: Effect of warming temperatures on US wheat yields. *Proceedings of the National Academy of Sciences of the United States of America*, **112** (22), 6931-6936. http://dx.doi.org/10.1073/pnas.1415181112

249. Labe, Z., T. Ault, and R. Zurita-Milla, 2017: Identifying anomalously early spring onsets in the CESM large ensemble project. *Climate Dynamics*, **48** (11), 3949-3966. http://dx.doi.org/10.1007/s00382-016-3313-2

250. Peterson, A.G. and J.T. Abatzoglou, 2014: Observed changes in false springs over the contiguous United States. *Geophysical Research Letters*, **41** (6), 2156-2162. http://dx.doi.org/10.1002/2014GL059266

251. Gammans, M., P. Mérel, and A. Ortiz-Bobea, 2017: Negative impacts of climate change on cereal yields: Statistical evidence from France. *Environmental Research Letters*, **12** (5), 054007. http://dx.doi.org/10.1088/1748-9326/aa6b0c

252. Liu, B., S. Asseng, C. Müller, F. Ewert, J. Elliott, David B. Lobell, P. Martre, Alex C. Ruane, D. Wallach, James W. Jones, C. Rosenzweig, Pramod K. Aggarwal, Phillip D. Alderman, J. Anothai, B. Basso, C. Biernath, D. Cammarano, A. Challinor, D. Deryng, Giacomo D. Sanctis, J. Doltra, E. Fereres, C. Folberth, M. Garcia-Vila, S. Gayler, G. Hoogenboom, Leslie A. Hunt, Roberto C. Izaurralde, M. Jabloun, Curtis D. Jones, Kurt C. Kersebaum, Bruce A. Kimball, A.-K. Koehler, Soora N. Kumar, C. Nendel, Garry J. O'Leary, Jørgen E. Olesen, Michael J. Ottman, T. Palosuo, P.V.V. Prasad, E. Priesack, Thomas A.M. Pugh, M. Reynolds, Ehsan E. Rezaei, Reimund P. Rötter, E. Schmid, Mikhail A. Semenov, I. Shcherbak, E. Stehfest, Claudio O. Stöckle, P. Stratonovitch, T. Streck, I. Supit, F. Tao, P. Thorburn, K. Waha, Gerard W. Wall, E. Wang, Jeffrey W. White, J. Wolf, Z. Zhao, and Y. Zhu, 2016: Similar estimates of temperature impacts on global wheat yield by three independent methods. *Nature Climate Change*, **6**, 1130-1136. http://dx.doi.org/10.1038/nclimate3115

253. Wienhold, B.J., M.F. Vigil, J.R. Hendrickson, and J.D. Derner, 2017: Vulnerability of crops and croplands in the US Northern Plains to predicted climate change. *Climatic Change*. http://dx.doi.org/10.1007/s10584-017-1989-x

254. Burke, M. and K. Emerick, 2016: Adaptation to climate change: Evidence from US agriculture. *American Economic Journal: Economic Policy*, **8** (3), 106-40. http://dx.doi.org/10.1257/pol.20130025

255. Margolis, E.Q., C.A. Woodhouse, and T.W. Swetnam, 2017: Drought, multi-seasonal climate, and wildfire in northern New Mexico. *Climatic Change*, **142** (3), 433-446. http://dx.doi.org/10.1007/s10584-017-1958-4

256. Dai, A. and T. Zhao, 2017: Uncertainties in historical changes and future projections of drought. Part I: estimates of historical drought changes. *Climatic Change*, **144** (3), 519-533. http://dx.doi.org/10.1007/s10584-016-1705-2

257. Ratcliffe, S., M. Baur, H. Beckie, L. Giesler, N. Leppla, and J. Schroeder, 2017: Crop Protection Contributions Toward Agricultural Productivity. A Paper in the Series on The Need for Agricultural Innovation to Sustainably Feed the World by 2050. CAST Issue Paper 58. Council for Agricultural Science and Technology (CAST), Ames, IA, 20 pp. http://www.cast-science.org/publications/?crop_protection_contributions_toward_agricultural_productivity&show=product&productID=284599

258. Baenziger, P.S., R. Mumm, R. Bernardo, E.C. Brummer, P. Langridge, P. Simon, and S. Smith, 2017: Plant Breeding and Genetics. A Paper in the Series on The Need for Agricultural Innovation to Sustainably Feed the World by 2050. CAST Issue Paper 57. Council for Agricultural Science and Technology (CAST), Ames, IA, 24 pp. http://www.cast-science.org/publications/?plant_breeding_and_genetics&show=product&productID=284583

259. Chavez, E., G. Conway, M. Ghil, and M. Sadler, 2015: An end-to-end assessment of extreme weather impacts on food security. *Nature Climate Change*, **5**, 997-1001. http://dx.doi.org/10.1038/nclimate2747

260. Zhao, T. and A. Dai, 2017: Uncertainties in historical changes and future projections of drought. Part II: Model-simulated historical and future drought changes. *Climatic Change*, **144** (3), 535-548. http://dx.doi.org/10.1007/s10584-016-1742-x

261. Easterling, D.R., K.E. Kunkel, J.R. Arnold, T. Knutson, A.N. LeGrande, L.R. Leung, R.S. Vose, D.E. Waliser, and M.F. Wehner, 2017: Precipitation change in the United States. *Climate Science Special Report: Fourth National Climate Assessment, Volume I*. Wuebbles, D.J., D.W. Fahey, K.A. Hibbard, D.J. Dokken, B.C. Stewart, and T.K. Maycock, Eds. U.S. Global Change Research Program, Washington, DC, USA, 207-230. http://dx.doi.org/10.7930/J0H993CC

262. Groisman, P.Y., R.W. Knight, and T.R. Karl, 2012: Changes in intense precipitation over the central United States. *Journal of Hydrometeorology*, **13**, 47-66. http://dx.doi.org/10.1175/JHM-D-11-039.1

263. Slater, L.J. and G. Villarini, 2016: Recent trends in U.S. flood risk. *Geophysical Research Letters*, **43** (24), 12,428-12,436. http://dx.doi.org/10.1002/2016GL071199

264. Mallakpour, I. and G. Villarini, 2015: The changing nature of flooding across the central United States. *Nature Climate Change*, **5** (3), 250-254. http://dx.doi.org/10.1038/nclimate2516

265. Smith, A.B. and R.W. Katz, 2013: U.S. billion-dollar weather and climate disasters: Data sources, trends, accuracy and biases. *Natural Hazards*, **67** (2), 387-410. http://dx.doi.org/10.1007/s11069-013-0566-5

266. Špitalar, M., J.J. Gourley, C. Lutoff, P.-E. Kirstetter, M. Brilly, and N. Carr, 2014: Analysis of flash flood parameters and human impacts in the US from 2006 to 2012. *Journal of Hydrology*, **519**, 863-870. http://dx.doi.org/10.1016/j.jhydrol.2014.07.004

267. TRIP, 2015: Rural Connections: Challenges and Opportunities in America's Heartland. TRIP, Washington, DC, 43 pp. http://www.tripnet.org/docs/Rural_Roads_TRIP_Report_May_2015.pdf

268. Lal, R., 2015: Sequestering carbon and increasing productivity by conservation agriculture. *Journal of Soil and Water Conservation*, **70** (3), 55A-62A. http://dx.doi.org/10.2489/jswc.70.3.55A

269. Wei, X., M. Shao, W. Gale, and L. Li, 2014: Global pattern of soil carbon losses due to the conversion of forests to agricultural land. *Scientific Reports*, **4**, 4062. http://dx.doi.org/10.1038/srep04062

270. Paustian, K., J. Lehmann, S. Ogle, D. Reay, G.P. Robertson, and P. Smith, 2016: Climate-smart soils. *Nature*, **532**, 49-57. http://dx.doi.org/10.1038/nature17174

271. Brown, J.R. and J.E. Herrick, 2016: Making soil health a part of rangeland management. *Journal of Soil and Water Conservation*, **71** (3), 55A-60A. http://dx.doi.org/10.2489/jswc.71.3.55A

272. Blanco-Canqui, H., T.M. Shaver, J.L. Lindquist, C.A. Shapiro, R.W. Elmore, C.A. Francis, and G.W. Hergert, 2015: Cover crops and ecosystem services: Insights from studies in temperate soils. *Agronomy Journal*, **107** (6), 2449-2474. http://dx.doi.org/10.2134/agronj15.0086

273. Parton, W.J., M.P. Gutmann, E.R. Merchant, M.D. Hartman, P.R. Adler, F.M. McNeal, and S.M. Lutz, 2015: Measuring and mitigating agricultural greenhouse gas production in the US Great Plains, 1870–2000. *Proceedings of the National Academy of Sciences of the United States of America*, **112** (34), E4681-E4688. http://dx.doi.org/10.1073/pnas.1416499112

274. Houghton, A., J. Austin, A. Beerman, and C. Horton, 2017: An approach to developing local climate change environmental public health indicators in a rural district. *Journal of Environmental and Public Health*, **2017**, 16. http://dx.doi.org/10.1155/2017/3407325

275. Black, H., 2008: Unnatural disaster: Human factors in the Mississippi floods. *Environmental Health Perspectives*, **116** (9), A390-393. http://dx.doi.org/10.1289/ehp.116-a390

276. Davies, J., 2017: The business case for soil. *Nature*, **543**, 309-311. http://dx.doi.org/10.1038/543309a

277. Vose, R.S., D.R. Easterling, K.E. Kunkel, A.N. LeGrande, and M.F. Wehner, 2017: Temperature changes in the United States. *Climate Science Special Report: Fourth National Climate Assessment, Volume I*. Wuebbles, D.J., D.W. Fahey, K.A. Hibbard, D.J. Dokken, B.C. Stewart, and T.K. Maycock, Eds. U.S. Global Change Research Program, Washington, DC, USA, 185-206. http://dx.doi.org/10.7930/J0N29V45

278. Anderson, G.B., K.W. Oleson, B. Jones, and R.D. Peng, 2018: Classifying heatwaves: Developing health-based models to predict high-mortality versus moderate United States heatwaves. *Climatic Change*, **146** (3), 439-453. http://dx.doi.org/10.1007/s10584-016-1776-0

279. Anderson, G.B. and M.L. Bell, 2011: Heat waves in the United States: Mortality risk during heat waves and effect modification by heat wave characteristics in 43 U.S. communities. *Environmental Health Perspectives*, **119** (2), 210-218. http://dx.doi.org/10.1289/ehp.1002313

280. Jagai, J.S., E. Grossman, L. Navon, A. Sambanis, and S. Dorevitch, 2017: Hospitalizations for heat-stress illness varies between rural and urban areas: An analysis of Illinois data, 1987–2014. *Environmental Health*, **16** (1), 38. http://dx.doi.org/10.1186/s12940-017-0245-1

281. Fechter-Leggett, E.D., A. Vaidyanathan, and E. Choudhary, 2016: Heat stress illness emergency department visits in national environmental public health tracking states, 2005–2010. *Journal of Community Health*, **41** (1), 57-69. http://dx.doi.org/10.1007/s10900-015-0064-7

282. Hess, J.J., S. Saha, and G. Luber, 2014: Summertime acute heat illness in U.S. emergency departments from 2006 through 2010: Analysis of a nationally representative sample. *Environmental Health Perspectives*, **122** (11), 1209-1215. http://dx.doi.org/10.1289/ehp.1306796

283. Sugg, M.M., C.E. Konrad, and C.M. Fuhrmann, 2016: Relationships between maximum temperature and heat-related illness across North Carolina, USA. *International Journal of Biometeorology*, **60** (5), 663-675. http://dx.doi.org/10.1007/s00484-015-1060-4

284. CDC, 2008: Heat-related deaths among crop workers—United States, 1992–2006. *MMWR: Morbidity and Mortality Weekly Report*, **57** (24), 649-653. http://www.ncbi.nlm.nih.gov/pubmed/18566563

285. Fortune, M.K., C.A. Mustard, J.J.C. Etches, and A.G. Chambers, 2013: Work-attributed illness arising from excess heat exposure in Ontario, 2004-2010. *Canadian Journal of Public Helath*, **104** (5), 7. http://dx.doi.org/10.17269/cjph.104.3984

286. Merte, S., 2017: Estimating heat wave-related mortality in Europe using singular spectrum analysis. *Climatic Change*, **142** (3), 321-330. http://dx.doi.org/10.1007/s10584-017-1937-9

287. Oleson, K.W., G.B. Anderson, B. Jones, S.A. McGinnis, and B. Sanderson, 2015: Avoided climate impacts of urban and rural heat and cold waves over the U.S. using large climate model ensembles for RCP8.5 and RCP4.5. *Climatic Change*. http://dx.doi.org/10.1007/s10584-015-1504-1

288. Marsha, A., S.R. Sain, M.J. Heaton, A.J. Monaghan, and O.V. Wilhelmi, 2016: Influences of climatic and population changes on heat-related mortality in Houston, Texas, USA. *Climatic Change*. http://dx.doi.org/10.1007/s10584-016-1775-1

289. Huber, V., D. Ibarreta, and K. Frieler, 2017: Cold- and heat-related mortality: A cautionary note on current damage functions with net benefits from climate change. *Climatic Change*, **142** (3), 407-418. http://dx.doi.org/10.1007/s10584-017-1956-6

290. Jones, B., B.C. O'Neill, L. McDaniel, S. McGinnis, L.O. Mearns, and C. Tebaldi, 2015: Future population exposure to US heat extremes. *Nature Climate Change*, **5**, 652-655. http://dx.doi.org/10.1038/nclimate2631

291. Hallström, E., Q. Gee, P. Scarborough, and D.A. Cleveland, 2017: A healthier US diet could reduce greenhouse gas emissions from both the food and health care systems. *Climatic Change*, **142** (1), 199-212. http://dx.doi.org/10.1007/s10584-017-1912-5

292. Capper, J.L. and D.E. Bauman, 2013: The role of productivity in improving the environmental sustainability of ruminant production systems. *Annual Review of Animal Biosciences*, **1** (1), 469-489. http://dx.doi.org/10.1146/annurev-animal-031412-103727

293. Eisler, M.C., M.R.F. Lee, J.F. Tarlton, G.B. Martin, J. Beddington, J.A.J. Dungait, H. Greathead, J. Liu, S. Mathew, H. Miller, T. Misselbrook, P. Murray, V.K. Vinod, R.V. Saun, and M. Winter, 2014: Agriculture: Steps to sustainable livestock. *Nature*, **507**, 32-34. http://dx.doi.org/10.1038/507032a

294. Lehner, F., C. Deser, and B.M. Sanderson, 2018: Future risk of record-breaking summer temperatures and its mitigation. *Climatic Change*, **146** (3-4), 363-375. http://dx.doi.org/10.1007/s10584-016-1616-2

295. ERS, 2017: Rural Education At A Glance, 2017 Edition. Economic Information Bulletin 171. USDA Economic Research Service (ERS), Washington, DC, 6 pp. https://www.ers.usda.gov/webdocs/publications/83078/eib-171.pdf?v=42830