6. Agriculture

Convening Lead Authors
Jerry Hatfield, U.S. Department of Agriculture
Gene Takle, Iowa State University

Lead Authors
Richard Grotjahn, University of California, Davis
Patrick Holden, Waterborne Environmental, Inc.
R. Cesar Izaurralde, Pacific Northwest National Laboratory
Terry Mader, University of Nebraska, Lincoln
Elizabeth Marshall, U.S. Department of Agriculture

Contributing Authors
Diana Liverman, University of Arizona

Key Messages

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

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

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

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

Increasing Impacts on Agriculture

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

Impacts on Crop Production

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

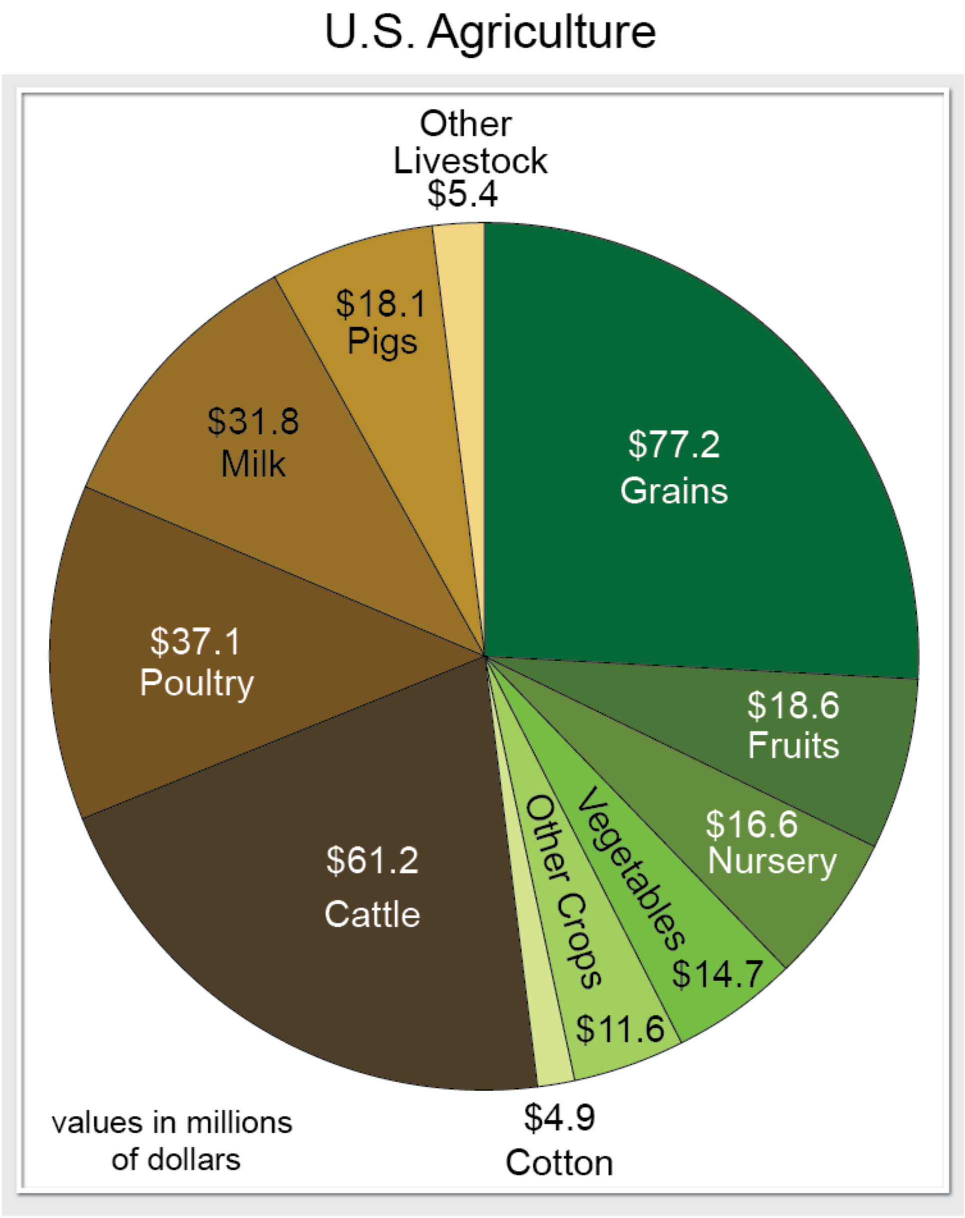

Figure 6.1: U.S. Agriculture

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

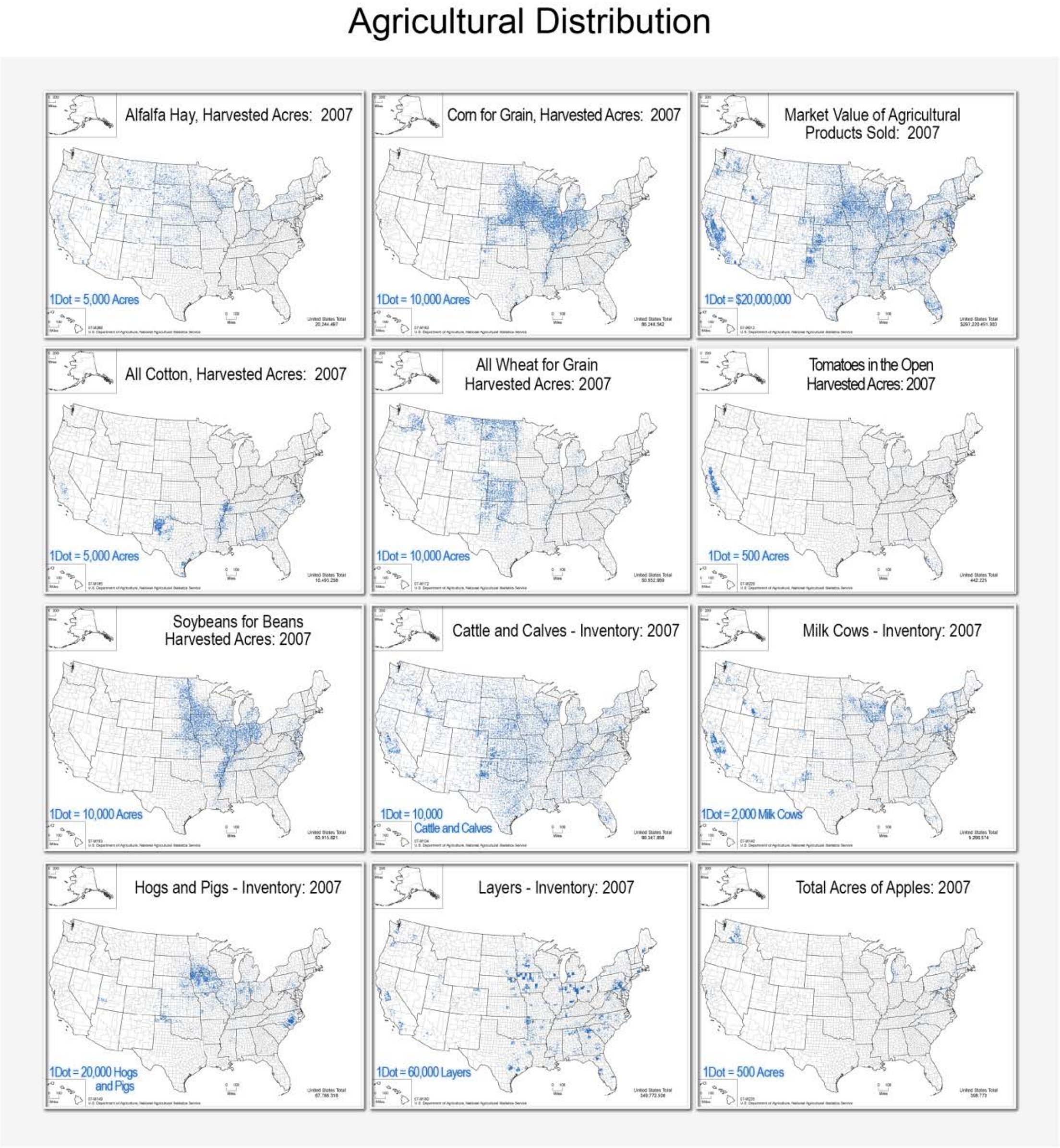

Figure 6.2: Agricultural Distribution

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

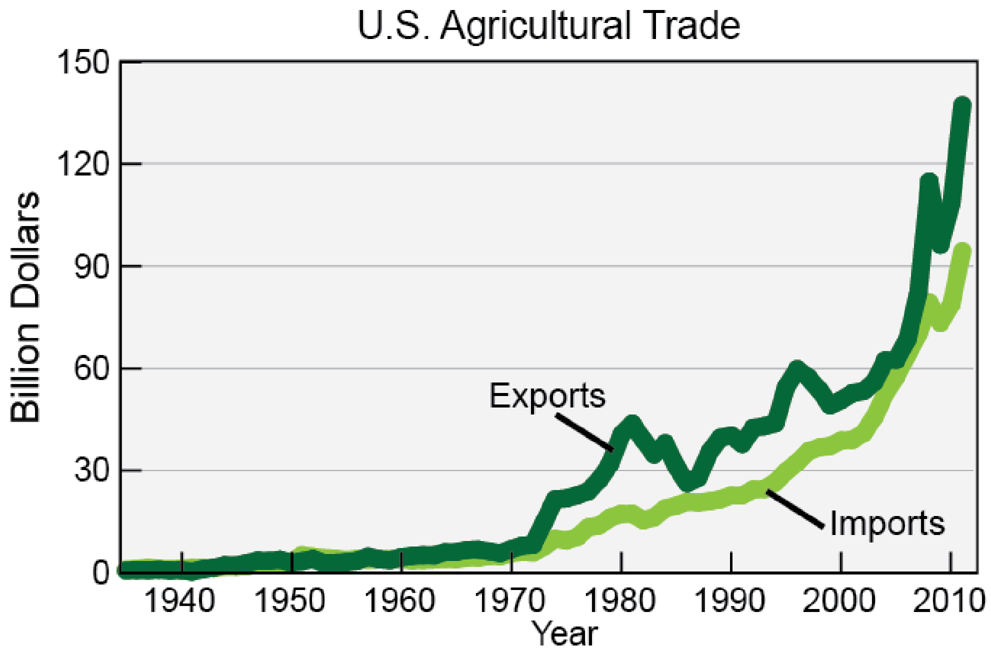

Figure 6.3: U.S. Agricultural Trade

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

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

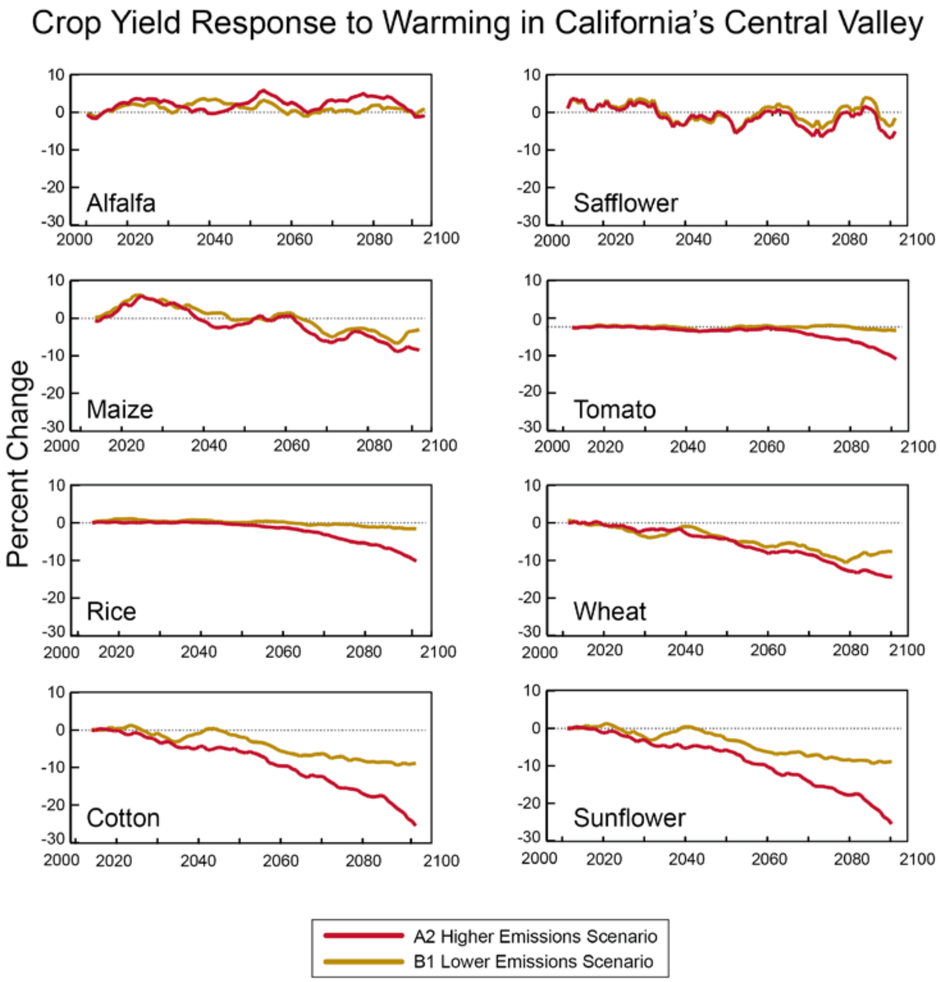

Figure 6.4: Crop Yield Response to Warming in California's Central Valley

Caption: Changes in climate through this century will affect crops differently because individual species respond differently to warming. This figure is an example of the potential impacts on different crops within the same geographic region. Crop yield responses for eight crops in the central valley of California are projected under two emissions scenarios, one in which heat-trapping gas emissions are substantially reduced (B1, in gold) and another in which these emissions continue to grow (A2, in red). This analysis assumes adequate water supplies (soil moisture) and nutrients are maintained while temperatures increase. The lines show five-year moving averages for the period from 2000 to 2097 with the yield changes shown as differences from the year 2000. Yield response varies among crops, with cotton, maize, wheat, and sunflower showing yield declines early in the period. Alfalfa and safflower showed no yield declines during the period. Rice and tomato do not show a yield response until the latter half of the period, with the higher emissions scenario resulting in a larger yield response. (Figure source: adapted from Lee et al. 2011).[16]

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

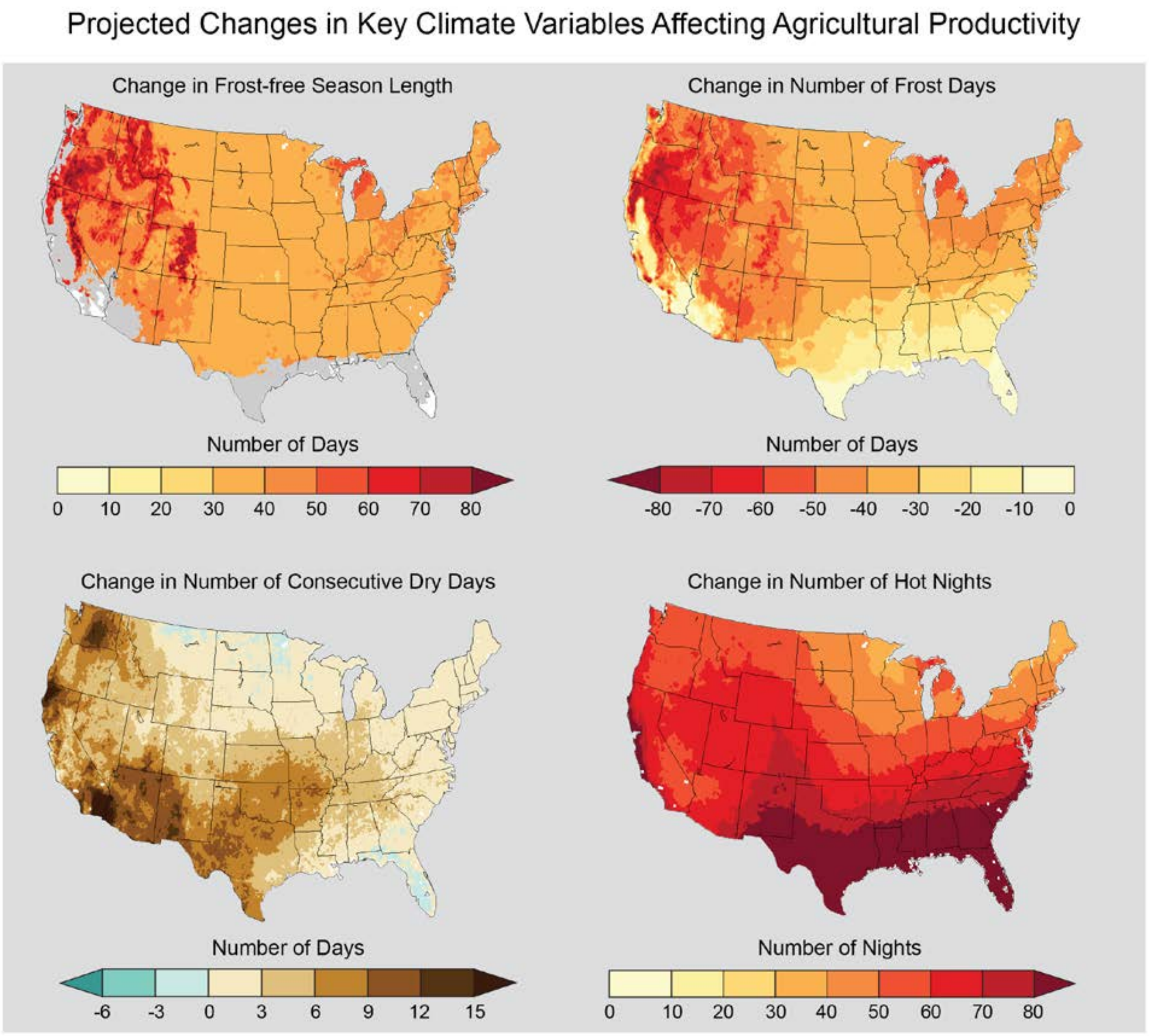

Figure 6.5: Projected Changes in Key Climate Variables Affecting Agricultural Productivity

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

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

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

A warmer climate will affect growing conditions; however, the lack of cold temperatures may threaten perennial crop production (Figure 6.6). Perennial specialty crops have a winter chilling requirement (typically expressed as hours when temperatures are between 32°F and 50°F) ranging from 200 to 2,000 cumulative hours. Yields decline if the chilling requirement is not completely satisfied, because flower emergence and viability is low.[20] Projections show that chilling requirements for fruit and nut trees in California will not be met by the middle to the end of this century.[21] For most of the Northeast, a 400-hour chilling requirement for apples is projected to continue to be met during this century, but crops with prolonged chilling requirements, such as plums and cherries (with chilling requirements of more than 700 hours), could be negatively affected, particularly in southern parts of the Northeast.[21,22] Warmer winters can lead to early bud-burst or bloom of some perennial plants, resulting in frost damage when cold conditions occur in late spring[15], as was the case with cherries in Michigan in 2012, leading to an economic impact of $220 million (Andresen 2012, personal communication).[23]

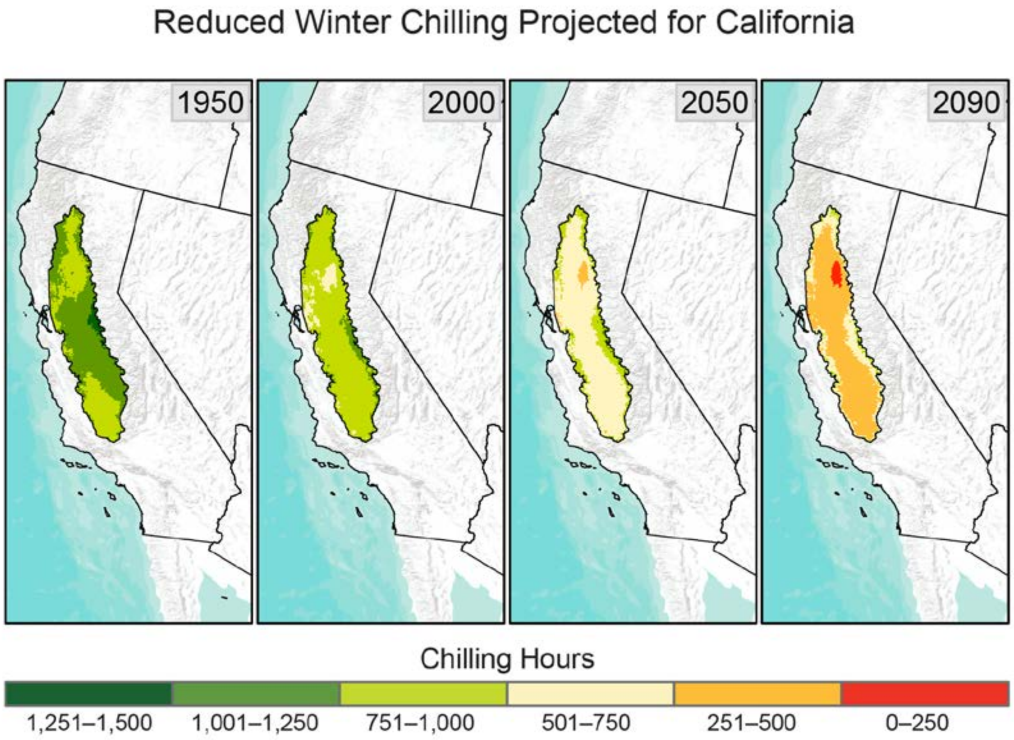

Figure 6.6: Reduced Winter Chilling Projected for California

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

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

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

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

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

Impacts on Animal Production from Temperature Extremes

Animal agriculture is a major component of the U.S. agriculture system (Figure 6.1). Changing climatic conditions affect animal agriculture in four primary ways: 1) feed-grain production, availability, and price; 2) pastures and forage crop production and quality; 3) animal health, growth, and reproduction; and 4) disease and pest distributions.[32] The optimal environmental conditions for livestock production include temperatures and other conditions for which animals do not need to significantly alter behavior or physiological functions to maintain relatively constant core body temperature. Optimum animal core body temperature is often maintained within a 4°F to 5°F range, while deviations from this range can cause animals to become stressed. This can disrupt performance, production, and fertility, limiting the animals' ability to produce meat, milk, or eggs. In many species, deviations in core body temperature in excess of 4°F to 5°F cause significant reductions in productive performance, while deviations of 9°F to 12.6°F often result in death.[33] For cattle that breed during spring and summer, exposure to high temperatures reduces conception rates. Livestock and dairy production are more affected by the number of days of extreme heat than by increases in average temperature.[34] Elevated humidity exacerbates the impact of high temperatures on animal health and performance.

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

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

Weeds, Diseases, and Pests

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

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

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

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

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

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

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

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

Extreme Precipitation and Soil Erosion

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

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

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

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

Box: It is All About the Water!

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

Figure 6.7

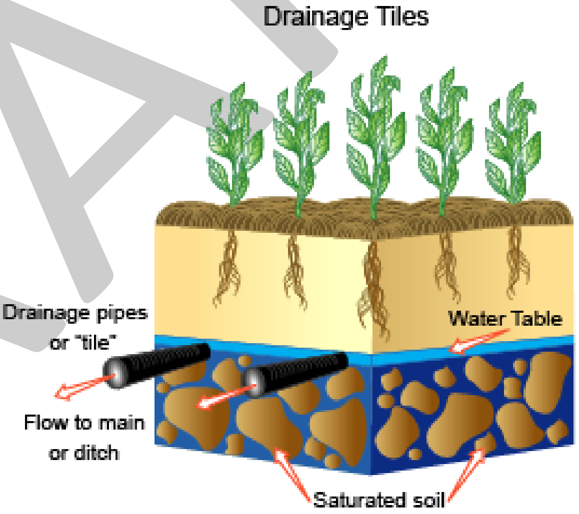

Figure 6.8

Water and soil that are lost from the field are no longer available to support crop growth. The increasing intensity of storms and the shifting of rainfall patterns toward more spring precipitation in the Midwest may lead to more scenes similar to this one (Figure 6.7). An analysis of the rainfall patterns across Iowa has shown there has not been an increase in total annual precipitation; however, there has been a large increase in the number of days with heavy rainfall (Figure 6.9). The increase in spring precipitation is evidenced by a decrease of three days in the number of workable days in the April to May period during 2001 through 2011in Iowa compared to the period from 1980-2000.[15] To offset this increased precipitation, producers have been installing subsurface drainage to remove more water from the fields at a cost of $500.00 per acre (Figure 6.8). These are elaborate systems designed to move water from the landscape to allow agricultural operations to occur in the spring. Water erosion and runoff is only one portion of the spectrum of extreme precipitation. Wind erosion could increase in areas with persistent drought because of the reduction in vegetative cover. (Photo credit (left): USDA Natural Resources Conservation Service; Figure source (right): NOAA NCDC / CICS-NC).

-- end box --

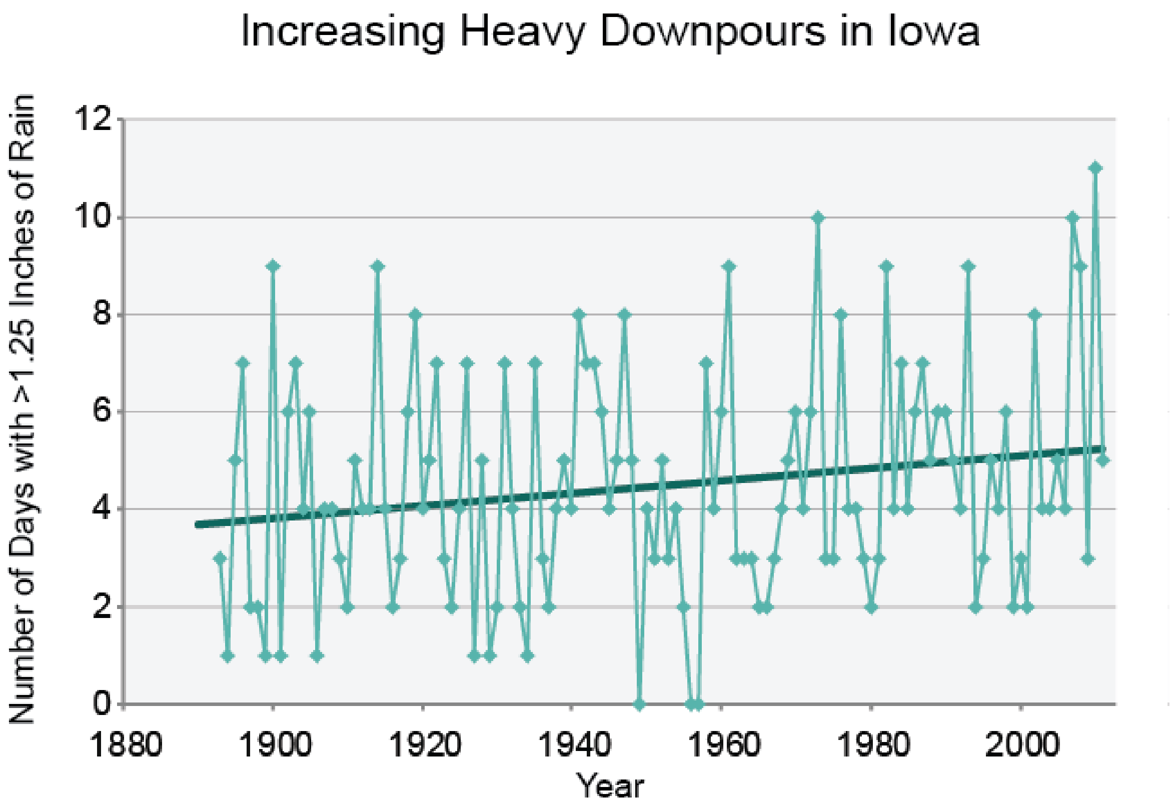

Figure 6.9: Increasing Heavy Downpours in Iowa

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

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

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

Heat and Drought Damage

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

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

Rate of Adaptation

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

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

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

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

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

The role of innovative management techniques and government policies as well as research and insurance programs will have a substantial impact on the degree to which the agricultural sector increases climate resilience in the longer term.

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

Food Security

Climate change effects on agriculture will have consequences for food security both in the U.S. and globally, through changes in crop yields and food prices, and in effects on food processing, storage, transportation, and retailing.

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

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

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

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

Traceable Accounts

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

The report team engaged in multiple technical discussions via teleconference, which included careful review of the foundational TIR[15] and of approximately 56 additional technical inputs provided by the public, as well as other published literature and professional judgment. Discussions were followed by expert deliberation of draft key messages by the authors, and targeted consultation with additional experts by the lead author of each message.

Key message #1/6	**Climate disruptions to agricultural production have increased in the past 40 years and are projected to increase over the next 25 years. By mid-century and beyond, these impacts will be increasingly negative on most crops and livestock.**
Description of evidence base	The key message and supporting text summarize extensive evidence documented in the Agriculture TIR, "Climate Change and Agriculture in the United States: An Assessment of Effects and Potential for Adaptation.[15] Additional Technical Input Reports (56) on a wide range of topics were also received and reviewed as part of the Federal Register Notice solicitation for public input. Evidence that climate change has had and will have impacts on crops and livestock is based on numerous studies and is incontrovertible.[6,7,8] The literature strongly suggests that carbon dioxide, temperature, and precipitation affect livestock and crop production. Plants have an optimal temperature range to which they are adapted and regional crop growth will be affected by shifts in that region's temperatures relative to each crop's optimal range. Large shifts in temperature can significantly impact seasonal biomass growth, while changes in the timing and intensity of extreme temperature effects are expected to negatively impact crop development during critical windows such as pollination. Crop production will also be impacted by changing patterns of seasonal precipitation; extreme precipitation events are expected to occur more frequently and negatively impact production levels. Livestock production is directly affected by extreme temperature as the animal makes metabolic adjustments to cope with heat stress.[15] Further, production costs in confined systems markedly increase when climate regulation is necessary.
New information and remaining uncertainties	Important new evidence (cited above) confirmed many of the findings in the past Synthesis Assessment Product on agriculture[82], which informed the 2009 National Climate Assessment.[83] There is insufficient understanding of the effects on crop production of rising carbon dioxide, changing temperatures and more variable precipitation patterns.[9] The combined effects on plant water demand and soil water availability will be critical to understanding regional crop response. The role of increasing minimum temperatures on water demand and growth and senescence rates of plants is an important factor. There is insufficient understanding of how prolonged exposure of livestock to high or cold temperatures affects metabolism and reproductive variables.[26] For grazing animals, climate conditions during the growing season are critical in determining feed availability and quality on rangeland and pastureland.[69]

	The information base can be enhanced by evaluating crop growth and livestock production models. This evaluation would further the understanding of the interactions of climate variables and the biological system. Better understanding of projected changes in precipitation will narrow uncertainty about future yield reductions.[9,69]
Assessment of confidence based on evidence	There are a range of controlled environment and field studies that provide the evidence for these findings. Confidence in this key message is therefore judged to be **high**.

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

Chapter 6: Agriculture

Key Message Process: See Key Message #1.

Key message #2/6	**Many agricultural regions will experience declines in crop and livestock production from increased stress due to weeds, diseases, insect pests, and other climate change induced stresses.**
Description of evidence base	The key message and supporting text summarizes extensive evidence documented in the Agriculture TIR, "Climate Change and Agriculture in the United States: An Assessment of Effects and Potential for Adaptation".[15] Additional Technical Input Reports (56) on a wide range of topics were also received and reviewed as part of the Federal Register Notice solicitation for public input. Numerous peer-reviewed publications describe the direct effects of climate on the ecological systems within which crop and livestock operations occur. Many weeds respond more strongly to CO_2 than do crops, and it is believed that the range of many diseases and pests (for both crop and livestock) will expand under warming conditions.[28,31,40] Pests may have increased overwinter survival and fit more generations into a single year, which may also facilitate faster evolution of pesticide resistance. Changing patterns of pressure from weeds, other pests, and disease can impact crop and livestock production in ways that may be costly or challenging to address.[9,15]
New information and remaining uncertainties	Important new evidence (cited above) confirmed many of the findings in the past Synthesis Assessment Product on agriculture [82], which informed the 2009 National Climate Assessment.[83] In addition to extant species already in the U.S., exotic weeds, diseases, and pests have particular significance in that: 1) they can often be invasive (that is, arrive without normal biological/ecological controls) and highly damaging; 2) with increasing international trade, there are numerous high-threat, high-impact species that will arrive on commodities from areas where some species even now are barely known to modern science but which have the potential to emerge under a changed climate regime to pose significant risk of establishment in the U.S. and economic loss; and 3) can take advantage of "disturbances" where climate variability acts as an additional ecological disturbance. Improved models and observational data related to how many agricultural regions will experience declines in animal and plant production from increased stress due to weeds, diseases, insect pests, and other climate change induced stresses will need to be developed. A key issue is the extent of the interaction between components of the natural biological system (for example, pests) and the economic biological system (for example, crop or animal). For insects, increased populations are a factor; however, their effect on the plant may be dependent upon the phenological stage of the plant when the insect is at specific phenological stages.[15] To enhance our understanding of these issues will require a concerted effort to begin to quantify the interactions of pests and the economic crop or livestock system and how each system and their interactions are affected by climate.[15]
Assessment of confidence based on evidence	The scientific literature is beginning to emerge; however, there are still some unknowns about the effects of biotic stresses, and there may well be emergent "surprises" resulting from departures from past ecological equilibria. Confidence is therefore judged to be **medium** that many agricultural regions will experience declines in animal and plant production from increased stress due to weeds, diseases, insect pests, and other climate change-induced stresses.

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

Chapter 6: Agriculture

Key Message Process: See Key Message #1.

Key message #3/6	**Current loss and degradation of critical agricultural soil and water assets due to increasing extremes in precipitation will continue to challenge both rainfed and irrigated agriculture unless innovative conservation methods are implemented.**
Description of evidence base	The key message and supporting text summarizes extensive evidence documented in the Agriculture TIR, "Climate Change and Agriculture in the United States: An Assessment of Effects and Potential for Adaptation."[15] Additional Technical Input Reports (56) on a wide range of topics were also received and reviewed as part of the Federal Register Notice solicitation for public input. Soil erosion is affected by rainfall intensity and there is evidence of increasing intensity in rainfall events even where the annual mean is reduced.[53] Unprotected soil surfaces will have increased erosion and require more intense conservation practices.[58,59] Shifts in seasonality and type of precipitation will affect both timing and impact of water availability for both rainfed and irrigated agriculture. Evidence is strong that in the future there will be more precipitation globally, and that rain events will be more intense even if separated by longer periods without rain.[6]
New information and remaining uncertainties	Important new evidence (cited above) confirmed many of the findings in the past Synthesis Assessment Product on agriculture[82], which informed the 2009 National Climate Assessment.[83] Both rainfed and irrigated agriculture will increasingly be challenged, based on improved models and observational data related to the effects of increasing precipitation extremes on loss and degradation of critical agricultural soil and water assets.[51,52] Precipitation shifts are the most difficult to project, and uncertainty in regional projections increases with time into the future.[61] To improve these projections will require enhanced understanding of shifts in timing, intensity, and magnitude of precipitation events. In the northern U.S., more frequent and severe winter and spring storms are projected, while there is a projected reduction in precipitation in the Southwest (See Ch. 2: Our Changing Climate).
Assessment of confidence based on evidence	The precipitation forecasts are the limiting factor in these assessments; the evidence of the impact of precipitation extremes on soil water availability and soil erosion is well established. Confidence in this key message is therefore judged to be **high**.

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

Chapter 6: Agriculture

Key Message Process: See Key Message #1.

Key message #4/6	**The rising incidence of weather extremes will have increasingly negative impacts on crop and livestock productivity because critical thresholds are already being exceeded.**
Description of evidence base	The key message and supporting text summarizes extensive evidence documented in the Agriculture TIR, “Climate Change and Agriculture in the United States: An Assessment of Effects and Potential for Adaptation”.[15] Additional Technical Input Reports (56) on a wide range of topics were also received and reviewed as part of the Federal Register Notice solicitation for public input. Numerous peer-reviewed publications [6,61,62] provide evidence that the occurrence of extreme events is increasing and exposure of plants or animals to temperatures and soil water conditions (drought, water-logging, flood) outside of the biological range for the given species will cause stress and reduce production.[6,61,62] The direct effects of an extreme event will depend upon the timing of the event relative to the growth stage of the biological system.
New information and remaining uncertainties	Important new evidence (cited above) confirmed many of the findings in the past Synthesis Assessment Product on agriculture [82], which informed the 2009 National Climate Assessment.[83] One key area of uncertainty is the timing of extreme events during the phenological stage of the plant or the growth stage of the animal. For example, plants are more sensitive to extreme high temperatures during the pollination stage compared to vegetative growth stages.[9] A parallel example for animals is relatively strong sensitivity to high temperatures during the conception phase.[34] Milk and egg production are also vulnerable to temperature extremes. The effects of extreme combinations of weather variables must be considered, such as elevated humidity in concert with high temperatures.[34] Other key uncertainties include inadequate precision in simulations of the timing of extreme events relative to short time periods of crop vulnerability, and temperatures close to key thresholds such as freezing.[22] The uncertainty is amplified by the rarity of extreme events; this rarity means there are infrequent opportunities to study the impact of extreme events. In general, a shift of the distribution of temperatures can increase the frequency of threshold exceedance.[15] The information base can be enhanced by improving the forecast of extreme events, given that the effect of extreme events on plants or animals is known.[3,61]
Assessment of confidence based on evidence	There is **high** confidence in the effects of extreme temperature events on crops and livestock, and the agreement in the literature is good.

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

Chapter 6: Agriculture

Key Message Process: See Key Message #1.

Key message #5/6	**Agriculture has been able to adapt to recent changes in climate; however, increased innovation will be needed to ensure the rate of adaptation of agriculture and the associated socioeconomic system can keep pace with climate change over the next 25 years.**
Description of evidence base	There is emerging evidence about the economic impacts of climate change on agriculture and the potential for adaptive strategies.[64] In the case of crop production, much of the economic literature suggests that in the short term, producers will continue to adapt to weather changes and shocks as they always have, with changes in the timing of field operations, shifts in crops grown, and changing tillage or irrigation practices.[64] In the longer term, however, existing adaptive technologies will likely not be sufficient to buffer the impacts of climate change without significant impacts to domestic producers, consumers, or both. New strategies for building long term resilience include both new technologies and new institutions to facilitate appropriate, informed producer response to a changing climate. Furthermore, there are both public and private costs to adjusting agricultural production and infrastructure in a manner that enables adaptation.[2]
New information and remaining uncertainties	Limits to public investment and constraints on private investment could slow the speed of adaptation, yet potential constraints and limits are not well-understood or integrated into economic impact assessments. The economic implications of changing biotic pressures on crops and livestock, and on the agricultural system as a whole, are not well-understood, either in the short or long term.[15] Adaptation may also be limited by availability of inputs (such as land or water), changing prices of other inputs with climate change (such as energy and fertilizer), and by the environmental implications of intensifying or expanding agricultural production. It is difficult to fully represent the complex interactions of the entire socio-ecological system within which agriculture operates, to assess the relative effectiveness and feasibility of adaptation strategies at various levels. Economic impact assessments require improved understanding of adaptation capacity and agricultural resilience at the system level, including the agri-ecosystem impacts related to diseases and pests. Economic impact assessments also require improved understanding of adaptation opportunities, economic resilience, and constraints to adaptation at the producer level.[2,64] The economic value of ecological services, such as pollination services, is particularly difficult to quantify and incorporate into economic impact efforts.[15]
Assessment of confidence based on evidence	Emerging evidence about adaptation of agricultural systems to changing climate is beginning to be developed. The complex interactions among all of the system components present a limitation to a complete understanding, but do provide a comprehensive framework for the assessment of agricultural responses to climate change. Given the overall and remaining uncertainty, there is **medium** confidence in this message.

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

Chapter 6: Agriculture

Key Message Process: See Key Message #1.

Key message #6/6	**Climate change effects on agriculture will have consequences for food security both in the U.S. and globally, through changes in crop yields and food prices, and in effects on food processing, storage, transportation, and retailing.**
Description of evidence base	The relationships among agricultural productivity, climate change, and food security have been documented through ongoing investigations by the Food and Agriculture Organization[81,84], as well as the U.S. Department of Agriculture[85], and the National Research Council[77]. There are many factors that affect food security, and agricultural yields are only one of them. Climate change is also expected to affect distribution of food- and waterborne diseases, and food trade and distribution.[78]
New information and remaining uncertainties	The components of food security derive from the intersection of political, physical, economic, and social factors. In many ways the impact of climate change on crop yields is the least complex of the factors that affect the four components of food security (availability, stability, access, and utilization). As the globalized food system is subject to conflicting pressures across scales, one approach to reducing risk is a “cross-scale problem-driven” approach to food security.[76] This and other approaches to understanding and responding to the complexities of the global food system need additional research. Climate change will have a direct impact on crop and livestock production by increasing the variability in production levels from year to year, with varying effects across different regions. Climate change will also affect the distribution of food supplies as a result of disruptions in transportation routes. Addressing food security will require integration of multiple factors, including the direct and indirect impacts of climate change.
Assessment of confidence based on evidence	Given the evidence base and remaining uncertainty, there is **high** confidence that climate change impacts will have consequences for food security both in the U.S. and globally, and **very high** confidence that other related factors, including food processing, storage, transportation, and retailing will also be affected by climate change

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

References

1. U.S. Census Bureau, 2012: The 2012 Statistical Abstract: Agriculture, 533-558 pp., U.S. Census Bureau, U.S Department of Commerce, Washington, D.C. [Available online at http://www.census.gov/prod/2011pubs/12statab/agricult.pdf]

2. 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, D.C. [Available online at http://papers.ssrn.com/sol3/Delivery.cfm/SSRN_ID2112045_code331453.pdf?abstractid=2112045&mirid=2]

3. Adams, R. M., B. Hurd, S. Lenhart, and N. Leary, 1987: Effects of global climate change on agriculture: an interpretative review. *Climate Research*, **11,** 19-30

4. Darwin, R., M. Tsigas, J. Lewandrowski, and A. Raneses, 1995: World agriculture and climate change: Economic adaptations. Agricultural Economic Report Number 703, 87 pp., U.S. Department of Agriculture Economic Research Service. [Available online at http://www.ers.usda.gov/media/926234/aer703_002.pdf];

Mendelsohn, R., W. D. Nordhaus, and D. Shaw, 1994: The impact of global warming on agriculture: a Ricardian analysis. *The American Economic Review***,** 753-771. [Available online at http://www.jstor.org/stable/pdfplus/2118029.pdf];

Reilly, J., F. Tubiello, B. McCarl, D. Abler, R. Darwin, K. Fuglie, S. Hollinger, C. Izaurralde, S. Jagtap, J. Jones, L. Mearns, D. Ojima, E. Paul, K. Paustian, S. Riha, N. Rosenberg, and C. Rosenzweig, 2003: US agriculture and climate change: new results. *Climatic Change*, **57,** 43-67, doi:10.1023/a:1022103315424. [Available online at http://link.springer.com/content/pdf/10.1023%2FA%3A1022103315424];

Rosenzweig, C., and M. L. Parry, 1994: Potential impact of climate change on world food supply. *Nature*, **367,** 133-138. [Available online at http://ecoethics.net/cyprus-institute.us/PDF/Rosensweig-Food-Supply.pdf];

Sands, R. D., and J. A. Edmonds, 2005: Climate Change Impacts for the Conterminous USA: An Integrated Assessment Part 7. Economic Analysis of Field Crops and Land use with Climate Change. *Climatic Change*, **69,** 127-150, doi:10.1007/s10584-005-3616-5. [Available online at http://www.springerlink.com/content/j20827v786460520/]

5. Crowl, T. A., T. O. Crist, R. R. Parmenter, G. Belovsky, and A. E. Lugo, 2008: The spread of invasive species and infectious disease as drivers of ecosystem change. *Frontiers in Ecology and the Environment*, **6,** 238-246, doi:10.1890/070151. [Available online at http://www.esajournals.org/doi/pdf/10.1890/070151];

Diez, J. M., C. M. D'Antonio, J. S. Dukes, E. D. Grosholz, J. D. Olden, C. J. B. Sorte, D. M. Blumenthal, B. A. Bradley, R. Early, I. Ibáñez, S. J. Jones, J. J. Lawler, and L. P. Miller, 2012: Will extreme climatic events facilitate biological invasions? *Frontiers in Ecology and the Environment*, **10,** 249-257, doi:10.1890/110137;

Epstein, P. R., 2001: Climate change and emerging infectious diseases. *Microbes and Infection*, **3,** 747-754, doi:10.1016/S1286-4579(01)01429-0. [Available online at http://www.sciencedirect.com/science/article/pii/S1286457901014290]

6. IPCC, 2007: *Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change.* S. Solomon, D. Qin, M. Manning, Z. Chen, M. Marquis, K. B. Averyt, M. Tignor, and H. L. Miller, Eds. Cambridge University Press, 996 pp. [Available online at http://www.ipcc.ch/publications_and_data/publications_ipcc_fourth_assessment_report_wg1_report_the_physical_science_basis.htm]

7. 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,** 46-58, doi:10.1016/j.agee.2008.01.019. [Available online at

http://ibp.generationcp.org/confluence/download/attachments/23069648/Ortiz_et_al_2008-Can_wheat_beat_the_heat-AgrEcosystEnv.pdf]];

Schlenker, W., W. M. Hanemann, and A. C. Fisher, 2005: Will U.S. Agriculture Really Benefit from Global Warming? Accounting for Irrigation in the Hedonic Approach. *The American Economic Review*, **95,** 395-406. [Available online at http://admin.water.columbia.edu/sitefiles/file/pub/White%20Papers/Schlenker2005Agriculture.pdf]

8. Lobell, D. B., G. L. Hammer, G. McLean, C. Messina, M. J. Roberts, and W. Schlenker, 2013: The critical role of extreme heat for maize production in the United States. *Nature Climate Change*, **3,** 497-501, doi:10.1038/nclimate1832

9. 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,** 351-370, doi:DOI 10.2134/agronj2010.0303

10. Lobell, D. B., and S. M. Gourdji, 2012: The influence of climate change on global crop productivity. *Plant Physiology*, **160,** 1686-1697. [Available online at http://www.plantphysiology.org/content/160/4/1686.full.pdf+html]

11. Diffenbaugh, N. S., T. W. Hertel, M. Scherer, and M. Verma, 2012: Response of corn markets to climate volatility under alternative energy futures. *Nature Climate Change*, **2,** 514-518, doi:10.1038/nclimate1491. [Available online at http://www.nature.com/nclimate/journal/v2/n7/pdf/nclimate1491.pdf]

12. USDA, 2008: Agricultural Statistics 2008, 529 pp., U.S. Department of Agriculture, National Agricultural Statistics Service, Washington, D.C. [Available online at http://www.nass.usda.gov/Publications/Ag_Statistics/2008/2008.pdf]

13. ——: Census of Agriculture, 2007 Census Ag Maps, Crops and Plants. U.S. Department of Agriculture. [Available online at http://www.agcensus.usda.gov/Publications/2007/Online_Highlights/Ag_Atlas_Maps/Crops_and_Plants/]

14. ERS, cited 2012: Value of U.S. agricultural trade, by fiscal year. U.S. Department of Agriculture, Economic Research Service. [Available online at http://www.ers.usda.gov/data-products/foreign-agricultural-trade-of-the-united-states-(fatus)/fiscal-year.aspx#.Uo5RlNKko9Z]

15. 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, 186 pp., U.S. Department of Agriculture and the U.S. Global Change Research Program, Unpublished. [Available online at http://www.usda.gov/oce/climate_change/effects_2012/CC%20and%20Agriculture%20Report%20(02-04-2013)b.pdf]

16. Lee, J., S. De Gryze, and J. Six, 2011: Effect of climate change on field crop production in California's Central Valley. *Climatic Change*, **109,** S335-S353, doi:10.1007/s10584-011-0305-4

17. Mader, T. L., 2012: Impact of environmental stress on feedlot cattle. *Western Section, American Society of Animal Science*, **62,** 335-339

18. Qian, T., A. Dai, and K. E. Trenberth, 2007: Hydroclimatic trends in the Mississippi River basin from 1948 to 2004. *Journal of Climate*, **20,** 4599-4614, doi:10.1175/JCLI4262.1. [Available online at http://journals.ametsoc.org/doi/pdf/10.1175/JCLI4262.1]

19. Pan, Z., M. Segal, R. W. Arritt, and E. S. Takle, 2004: On the potential change in solar radiation over the US due to increases of atmospheric greenhouse gases. *Renewable Energy*, **29,** 1923-1928, doi:10.1016/j.renene.2003.11.013

20. Luedeling, E., 2012: Climate change impacts on winter chill for temperate fruit and nut production: A review. *Scientia Horticulturae*, **144,** 218-229, doi:10.1016/j.scienta.2012.07.011. [Available online at http://www.sciencedirect.com/science/article/pii/S0304423812003305]

21. Luedeling, E., M. Zhang, and E. H. Girvetz, 2009: Climatic changes lead to declining winter chill for fruit and nut trees in California during 1950–2099. *PLoS ONE*, **4,** e6166, doi:10.1371/journal.pone.0006166. [Available online at http://www.plosone.org/article/fetchObjectAttachment.action?uri=info%3Adoi%2F10.1371%2Fjournal.pone.0006166&representation=PDF]

22. Wolfe, D. W., L. Ziska, C. Petzoldt, A. Seaman, L. Chase, and K. Hayhoe, 2008: Projected change in climate thresholds in the Northeastern U.S.: implications for crops, pests, livestock, and farmers. *Mitigation and Adaptation Strategies for Global Change*, **13,** 555-575, doi:10.1007/s11027-007-9125-2

23. Andresen, J., 2012: personal communication.

24. White, M. A., N. S. Diffenbaugh, G. V. Jones, J. S. Pal, and F. Giorgi, 2006: Extreme heat reduces and shifts United States premium wine production in the 21st century. *Proceedings of the National Academy of Sciences*, **103,** 11217-11222, doi:10.1073/pnas.0603230103. [Available online at http://www.pnas.org/content/103/30/11217.full.pdf+html]

25. Akin, D. E., L. L. Rigsby, S. L. Fales, and M. E. Snook, 1987: Temperature effects on leaf anatomy, phenolic acids, and tissue digestibility in tall fescue. *Agronomy Journal*, **79,** 271-275. [Available online at https://www.agronomy.org/publications/aj/pdfs/79/2/AJ0790020271];

Dijkstra, F. A., D. Blumenthal, J. A. Morgan, E. Pendall, Y. Carrillo, and R. F. Follett, 2010: Contrasting effects of elevated CO_2 and warming on nitrogen cycling in a semiarid grassland. *New Phytologist*, **187,** 426-437, doi:10.1111/j.1469-8137.2010.03293.x;

Gentile, R., M. Dodd, M. Lieffering, S. C. Brock, P. W. Theobald, and P. C. D. Newton, 2012: Effects of long-term exposure to enriched CO_2 on the nutrient-supplying capacity of a grassland soil. *Biology and Fertility of Soils*, **48,** 357-362, doi:10.1007/s00374-011-0616-7;

Henderson, M. S., and D. L. Robinson, 1982: Environmental influences on yield and in vitro true digestibility of warm-season perennial grasses and the relationships to fiber components. *Agronomy Journal*, **74,** 943-946, doi:10.2134/agronj1982.00021962007400060004x;

Morgan, J. A., J. D. Derner, D. G. Milchunas, and E. Pendall, 2008: Management implications of global change for Great Plains rangelands. *Rangelands*, **30,** 18-22, doi:10.2111/1551-501X(2008)30[18:MIOGCF]2.0.CO;2. [Available online at http://www.jstor.org/stable/pdfplus/25145388.pdf?acceptTC=true];

Newman, Y. C., L. E. Sollenberger, K. J. Boote, L. H. Allen, J. C. V. Vu, and M. B. Hall, 2005: Temperature and carbon dioxide effects on nutritive value of rhizoma peanut herbage. *Crop science*, **45,** 316-321, doi:10.2135/cropsci2005.0316

26. Craine, J. M., A. J. Elmore, K. Olson, and D. Tolleson, 2010: Climate change and cattle nutritional stress. *Global Change Biology*, **16,** 2901-2911, doi:10.1111/j.1365-2486.2009.02060.x

27. Ainsworth, E. A., P. A. Davey, C. J. Bernacchi, O. C. Dermody, E. A. Heaton, D. J. Moore, P. B. Morgan, S. L. Naidu, H. Y. Ra, X. Zhu, P. S. Curtis, and S. P. Long, 2002: A meta-analysis of elevated CO_2 effects on soybean (glycine max) physiology, growth and yield. *Global Change Biology*, **8,** 695-709, doi:10.1046/j.1365-2486.2002.00498.x;

Kimball, B. A., 1983: Carbon dioxide and agricultural yield: an assemblage and analysis of 430 prior observations. *Agronomy Journal*, **75,** 779-788, doi:10.2134/agronj1983.00021962007500050014x;

——, 2011: Lessons from FACE: CO_2 Effects and interactions with water, nitrogen, and temperature. *Handbook of Climate Change and Agroecosystems: Impacts, Adaptation, and Mitigation***,** 87-107

28. Ziska, L. H., 2003: Evaluation of the growth response of six invasive species to past, present and future atmospheric carbon dioxide. *Journal of Experimental Botany*, **54,** 395-404

29. Sardans, J., and J. Peñuelas, 2012: The role of plants in the effects of global change on nutrient availability and stoichiometry in the plant-soil system. *Plant Physiology*, **160,** 1741-1761, doi:10.1104/pp.112.208785. [Available online at http://www.plantphysiology.org/content/160/4/1741.full.pdf];

Booker, F., R. Muntifering, M. McGrath, K. Burkey, D. Decoteau, E. Fiscus, W. Manning, S. Krupa, A. Chappelka, and D. Grantz, 2009: The ozone component of global change: Potential effects on agricultural and horticultural plant yield, product quality and interactions with invasive species. *Journal of Integrative Plant Biology*, **51,** 337-351, doi:10.1111/j.1744-7909.2008.00805.x. [Available online at http://onlinelibrary.wiley.com/store/10.1111/j.1744-7909.2008.00805.x/asset/j.1744-7909.2008.00805.x.pdf?v=1&t=ho48uurh&s=9ada8e3fec754579888cae42ff8ca592ed1f4a0c];

Grantz, D. A., S. Gunn, and H. B. Vu, 2006: O3 impacts on plant development: A meta-analysis of root/shoot allocation and growth. *Plant, Cell & Environment*, **29,** 1193-1209, doi:10.1111/j.1365-3040.2006.01521.x. [Available online at http://onlinelibrary.wiley.com/doi/10.1111/j.1365-3040.2006.01521.x/pdf]

30. Morgan, J., A. Mosier, D. Milchunas, D. Lecain, J. Nelson, and W. Parton, 2004: CO2 Enhances Productivity of the Shortgrass Steppe, Alters Species Composition and Reduces Forage Digestibility. *Ecological Applications*, **14,** 208-219;

Morgan, J. A., 2002: Looking Beneath the Surface. *Science*, **298,** 1903-1904, doi:10.1126/science.1079808

31. Ziska, L. H., 2001: Changes in competitive ability between a C4 crop and a C3 weed with elevated carbon dioxide. *Weed Science*, **49,** 622-627, doi:10.1614/0043-1745(2001)049[0622:CICABA]2.0.CO;2. [Available online at http://www.bioone.org/doi/pdf/10.1614/0043-1745%282001%29049%5B0622%3ACICABA%5D2.0.CO%3B2]

32. Rötter, R., and S. C. Van de Geijn, 1999: Climate change effects on plant growth, crop yield and livestock. *Climatic Change*, **43,** 651-681. [Available online at http://download.springer.com/static/pdf/581/art%253A10.1023%252FA%253A1005541132734.pdf?auth66=1362750472_6401cb6754a5956f6ada147382a4a215&ext=.pdf]

33. Gaughan, J., N. Lacetera, S. E. Valtorta, H. H. Khalifa, L. Hahn, and T. Mader, 2009: Ch. 7: Response of domestic animals to climate challenges. *Biometeorology for Adaptation to Climate Variability and Change*, K. L. Ebi, I. Burton, and G. R. McGregor, Eds., Springer Netherlands, 131-170

34. Mader, T. L., 2003: Environmental stress in confined beef cattle. *Journal of Animal Science*, **81,** E110-E119. [Available online at http://www.animal-science.org/content/81/14_suppl_2/E110.full.pdf]

35. NOAA, cited 2012: Billion-Dollar Weather/Climate Disasters, Distribution and Change: 2000 to 2010, summary statistics. NOAA's National Climatic Data Center. [Available online at http://www.ncdc.noaa.gov/billions/summary-stats]

36. Oerke, E.-C., 2006: Crop losses to pests. *The Journal of Agricultural Science*, **144,** 31-43, doi:10.1017/S0021859605005708

37. Garrett, K. A., S. P. Dendy, E. E. Frank, M. N. Rouse, and S. E. Travers, 2006: Climate change effects on plant disease: Genomes to ecosystems. *Annual Review Phytopathology*, **44,** 489-509, doi:10.1146/annurev.phyto.44.070505.143420

38. Ziska, L. H., 2010: Elevated carbon dioxide alters chemical management of Canada thistle in no-till soybean. *Field Crops Research*, **119,** 299-303, doi:10.1016/j.fcr.2010.07.018

39. Bradley, B. A., D. S. Wilcove, and M. Oppenheimer, 2010: Climate change increases risk of plant invasion in the Eastern United States. *Biological Invasions*, **12,** 1855-1872, doi:10.1007/s10530-009-9597-y. [Available online at http://europepmc.org/abstract/AGR/IND44367832/reload=0;jsessionid=geMUvZpMPs0zzRUz8D6h.2]

40. Bradley, B. A., D. M. Blumenthal, R. Early, E. D. Grosholz, J. J. Lawler, L. P. Miller, C. J. B. Sorte, C. M. D'Antonio, J. M. Diez, J. S. Dukes, I. Ibanez, and J. D. Olden, 2012: Global change, global trade, and the next wave of plant invasions. *Frontiers in Ecology and the Environment*, **10,** 20-28, doi:10.1890/110145

41. Koleva, N. G., and U. A. Schneider, 2009: The impact of climate change on the external cost of pesticide applications in US agriculture. *International Journal of Agricultural Sustainability*, **7,** 203-216, doi:10.3763/ijas.2009.0459

42. Ziska, L. H., J. R. Teasdale, and J. A. Bunce, 1999: Future atmospheric carbon dioxide may increase tolerance to glyphosate. *Weed Science*, **47,** 608-615

43. Coakley, S. M., H. Scherm, and S. Chakraborty, 1999: Climate change and plant disease management. *Annual Review of Phytopathology*, **37,** 399-426, doi:10.1146/annurev.phyto.37.1.399

44. Wu, F., D. Bhatnagar, T. Bui-Klimke, I. Carbone, R. Hellmich, G. Munkvold, P. Paul, G. Payne, and E. Takle, 2011: Climate change impacts on mycotoxin risks in US maize. *World Mycotoxin Journal*, **4,** 79-93, doi:10.3920/WMJ2010.1246

45. Roff, D., 1983: Phenological adaptation in a seasonal environment: a theoretical perspective. *Diapause and life cycle strategies in insects*, V. K. Brown, and I. Hodek, Eds., Kluwer, 253-270. [Available online at http://books.google.com/books?id=f0ogAQAAMAAJ]

46. Porter, J. H., M. L. Parry, and T. R. Carter, 1991: The potential effects of climatic change on agricultural insect pests. *Agricultural and Forest Meteorology*, **57,** 221-240, doi:10.1016/0168-1923(91)90088-8

47. Showers, W. B., 1993: Diversity and variation of European corn borer populations. *Evolution of Insect Pests: Patterns of Variation*, K. C. Kim, and B. A. McPheron, Eds., Wiley and Sons, Inc., 287-309. [Available online at http://books.google.com/books?id=KEEgAQAAMAAJ]

48. Parmesan, C., N. Ryrholm, C. Stefanescu, J. K. Hill, C. D. Thomas, H. Descimon, B. Huntley, L. Kaila, J. Kullberg, T. Tammaru, W. J. Tennent, J. A. Thomas, and M. Warren, 1999: Poleward shifts in geographical ranges of butterfly species associated with regional warming. *Nature*, **399,** 579-583, doi:10.1038/21181. [Available online at http://www.nature.com/nature/journal/v399/n6736/pdf/399579a0.pdf]

49. Baylis, M., and A. K. Githeko, 2006: The effects of climate change on infectious diseases of animals. Report for the Foresight Project on Detection of Infectious Diseases, Department of Trade and Industry, 19 pp., UK Government Foresight Project, Infectious Diseases: preparing for the future, Office of Science and Innovation

50. Favis-Mortlock, D. T., and A. J. T. Guerra, 1999: The implications of general circulation model estimates of rainfall for future erosion: a case study from Brazil. *Catena*, **37,** 329-354, doi:10.1016/S0341-8162(99)00025-9 ;

Favis-Mortlock, D. T., M. R. Savabi, M. G. Anderson, and S. Brooks, 1996: Shifts in rates and spatial distributions of soil erosion and deposition under climate change. *Advances in hillslope processes: volume 1.*, M. G. Anderson, and S. M. Brooks, Eds., 529-560;

Nearing, M. A., 2001: Potential changes in rainfall erosivity in the US with climate change during the 21st century. *Journal of Soil and Water Conservation*, **56,** 229-232;

Pruski, F. F., and M. A. Nearing, 2002: Climate-induced changes in erosion during the 21st century for eight U.S. locations. *Water Resources Research*, **38,** 34-31 - 34-11, doi:10.1029/2001WR000493. [Available online at http://onlinelibrary.wiley.com/doi/10.1029/2001WR000493/pdf];

——, 2002: Runoff and soil-loss responses to changes in precipitation: a computer simulation study. *Journal of Soil and Water Conservation*, **57,** 7-16

51. Kunkel, K. E., L. E. Stevens, S. E. Stevens, L. Sun, E. Janssen, D. Wuebbles, and J. G. Dobson, 2013: Regional Climate Trends and Scenarios for the U.S. National Climate Assessment: Part 9. Climate of the Contiguous United States. NOAA Technical Report NESDIS 142-9, 85 pp, National Oceanic and Atmospheric Administration, National Environmental Satellite, Data, and Information Service, Washington, D.C. [Available online at http://www.nesdis.noaa.gov/technical_reports/NOAA_NESDIS_Tech_Report_142-9-Climate_of_the_Contiguous_United_States.pdf]

52. Mass, C., A. Skalenakis, and M. Warner, 2011: Extreme Precipitation over the West Coast of North America: Is There a Trend? *Journal of Hydrometeorology*, **12,** 310-318, doi:10.1175/2010JHM1341.1. [Available online at http://journals.ametsoc.org/doi/pdf/10.1175/2010JHM1341.1]

53. Pan, Z., D. Andrade, M. Segal, J. Wimberley, N. McKinney, and E. Takle, 2010: Uncertainty in future soil carbon trends at a central US site under an ensemble of GCM scenario climates. *Ecological Modelling*, **221,** 876-881, doi:10.1016/j.ecolmodel.2009.11.013

54. Dominati, E., M. Patterson, and A. Mackay, 2010: A framework for classifying and quantifying the natural capital and ecosystem services of soils. *Ecological Economics*, **69,** 1858-1868, doi:10.1016/j.ecolecon.2010.05.002

55. Kunkel, K. E., P. D. Bromirski, H. E. Brooks, T. Cavazos, A. V. Douglas, D. R. Easterling, K. A. Emanuel, P. Y. Groisman, G. J. Holland, T. R. Knutson, J. P. Kossin, P. D. Komar, D. H. Levinson, and R. L. Smith, 2008: Ch. 2: Observed changes in weather and climate extremes. *Weather and Climate Extremes in a Changing Climate. Regions of Focus: North America, Hawaii, Caribbean, and U.S. Pacific Islands. A Report by the U.S. Climate Change Science Program and the Subcommittee on Global Change Research*, T. R. Karl, G. A. Meehl, C. D. Miller, S. J. Hassol, A. M. Waple, and W. L. Murray, Eds., 35-80. [Available online at http://downloads.climatescience.gov/sap/sap3-3/sap3-3-final-all.pdf]

56. Takle, E., 2011: Ch. 2: Climate changes in Iowa. Iowa Climate Change Impacts Committee, Iowa Department of Natural Resources, 8-13. [Available online at http://www.iowadnr.gov/portals/idnr/uploads/air/environment/climatechange/complete_report.pdf?amp;tabid=1077]

57. O'Neal, M. R., M. A. Nearing, R. C. Vining, J. Southworth, and R. A. Pfeifer, 2005: Climate change impacts on soil erosion in Midwest United States with changes in crop management. *Catena*, **61,** 165-184, doi:10.1016/j.catena.2005.03.003. [Available online at http://ddr.nal.usda.gov/bitstream/10113/6789/1/IND43978173.pdf&embedded=true]

58. Wischmeier, W. H., and D. D. Smith, 1978: *Predicting rainfall erosion losses: a guide to conservation planning. Agriculture handbook No. 537.* Vol. 537, U.S. Department of Agriculture, 62 pp. [Available online at http://naldc.nal.usda.gov/download/CAT79706928/PDF]

59. Delgado, J. A., P. M. Groffman, M. A. Nearing, T. Goddard, D. Reicosky, R. Lal, N. R. Kitchen, C. W. Rice, D. Towery, and P. Salon, 2011: Conservation practices to mitigate and adapt to climate change. *Journal of Soil and Water Conservation*, **66,** 118A-129A, doi:http://www.jswconline.org/content/66/4/118A.full.pdf+html. [Available online at http://www.jswconline.org/content/66/4/118A.full.pdf+html]

60. Peterson, T. C., P. A. Stott, and S. Herring, 2012: Explaining extreme events of 2011 from a climate perspective. *Bulletin of the American Meteorological Society*, **93,** 1041-1067, doi:10.1175/BAMS -D-12-00021.1. [Available online at http://journals.ametsoc.org/doi/pdf/10.1175/BAMS-D-12-00021.1]

61. Alexander, L. V., X. Zhang, T. C. Peterson, J. Caesar, B. Gleason, A. M. G. Klein Tank, M. Haylock, D. Collins, B. Trewin, F. Rahimzadeh, A. Tagipour, K. Rupa Kumar, J. Revadekar, G. Griffiths, L. Vincent, D. B. Stephenson, J. Burn, E. Aguilar, M. Brunet, M. Taylor, M. New, P. Zhai, M. Rusticucci, and J. L. Vazquez-Aguirre, 2006: Global observed changes in daily climate extremes of temperature and precipitation. *Journal of Geophysical Research*, **111,** 22, doi:10.1029/2005JD006290. [Available online at http://www.agu.org/journals/jd/jd0605/2005JD006290/2005JD006290.pdf]

62. Karl, T. R., B. E. Gleason, M. J. Menne, J. R. McMahon, R. R. Heim, Jr., M. J. Brewer, K. E. Kunkel, D. S. Arndt, J. L. Privette, J. J. Bates, P. Y. Groisman, and D. R. Easterling, 2012: U.S. temperature and drought: Recent Anomalies and Trends. *EOS Transactions, American Geophysical Union*, **93,** 473-474, doi:10.1029/2012EO470001. [Available online at http://onlinelibrary.wiley.com/doi/10.1029/2012EO470001/pdf];

Zhang, X., F. W. Zwiers, G. C. Hegerl, F. H. Lambert, N. P. Gillett, S. Solomon, P. A. Stott, and T. Nozawa, 2007: Detection of human influence on twentieth-century precipitation trends. *Nature*, **448,** 461-465, doi:10.1038/nature06025

63. Gaughan, J. B., T. L. Mader, S. M. Holt, G. L. Hahn, and B. A. Young, 2002: Review of current assessment of cattle and microclimate during periods of high heat load. *24th Biennial Conference of the Australian Society of Animal Production*. [Available online at http://www.researchgate.net/publication/43464350_Review_of_current_assessment_of_cattle_and_microclimate_during_periods_of_high_heat_load];

Gaughan, J. G., J. Goopy, and J. Spark, 2002: Excessive heat load index for feedlot cattle. Meat and Livestork-Australia project report, FLOT.316. MLA, Ltd, Sydney, Australia;

Mader, T. L., M. S. Davis, and J. B. Gaughan, 2007: Effect of sprinkling on feedlot microclimate and cattle behavior. *International Journal of Biometeorology*, **51,** 541-551, doi:10.1007/s00484-007-0093-8

64. Antle, J. M., S. M. Capalbo, E. T. Elliott, and K. H. Paustian, 2004: Adaptation, spatial heterogeneity, and the vulnerability of agricultural systems to climate change and CO_2 fertilization: an integrated assessment approach. *Climatic Change*, **64,** 289-315, doi:10.1023/B:CLIM.0000025748.49738.93

65. Easterling, W. E., 2010: Guidelines for adapting agriculture to climate change. *Handbook of Climate Change and Agroecosystems: Impacts, Adaptation, and Mitigation, ICP Series in Climate Change Impacts, Adaptation, and Mitigation – Vol. 1*, D. Hillel, and C. Rosenzweig, Eds., Imperial College Press, 452

66. Lin, B. B., 2011: Resilience in agriculture through crop diversification: adaptive management for environmental change. *BioScience*, **61,** 183-193, doi:10.1525/bio.2011.61.3.4. [Available online at http://www.bioone.org/doi/full/10.1525/bio.2011.61.3.4];

Tomich, T., S. Brodt, F. Ferris, R. Galt, W. Horwath, E. Kebreab, J. Leveau, D. Liptzin, M. Lubell, and P. Merel, 2011: Agroecology: A review from a global-change perspective. *The Annual Review of Environment and Resources*, **36,** 193-222, doi:10.1146/annurev-environ-012110-121302;

Wall, E., and B. Smit, 2005: Climate change adaptation in light of sustainable agriculture. *Journal of Sustainable Agriculture*, **27,** 113-123, doi:10.1300/J064v27n01_07

67. USDA, cited 2012: Quick Stats. U.S. Department of Agriculture, National Agricultural Statistics Service. [Available online at http://www.nass.usda.gov/Quick_Stats/]

68. Jackson, L. E., F. Santos-Martin, A. D. Hollander, W. R. Horwath, R. E. Howitt, J. B. Kramer, A. T. O'Geen, B. S. Orlove, J. W. Six, S. K. Sokolow, D. A. Sumner, T. P. Tomich, and S. M. Wheeler, 2009: Potential for adaptation to climate change in an agricultural landscape in the Central Valley of California. Publication number: CEC-500-2009-044-F, 165 pp., California Energy Commission, PIER Energy-Related Environmental Research Program. [Available online at http://www.energy.ca.gov/2009publications/CEC-500-2009-044/CEC-500-2009-044-F.PDF]

69. Izaurralde, R. C., A. M. Thomson, J. A. Morgan, P. A. Fay, H. W. Polley, and J. L. Hatfield, 2011: Climate impacts on agriculture: Implications for forage and rangeland production. *Agronomy Journal*, **103,** 371-381, doi:10.2134/agronj2010.0304

70. Knutson, C. L., T. Haigh, M. J. Hayes, M. Widhalm, J. Nothwehr, M. Kleinschmidt, and L. Graf, 2011: Farmer perceptions of sustainable agriculture practices and drought risk reduction in Nebraska, USA. *Renewable Agriculture and Food Systems*, **26,** 255-266, doi:10.1017/S174217051100010X

71. Beach, R. H., C. Zhen, A. Thomson, R. M. Rejesus, P. Sinha, A. W. Lentz, D. V. Vedenov, and B. A. McCarl, 2010: *Climate Change Impacts on Crop Insurance.* DIANE Publishing, 215 pp;

Smit, B., and M. W. Skinner, 2002: Adaptation options in agriculture to climate change: a typology. *Mitigation and Adaptation Strategies for Global Change*, **7,** 85-114, doi:10.1023/A:1015862228270

72. Harwood, J., R. Heifner, K. Coble, J. Perry, and A. Somwaru, 1999: Managing Risk in Farming: Concepts, Research, and Analysis. Agricultural Economic Report No. 774, 136 pp., Economic Research Service, U.S. Department of Agriculture. [Available online at http://www.ers.usda.gov/publications/aer774/];

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,** 19691-19696, doi:http://dx.doi.org/10.1073%2Fpnas.0701890104. [Available online at http://www.pnas.org/cgi/content/full/0701890104/DC1];

Pfeifer, R. A., and M. Habeck, 2002: Farm-level economic impacts of climate change. *Effects of Climate Change and Variability on Agricultural Production Systems*, O. C. Doering, III , J. C. Randolph, J. Southworth, and R. A. Pfeifer, Eds., Kluwer Academic Publishers, 159-177

73. FAO, 2001: The State of Food Insecurity in the World. Food and Agriculture Organization of the United Nations, Rome, Italy. [Available online at http://www.fao.org/docrep/003/y1500e/y1500e00.htm]

74. Coleman-Jensen, A., M. Nord, M. Andrews, and S. Carlson, 2012: Statistical Supplement to Household Food Security in the United States in 2011, AP-058, 30 pp., U.S. Department of Agriculture, Economic Research Service

75. Ericksen, P. J., J. S. I. Ingram, and D. M. Liverman, 2009: Food security and global environmental change: emerging challenges. *Environmental Science & Policy*, **12,** 373-377, doi:10.1016/j.envsci.2009.04.007

76. Misselhorn, A., P. Aggarwal, P. Ericksen, P. Gregory, L. Horn-Phathanothai, J. Ingram, and K. Wiebe, 2012: A vision for attaining food security. *Current Opinion in Environmental Sustainability*, **4,** 7-17, doi:10.1016/j.cosust.2012.01.008

77. NRC, 2007: *Understanding Multiple Environmental Stresses: Report of a Workshop.* National Research Council. The National Academy Press, 154 pp. [Available online at www.nap.edu]

78. Schmidhuber, J., and F. N. Tubiello, 2007: Global food security under climate change. *Proceedings of the National Academy of Sciences of the United States of America*, **104,** 19703-19708, doi:10.1073/pnas.0701976104. [Available online at http://www.pnas.org/content/104/50/19703.full.pdf];

Tirado, M. C., M. J. Cohen, N. Aberman, J. Meerman, and B. Thompson, 2010: Addressing the challenges of climate change and biofuel production for food and nutrition security. *Food Research International*, **43,** 1729-1744, doi:10.1016/j.foodres.2010.03.010

79. USDA, cited 2012: Import Share of Consumption. U.S. Department of Agriculture. [Available online at http://www.ers.usda.gov/topics/international-markets-trade/us-agricultural-trade/import-share-of-consumption.aspx]

80. Godfray, H. C. J., I. R. Crute, L. Haddad, D. Lawrence, J. F. Muir, N. Nisbett, J. Pretty, S. Robinson, C. Toulmin, and R. Whiteley, 2010: The future of the global food system. *Philosophical Transactions of the Royal Society B:*

Biological Sciences, **365,** 2769-2777, doi:10.1098/rstb.2010.0180. [Available online at http://rstb.royalsocietypublishing.org/content/365/1554/2769.full.pdf+html]

81. FAO, 2011: The State of Food Insecurity in the World - How Does International Price Volatility Affect Domestic Economies and Food Security?, 51 pp., Food and Agriculture Organization of the United Nations, Rome, Italy. [Available online at www.fao.org/docrep/014/i2330e/i2330e.pdf]

82. CCSP, 2008: *The Effects of Climate Change on Agriculture, Land Resources, Water Resources, and Biodiversity. A Report by the U.S. Climate Change Science Program and the Subcommittee on Global Change Research.* P. Backlund, A. Janetos, D. Schimel, J. Hatfield, K. Boote, P. Fay, L. Hahn, C. Izaurralde, B. A. Kimball, T. Mader, J. Morgan, D. Ort, W. Polley, A. Thomson, D. Wolfe, M. Ryan, S. Archer, R. Birdsey, C. Dahm, L. Heath, J. Hicke, D. Hollinger, T. Huxman, G. Okin, R. Oren, J. Randerson, W. Schlesinger, D. Lettenmaier, D. Major, L. Poff, S. Running, L. Hansen, D. Inouye, B. P. Kelly, L. Meyerson, b. Peterson, and R. Shaw, Eds. U.S. Environmental Protection Agency, 362 pp. [Available online at http://library.globalchange.gov/products/assessments/2004-2009-synthesis-and-assessment-products/sap-3-4-the-effects-of-climate-change-on-agcriculture-land-resources-water-resources-and-biodiversity]

83. Karl, T. R., J. T. Melillo, and T. C. Peterson, Eds., 2009: *Global Climate Change Impacts in the United States*. Cambridge University Press, 189 pp. [Available online at http://www.globalchange.gov/publications/reports/scientific-assessments/us-impacts]

84. FAO, 2008: *The State of Food Insecurity in the World, 2008: High Food Prices and Food Security Threats and Opportunities.* F. a. A. O. o. t. U. Nations, Ed. Food and Agriculture Organization of the United Nations, 56 pp

85. ERS, cited 2012: Data sets. State fact sheets. U.S. Department of Agriculture, Economic Research Service. [Available online at http://ers.usda.gov/data-products/state-fact-sheets.aspx]