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 recent past and are projected to increase further 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 by increasing extremes in precipitation will continue to challenge both rain-fed 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 future climate change.**
6. **Climate change effects on agriculture will have consequences for food security both in the U.S. and globally, not only through changes in crop yields, but also changes in the ways climate affects food processing, storage, transportation, and retailing.**

The United States produces nearly $300 billion per year in agricultural commodities, with the contributions from livestock accounting for roughly half of that value. Production of all commodities will be vulnerable to direct impacts from changing climate conditions on crop and livestock development and yield, and indirect impacts through increasing pressures from pests and pathogens that will benefit from a changing climate. Agriculture continually adapts to climate change through changes in crop rotations, planting times, genetic selection, water management, and shifts in areas of crop production. These have proven to be effective strategies to allow agricultural production to increase as evidenced by the continued increase in production and efficiency of production 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. Climate change has the potential to both positively and negatively affect the patterns and productivity of crop, livestock, and fishery systems at the local, national, and global scales. It will also alter the stability of food supplies and create new food security challenges for the United States as the world seeks to feed nine billion people by 2050. U.S. agriculture exists as part of the global economy and agricultural exports have outpaced imports as part of the overall balance of trade; however, climate change will affect the quantity of produce available for export and import as well as the prices.

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, 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 include seizing opportunities to increase profitability and minimizing threats posed by unfavorable conditions.

Increasing Impacts on Agriculture

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

Strategies are available to producers for adapting to mean temperature and precipitation changes projected (Malcolm et al. 2012; Ch. 2: Our Changing Climate) for the next 25 years. Future changes in extremes are less well understood however, and increases could lead to disruption of national food production and prices. These strategies include continued technological advancements, expansion of irrigated acreage, regional shifts in crop acreage, other adjustments in inputs and outputs, and changes in livestock management practices caused by changing climate patterns (Adams et al. 1987; Darwin et al. 1995; Mendelsohn et al. 1994; Reilly et al. 2003; Rosenzweig and Parry 1994; Sands and Edmonds 2005). However, such projections often fail to consider the impacts from weeds, insects, and diseases that accompany changes in both trends and extremes, which can increase losses significantly (Malcolm et al. 2012). By mid-century, when temperature increases are projected to exceed 1.8°F to 5.4°F and precipitation extremes are further intensified, yields of major U.S. crops and farm profits are expected to decline (IPCC 2007; Ortiz et al. 2008; Schlenker et al. 2005). There have been detectable impacts on production already due to the increasing temperatures (Lobell et al. 2011). 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 numbers of extreme weather events, resulting in more variation in production over time (Hatfield et al. 2011; Lobell and Gourdji 2012). The overall implications for production are for increased uncertainty in production totals, which affect both domestic and international markets and food prices. This will affect the potential for adequate food, feed, fiber, and fuel derived from agricultural production systems.

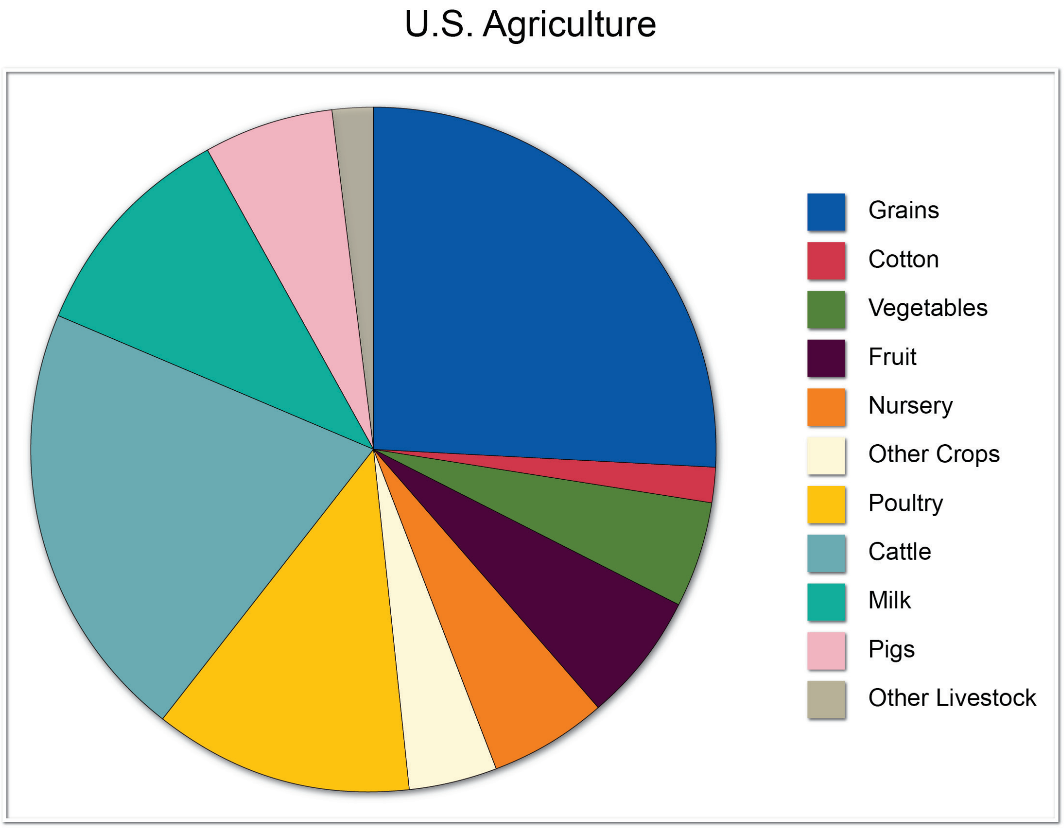

Figure 6.1: U.S. Agriculture

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

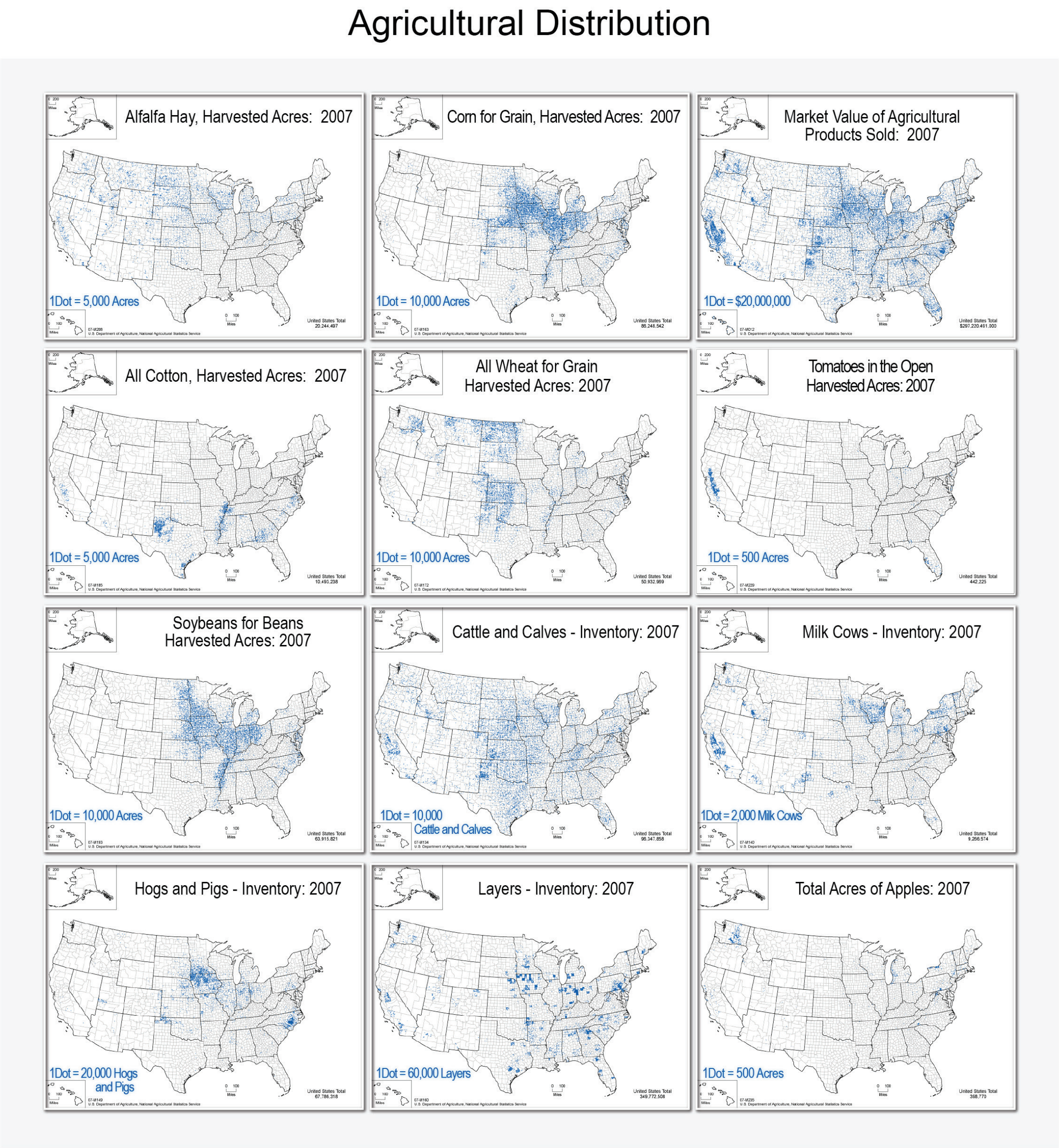

Figure 6.2: Agricultural Distribution

Caption: Agriculture is distributed across the United States with market value and crop types varying by region. In 2007, the total market value was nearly $300 billion dollars. The wide distribution of agricultural commodities across the U.S. is expected to result in differing effects of climate change on these commodities. (Source: 2007 Census of Agriculture, USDA National Agricultural Statistics Service, 2008)

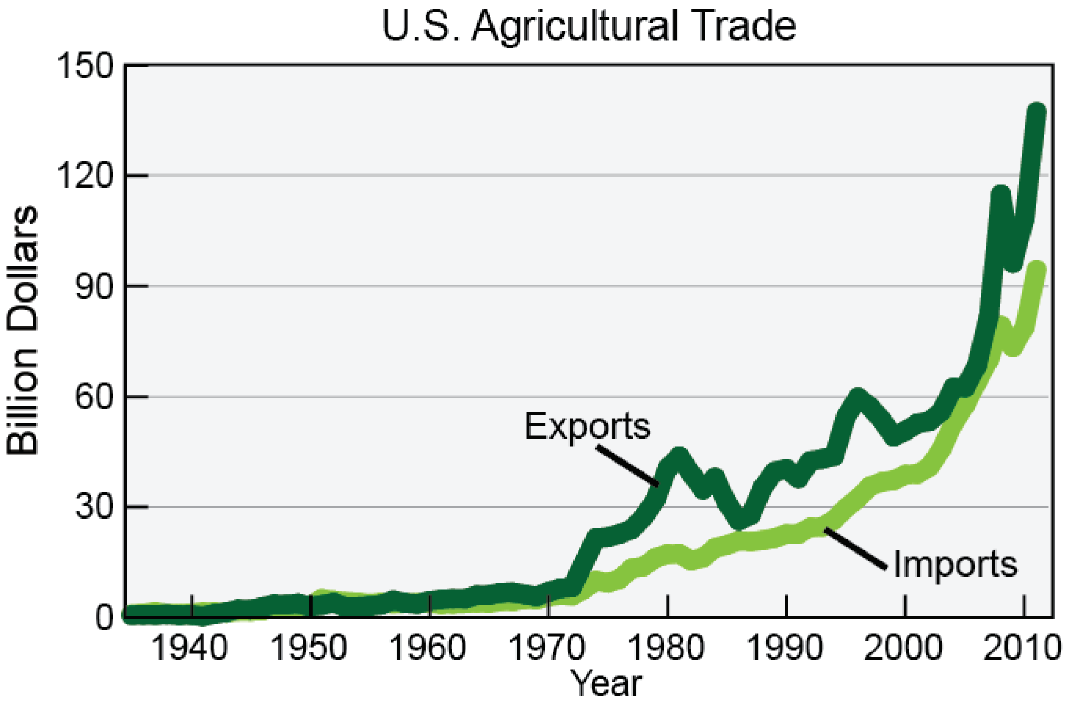

Figure 6.3: U.S. Agricultural Trade

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 impacts on harvests and other impacts, climate change will continue to be a factor in global markets. (Data from USDA, Economic Research Service, 2012)

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 given set of temperature thresholds that define the upper and lower boundaries for growth, along with an optimum temperature (Hatfield et al. 2011). Plants are currently grown in areas where temperatures match their thresholds. 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, and production over years in a given location is more affected by available soil water during the growing season than temperature (Hatfield et al. 2011; Walthall et al. 2012).

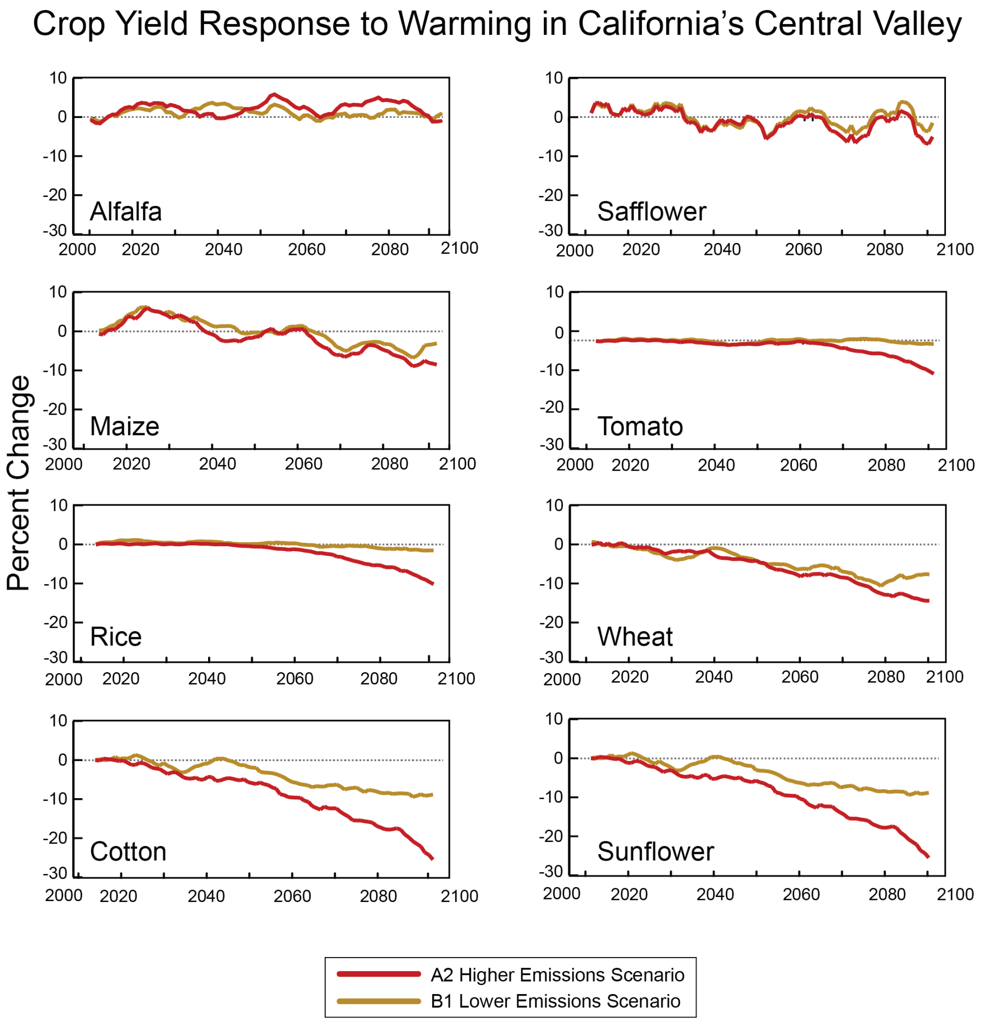

Figure 6.4: Crop Yield Response to Warming in California’s Central Valley

Caption: Changes in climate through this century will affect crops differently because individual species respond differently to warming. 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). The crop model used in this analysis (DAYCENT) assumes that water supplies and nutrients are maintained at adequate levels. The lines show five-year moving averages for the period from 2000 to 2097 with the yield changes shown as differences from the 2000 baseline. Yield response varies among crops with alfalfa showing only year-to-year variation across the whole period, while cotton, maize, wheat, and sunflower begin to show yield declines early in 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 (Lee et al. 2011).

One critical period in which temperatures are a major factor is the pollination stage; pollen release triggers 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 (Walthall et al. 2012). These effects have already begun to occur; corn yields were affected by high nighttime temperatures in 2010 and 2012 across the Corn Belt, and with the number of nights with hot temperatures projected to increase as much as 30%, yield reductions will become more prevalent. (Hatfield 2012, personal communication; Hatfield et al. 2011; Ch. 2: Our Changing Climate).

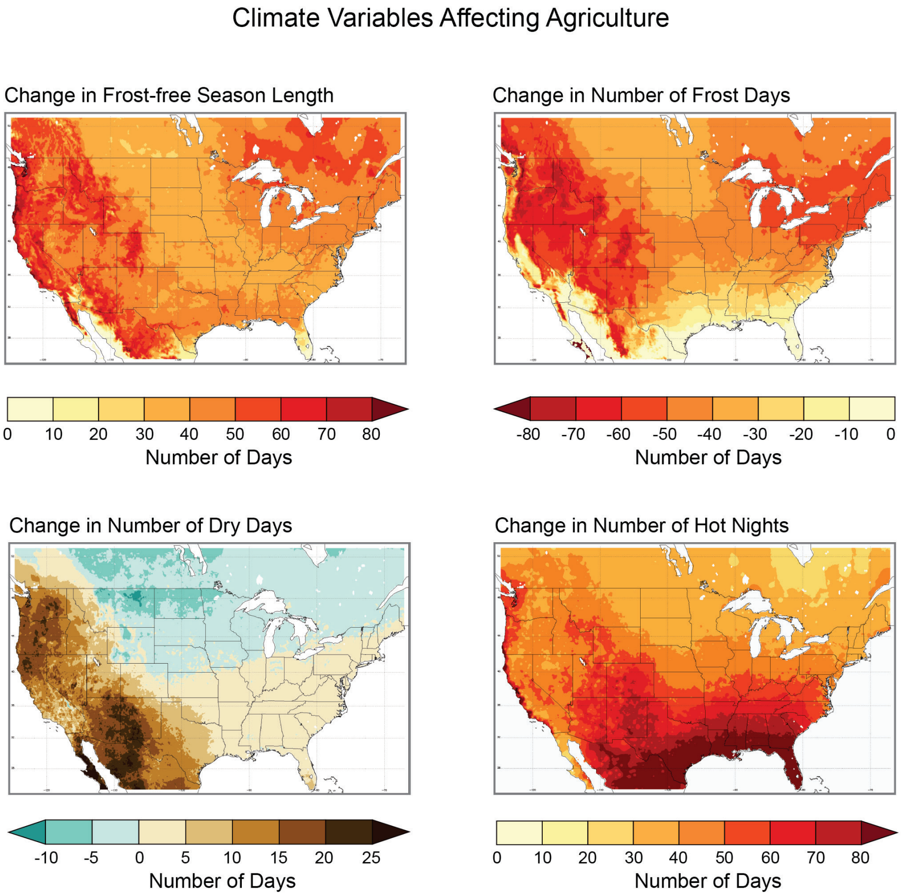

Figure 6.5: Climate Variables Affecting Agriculture

Caption: Many climate variables affect agriculture. Changes in climate parameters critical to agriculture show lengthening of the growing season and reductions in the number of frost days (days with minimum temperatures below freezing) for 2100, 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 (Hatfield et al. 2011). 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. In the lower, right graph, hot nights are defined as nights with a minimum temperature warmer than 90% of the minimum temperatures between 1971 and 1990 (Source: Walthall et al. 2012).

Temperature and precipitation will be affected by an increase in both the number of consecutive dry days (less frequent precipitation events) and the number of hot nights. 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 efficient 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. A similar response is found in animals in which exposure to multiple hot nights increases the degree of stress imposed on the animal (Mader 2012).

Increasing temperatures cause cultivated plants to grow and mature more quickly, causing plants to be smaller because soil may not be able to supply nutrients at required rates, thereby reducing growth and reducing grain, forage, fruit, or fiber production. Reduction in solar radiation in agricultural areas in the last 60 years (Qian et al. 2007) is projected to continue (Pan et al. 2004). Decreases in solar radiation may partially offset the acceleration of plant growth due to higher temperature and CO_2 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 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, or more, years, greatly limiting adaptive opportunity unless varieties could be introduced from other areas.

A warmer climate will impact growing conditions in many ways. For example, 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. Chilling requirements for fruit and nut trees in California are projected to not be met by the middle to the end of this century (Luedeling et al. 2009). For most of the Northeast, a 400-hour chilling requirement is projected to continue to be met during this century, but crops (such as cherries) with prolonged chilling requirements (1,000 or more hours) could be negatively affected, particularly in southern parts of the Northeast (Wolfe et al. 2008). 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 (Walthall et al. 2012), as was the case with cherries in Michigan in 2012 (Andresen 2012, personal communication).

Many Plants Need Chilling to Produce Fruit — Reduced Chilling is Projected

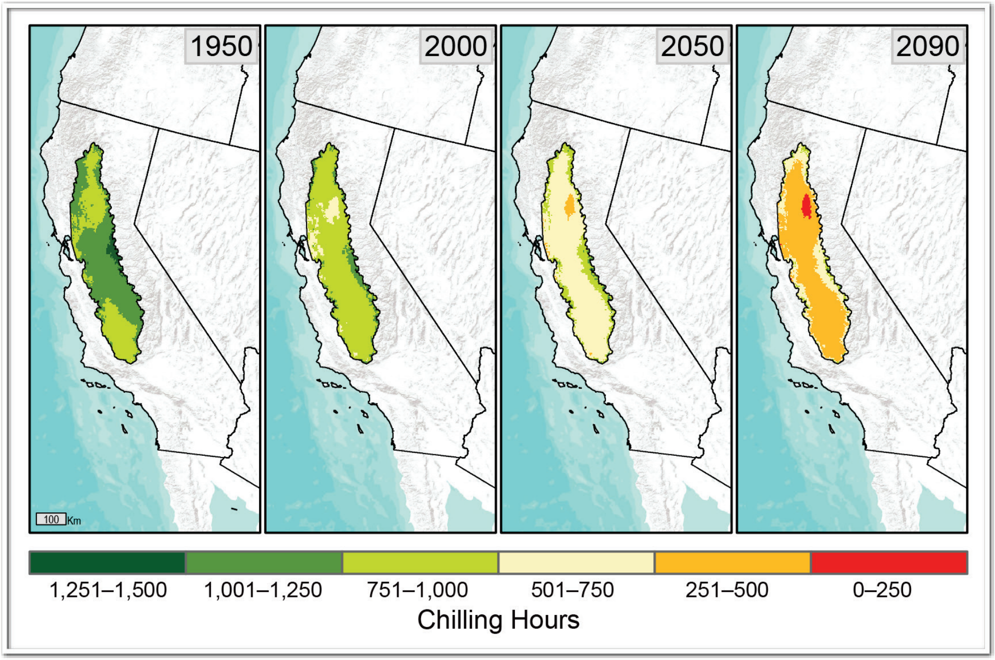

Figure 6.6: Many Plants Need Chilling to Produce Fruit – Reduced Chilling is Projected

Caption: Many perennial plants (fruit trees, grape vines) require exposure to particular numbers of chilling hours (hours in which the temperatures are below a given value over the winter). These values vary among species, and many trees require chilling hours before flowering and fruit set 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 over the next 100 years.

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 *increasing* temperature trends rather than simply continuations of observed trends as assumed here. To adapt to these kinds of changes, trees with a lower chilling requirement would have to be planted or chemical manipulation would be required to induce chilling.

Various trees and grape vines differ in their chilling requirements, with grapes requiring 90 hours, peaches 225, apples 400, and cherries above 1,000 (Source: Luedeling et al. 2009).

Experiments have documented that elevated CO_2 concentrations can increase plant growth while increasing water use efficiency; however, the impacts of elevated CO_2 on grain and fruit yield and quality are mixed (Akin et al. 1987; Craine et al. 2010; Dijkstra et al. 2010; Gentile et al. 2012; Henderson and Robinson 1982; Morgan et al. 2008; Newman et al. 2005). Reduced nitrogen and protein content are observed in some plants such as soybean and alfalfa, causing a reduction in grain and forage quality, and reducing the ability of pasture and rangeland to support grazing livestock. The magnitude of CO_2 growth stimulation in the absence of other stressors has been extensively analyzed for crop and tree species (Ainsworth et al. 2002; Kimball 1983, 2011; Ziska 2003) and is relatively well understood; however, the interaction with changing temperature and water and nutrient constraints creates uncertainty in the magnitude of these responses (Sardans and Peñuelas 2012). Because the growth stimulation effect of CO_2 has a disproportionately positive impact on several weed species, this effect will contribute to increased risk of crop loss due to weed pressure (Ziska 2003, 2009).

The advantage of increased water use efficiency due to elevated CO_2 in areas with limited precipitation 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. Increasing temperatures coupled with more extreme wet and dry events, or seasonal shifts in precipitation, will affect both crop water demand and plant production.

Animal agriculture is a major component of the U.S. agriculture system. 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 (Rötter and Van de Geijn 1999). 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 disruptions in performance, production, and fertility that limit 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 (Gaughan et al. 2009). For cattle that breed during spring and summer, exposure to high temperatures reduces conception rates. Livestock and dairy production is more affected by the number of days of extreme heat than by increases in average temperature (Mader 2003). Elevated humidity exacerbates the impact of high temperatures on animal health and performance.

Animal Response to Temperature Extremes

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 impacted. 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 (Mader 2003). 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 causes problems for 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 (NOAA 2012).

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.

Several weeds benefit more than crops from higher temperatures and CO_2 levels (Ziska 2003, 2009). One concern involves the northward spread of invasive weeds like privet and kudzu, which are already present in the South (Bradley et al. 2010). 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. 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 (Ziska et al. 1999). Higher concentrations of the chemical and more frequent sprayings thus will be needed, increasing economic and environmental costs associated with chemical use.

A warmer world brings higher humidity in wet years. This helps insects and diseases flourish, with negative indirect impacts on animal health and productivity (De Lucia et al. 2012; Garrett et al. 2006; Garrett et al. 2011; Jamieson et al. 2012; Wu et al. 2011). Climate affects microbial populations and distribution, the distribution of diseases carried by insects and rodents, animal and plant resistance to infections, food and water shortages, and food-borne diseases (Baylis and Githeko 2006; Gaughan et al. 2009; Thornton 2010). Earlier spring and warmer winter conditions may increase survival and proliferation of disease-causing agents and parasites. Regional warming and changes in rainfall distribution may 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 (Baylis and Githeko 2006; Gaughan et al. 2009).

Extreme Precipitation

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

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. 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 (Pan et al. 2010).

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 (Dominati et al. 2010). 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.

Several processes act to degrade soils, however, including erosion, compaction, acidification, salinization, toxification, and net loss of organic matter. 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 (Favis-Mortlock et al. 1996; Favis-Mortlock and Guerra 1999; Nearing 2001; Pruski and Nearing 2002a, 2002b). Projected shifts in rainfall intensity that include more extreme events will increase soil erosion in the absence of conservation practices (Kunkel et al. 2012; Mass et al. 2010).

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

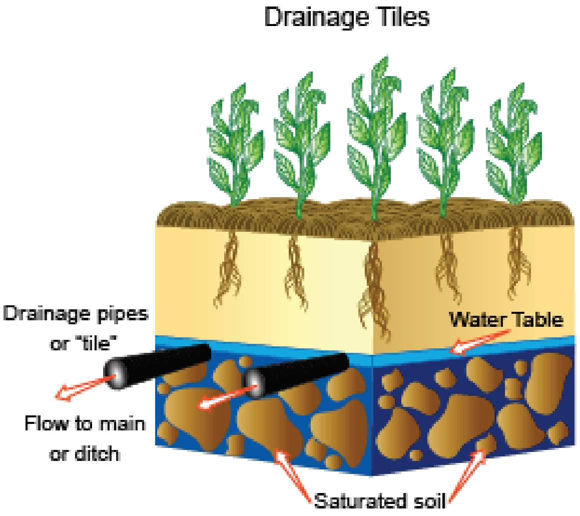

Figure 6.8

Water lost from the edge of the field is no longer available to the crop, and the soil that is removed is no longer in place 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. 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. This has been coupled with an increase in spring precipitation, which has decreased the number of workable days in the April to May period in Iowa by 3 days compared to the period from 1980-2000. To offset this increased precipitation, producers have been installing subsurface drainage to remove more water from the fields. 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. The potential for wind erosion, for example, could be increased in areas with persistent drought because of the reduction in vegetative cover and in many areas will increase erosion.

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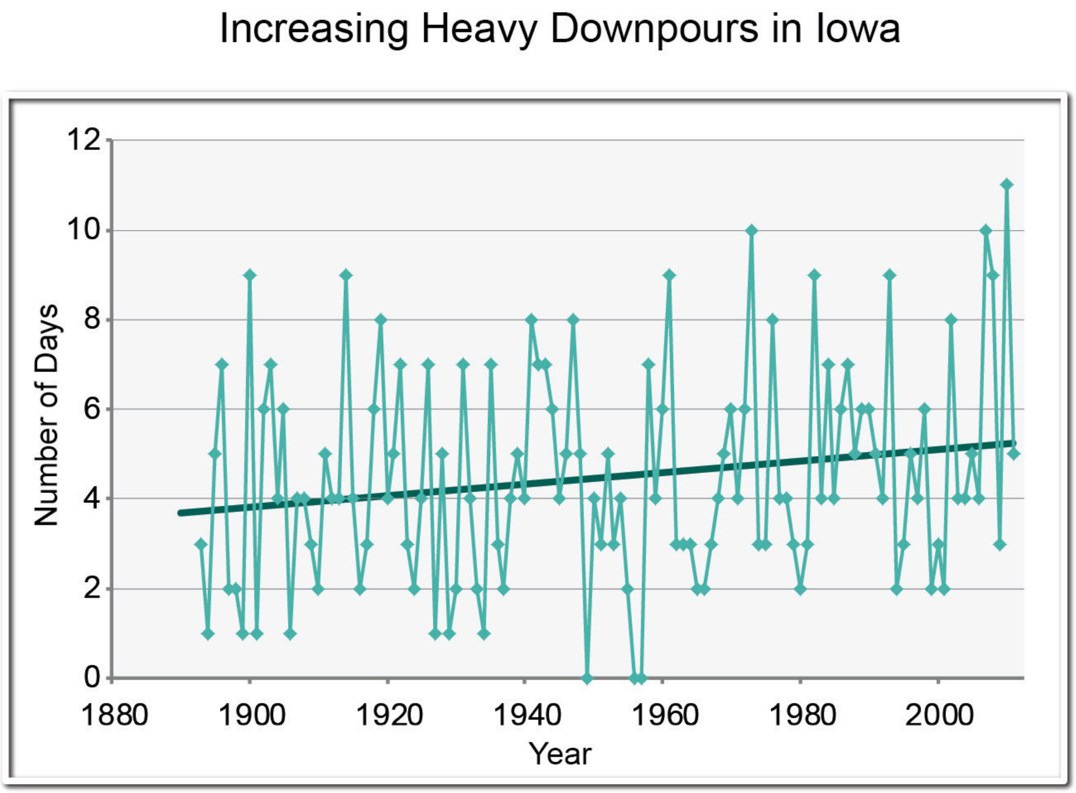

Figure 6.9: Increasing Heavy Downpours in Iowa

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 shows the number of days per year during which more than 1.25 inches of rain fell in Des Moines, Iowa. The upward trend is evident, with many recent years having more than 8 days with such heavy rainfall, which used to be rare. (Data from NWS Cooperative Observer Program, 2012)

Changes in production practices can have more effect than climate change on soil erosion. Though uncertainty is high, 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 (O'Neal et al. 2005; Wischmeier and Smith 1978). 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 (Delgado et al. 2011).

Rising temperatures 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 competitiveness, in turn, will drive changes in cropland allocations and production systems.

Heat and Drought

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 (Peterson et al. 2012). 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. Extreme events at vulnerable times could result in major impacts on growth or productivity, like hot-temperature extreme weather events on corn during pollination. Recent studies suggest that, with increased average temperature, during times of future droughts the higher temperatures and dry conditions will amplify drought severity and temperature extremes (Alexander et al. 2006; IPCC 2007; Karl et al. 2012; Zhang et al. 2007).

The occurrence of very hot nights and the duration of periods lacking agriculturally significant rainfall are projected to increase by the end of this century.

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 (Gaughan et al. 2002a; Gaughan et al. 2002b; Mader et al. 2007). 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 (Mader 2003).

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 future climate change.

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 (Easterling 2010; Lin 2011; Tomich et al. 2011; Wall and Smit 2005). In the Midwest, there have been shifts in the distribution of crops partially related to the increased demand for biofuels (USDA-NASS 2012; See also Ch. 10: Water, Energy, and Land Use 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 (Jackson et al. 2009). 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 United States, agricultural systems may have to undergo more transformative changes to remain productive and profitable in the long-term (Easterling 2010). 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 (Izaurralde et al. 2011).

While there are many possible adaptive responses to climate change, 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 (Antle et al. 2004; Knutson et al. 2011; Wolfe et al. 2008). 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 (Beach et al. 2009; Smit and Skinner 2002). As climate change intensifies, "climate risk" from more frequent and intense weather events will add to the risks commonly managed by producers, such as those related to production, marketing, finances, regulation, and personal health and safety factors (Harwood et al. 1999; Howden et al. 2007). 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 less reliable.

Food Security

Climate change effects on agriculture will have consequences for food security both in the U.S. and globally, not only through changes in crop yields, but also changes in the ways climate affects 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 (FAO 2001). 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 (Coleman-Jensen et al. 2012). 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 (Ericksen et al. 2009; Misselhorn et al. 2012).

Within the complex global food system, climate change is expected to impact food security in multiple ways. In addition to changes in agricultural yields, projected rising temperatures, changing weather patterns, and increases in frequency of extreme weather events will impact distribution of food- and waterborne diseases as well as food trade and distribution (Schmidhuber and Tubiello 2007; Tirado et al. 2010). This means that U.S. food security depends not only on how climate affects crop yields at the local and national level, but also on how climate extremes and changes affect food processing, storage, transportation, and retailing, 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 (USDA 2012). 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 impact food security in the U.S. while climate events in the U.S. may impact 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 shocks globally (Godfray et al. 2010).

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 FAO food price index over just a few months 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 (FAO 2011).

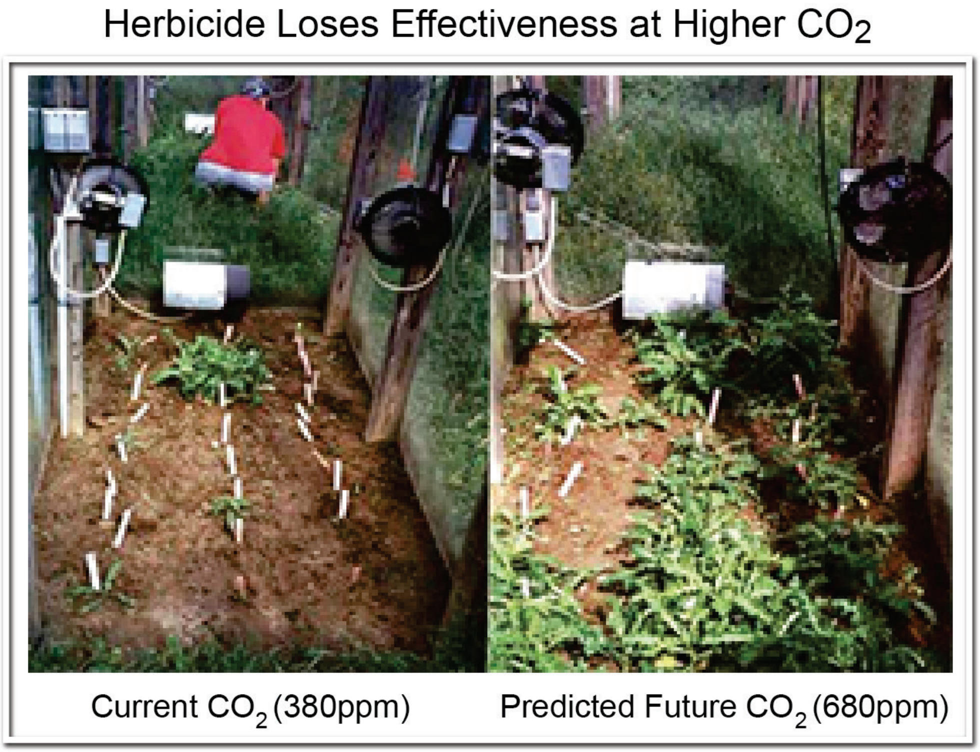

Figure 6.10: Herbicide Loses Effectiveness at Higher CO_2

Caption: The left photo shows weeds in a plot grown at a carbon dioxide (CO_2) concentration of about 380 parts per million (ppm), which approximates the current level of about 390 ppm. The right photo shows a plot in which the CO_2 level has been raised to about 680 ppm. Both plots were equally treated with herbicide (Wolfe et al. 2008). Photo credit: Lewis Ziska, USDA ARS.

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" (Walthall et al. 2012). 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, as did numerous technical teleconferences among the TIR authors.

The report team engaged in multiple technical discussions via teleconference, which included careful review of the foundational TIR (Walthall et al. 2012) and of approximately 55 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 recent past and are projected to increase further 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 summarizes extensive evidence documented in the Agriculture TIR, "Climate Change and Agriculture in the United States: An Assessment of Effects and Potential for Adaptation (Walthall et al. 2012). Technical Input reports (55) 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 will have impacts on crops and livestock is based on numerous studies and is incontrovertible (IPCC 2007; Lobell et al. 2011; Ortiz et al. 2008; Schlenker et al. 2005). 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 (Walthall et al. 2012). Further production costs in confined systems markedly increase when heat abatement strategies and climate regulation are necessary.
New information and remaining uncertainties	Important new evidence (cited above) confirmed many of the findings from the prior Agriculture assessment (Synthesis and Assessment Product 4.3, The Effects of Climate Change on Agriculture, Land Resources, Water Resources, and Biodiversity in the United States): http://library.globalchange.gov/products/assessments/2004-2009-synthesis-and-assessment-products (Backlund et al. 2009). There is insufficient understanding of the interactions of rising carbon dioxide, changing temperatures and more variable precipitation patterns on crop production (Hatfield et al. 2011). 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 on how prolonged exposure of livestock to high or cold temperatures affect metabolism and reproductive variables (Craine et al. 2010). For grazing animals, there is a critical interaction with feed availability and quality on rangeland and pastureland that is determined by climate conditions during the growing season (Izaurralde et al. 2011). The information base can be enhanced by evaluating crop growth and livestock production models to enhance the understanding of the interactions of climate variables and the biological system. Better understanding of projected changes in precipitation will narrow uncertainty in future yield reductions (Hatfield et al. 2011; Izaurralde et al. 2011).
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

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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" (Walthall et al. 2012). 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 effect 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 (Ziska 2001). 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 (Hatfield et al. 2011; Walthall et al. 2012).
New information and remaining uncertainties	Important new evidence (cited above) confirmed many of the findings from the prior Agriculture assessment (Backlund et al. 2009; Janetos et al. 2008) 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. A key issue is the extent of the interaction between components of the natural biological system (e.g., pests) and the economic biological system (e.g., 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 (Walthall et al. 2012). 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 (Walthall et al. 2012).
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

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Key Message Process: See Key Message #1.

Key message #3/6	**Current loss and degradation of critical agricultural soil and water assets by increasing extremes in precipitation will continue to challenge both rain-fed 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” (Walthall et al. 2012). 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 (Pan et al. 2010). Unprotected soil surfaces will have increased erosion and require more intense conservation practices (Delgado et al. 2011; Wischmeier and Smith 1978). Shifts in seasonality and type of precipitation will affect both timing and impact of water availability for both rain-fed 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 (IPCC 2007).
New information and remaining uncertainties	Important new evidence (cited above) confirmed many of the findings from the prior Agriculture assessment (Synthesis and Assessment Product 4.3, The Effects of Climate Change on Agriculture, Land Resources, Water Resources, and Biodiversity in the United States): http://library.globalchange.gov/products/assessments/2004-2009-synthesis-and-assessment-products (Backlund et al. 2009). Improved models and observational data related to how current loss and degradation of critical agricultural soil and water assets by increasing extremes in precipitation will continue to challenge both rain-fed and irrigated agriculture. Precipitation shifts are the most difficult to project, and uncertainty in regional projections increases with time into the future (Alexander et al. 2006). To improve these projections will require enhanced understanding of shifts in timing, intensity, and magnitude of precipitation events. “The projected changes in the northern U.S. are a direct consequence of a warmer atmosphere. Warmer air can be moister than colder air, leading to more frequent and severe winter and spring storms. The projected reduction in Southwest precipitation is an indirect result of changes in atmospheric circulation caused by the global changes in climate. Recent improvements in the understanding of these mechanisms of change increase confidence in these projections” (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 on soil water availability and soil erosion are 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

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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" (Walthall et al. 2012). 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 evidence that the occurrence of extreme events is increasing and exposure of plants or animals to temperatures and soil water conditions (drought, water-logged, flood) outside of the biological range for the given species will cause stress and reduce production. Direct effects of extreme events will be dependent 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 from the prior Agriculture assessment (Synthesis and Assessment Product 4.3, "The Effects of Climate Change on Agriculture, Land Resources, Water Resources, and Biodiversity in the United States"): http://library.globalchange.gov/products/assessments/2004-2009-synthesis-and-assessment-products (Backlund et al. 2009). One key area of uncertainty is the timing of the extreme events during the phenological stage of the plant or the growth cycle of the animal. For example, plants are more sensitive to extreme high temperatures during the pollination stage compared to vegetative growth stages (Hatfield et al. 2011). A similar response for animals is exposure to high temperatures during the conception phase (Mader 2003). Milk and egg production are also vulnerable to temperature extremes. Extreme combinations of weather variables must be considered, such as elevated humidity in concert with high temperatures (Mader 2003). Other key uncertainties include adequate precision in simulations of: the timing of extreme events relative to short time periods of crop vulnerability and the temperatures close to key thresholds such as freezing (Wolfe et al. 2008). The uncertainty is amplified by the rarity of extreme events. However, a shift of the distribution of temperatures can increase the frequency of threshold exceedance (Walthall et al. 2012). The information base can be enhanced by improving the forecast of extreme events, since the effect of extreme events on plants or animals is known (Adams et al. 1987; Alexander et al. 2006).
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

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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 future climate change.**
Description of evidence base	There is emerging evidence about the economic impacts of climate change on agriculture and the potential for adaptive strategies (Antle et al. 2004). 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, for the case of crop production (Antle et al. 2004). 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 (Malcolm et al. 2012). 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 (Walthall et al. 2012). 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.
New information and remaining uncertainties	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) and also improved understanding of adaptation opportunities, economic resilience, and constraints to adaptation at the producer level (Antle et al. 2004; Malcolm et al. 2012). The economic value of ecological services such as pollinator services is particularly difficult to quantify and incorporate into economic impact efforts (Walthall et al. 2012).
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 presents a limitation to a complete understanding but does provide a comprehensive framework for the assessment of agricultural responses to climate change, providing **medium** confidence.

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

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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, not only through changes in crop yields, but also changes in the ways climate affects food processing, storage, transportation, and retailing.**
Description of evidence base	Ongoing investigations conducted by the Food and Agriculture Organization (FAO 2008, 2011) as well as the U.S. Department of Agriculture (ERS 2012) and the National Research Council (2007) have documented the relationships between agricultural productivity, climate change, and food security. There are many factors that affect food security, and agricultural yields are only one of them. However, there is abundant evidence that changes in yield have impacts on prices and access to commodities both within the U.S. and across the globe (Liverman and Ingram 2010).
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 (Misselhorn et al. 2012). This and other approaches to understanding and responding to the complexities of the global food system need additional research.
Assessment of confidence based on evidence	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

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