Climate Change and Agriculture

In the United States

An Assessment of Effects and Potential for Adaptation

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Executive Summary

About this report: This technical synthesis report describes the main findings and conclusions of an ongoing assessment of climate change effects on U.S. agriculture. This assessment effort is led by the U.S. Department of Agriculture (USDA) and conducted as part of the U.S. Global Change Research Program (USGCRP). It also includes participation by scientists at a variety of U.S. universities and research centers. The project will result in two documents: this Synthesis report and a longer, more comprehensive USDA technical report. It is expected that both documents will help provide the technical foundation for the next U.S. National Assessment of Climate Change. This document builds on the 2008 report, *The Effects of Climate Change on Agriculture, Land Resources, Water Resources, and Biodiversity in the United States* (CCSP 2008), but is different in several important ways. First, it focuses on agriculture alone and takes advantage of a wide range of new findings published since 2008. It includes assessment of new analyses of indirect climate impacts on agriculture – how changes in temperature and precipitation affect pests, weeds, and disease – and how those changes play out in agricultural systems. Second, it covers adaptation issues. Agricultural producers and related land management professionals respond to changing conditions almost every day. Those responses, be they environmental or economic, are termed “adaptations” and play an important role in how climate change will influence agricultural landscapes and management needs. An assessment of how climate change will affect agriculture is thus incomplete if it does not include consideration of adaptation. The final major addition to the scope of this report is the inclusion of the economics of changes in climate – how climate influences the economics of

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agricultural production, how economically-driven choices influence management decisions, and how those decisions, in turn, influence climate's effects on the landscape.

Main Messages: A growing body of evidence shows that U.S climate has changed substantially since 1900, that this change is accelerating, and that even larger change is very likely to occur over the next 100 years. The United States is projected to warm by 1-2°C in the next 40 years, and as much as 3-6°C by the 2080s, depending on the amount of greenhouse gases emitted during this period. Shifts in the distribution, timing, and intensity of precipitation are very likely to accompany this change in temperatures. These changes will affect U.S. agriculture. The agricultural sector has a strong record of innovation and adaptability, but the magnitude of climate changes projected for the next century far exceed the variations that have been managed in the past. The projected climate changes may themselves limit adaptive capacity, particularly with regard to water availability. The overall effects of climate change on the agricultural system will depend on the balance of regional effects and the effectiveness of adaptation actions.

This synthesis was assembled by Peter Backlund (NCAR), Jerry Hatfield (USDA-ARS), Laura Lengnick (Warren Wilson College), Elizabeth Marshall (USDA-ARS), Margaret Walsh (USDA-OCE), and Charles Walthall (USDA-ARS). We appreciate the efforts by a large number of contributors from the agricultural community for their help in compiling the background information for this summary.

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1. Introduction

Agriculture in the United States is a dynamic, self-adjusting system that responds to changes or fluctuations in trade, policy, markets, technology, and climate. Since 1900, farms have grown larger, more mechanized, less labor intensive, and more specialized. Across the United States, the total amount of land in agriculture has remained fairly constant and the number of farms has decreased, while production and productivity have increased dramatically. Agricultural exports are slightly less than $140 billion, while imports of agricultural products are less than $90 billion, demonstrating that agriculture is a net positive to the United States balance of trade, with large international implications as a global supplier of agricultural products to countries. Across the United States more than 200 different agricultural goods are produced livestock products accounting for slightly more than half of the economic value of the agricultural sector. All of these different grains, fruits, vegetables, fibers, and livestock systems exhibit sensitivity to climate variability and change.

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Agricultural systems are primarily defined by prevailing climatic and soil conditions. As such, changes in key climate variables (e.g., seasonal mean temperatures or precipitation patterns) can result in shifts, perhaps significant shifts, in the mix of commodities produced and the systems and technologies that farmers employ to produce them. Agriculture is also a major economic sector that includes more than two million farms, which cover about 900 million acres and generate gross annual farm income of $300-$350 billion. Agriculture and its related industries have a long history of innovating and adapting to changing economic, environmental, regulatory, and climate conditions, and has become much more productive over time. For example, in 1910 U.S. farmers cultivated 330 million acres and supplied food and fiber to population of 92.2 million. In 2006, U.S. farmers supplied food and fiber to 297.5 million people, on the same cultivated land area.

A growing body of evidence shows that U.S climate has changed substantially since 1900, that this change is accelerating, and that even larger change is very likely to occur over the next 100 years. A wide variety of human activities, including burning of fossil fuels, land use, and land cover change, industrial processes, and agricultural practices, are resulting in increasing emissions of greenhouse gases. This is increasing the atmospheric concentration of such gases, which in turn increases the capacity of the atmosphere to retain heat, leading to higher surface temperatures and altered patterns of precipitation worldwide. The Earth's average surface temperature has warmed by about 0.74°C since 1900 and is projected to warm another 1.9 to 5°C over the next century, depending on the amount of greenhouse gases emitted during this period.

The changing climate will impact all aspects of the agricultural system, including the water and soil resources needed to support agricultural operations, the plants and animals that are grown, the pests and diseases that affect plants and animals, the means of transportation to reach consumers, and the markets that determine the prices and distribution of agricultural products.

2. Past and Future U.S. Climate

2.1 U.S. Climate Over the Last 100 Years

U.S agriculture developed during a time of fairly stable climate and is well adapted to prevailing regional climate conditions. A large country with complex topography, the United States has a considerable variety of regional climates. Alaska and Florida both experience high annual precipitation; however their average temperatures are very different. The Southwest and the upper Midwest both experience warm summers, but the Southwest is much drier. U.S. regional climates have been very different in the distant past due to large-scale natural climate fluctuations, but they have been relatively stable during the last 1,000 years as Europeans explored and migrated to North America, and the United States was founded and developed into a modern nation. However, there have been significant inter-annual variations within U.S. regions during this period. For instance the El Niño-Southern Oscillation and other large-scale patterns of natural variability have produced extended droughts and shifts in the timing and distribution of precipitation in some areas, which have been relatively short-lived (seasonal to decadal) anomalies followed by returns to more typical regional conditions.

Multiple analyses of long-term records make it now increasingly clear that the relative stability of U.S. climate conditions is ending. The observational record for the last century clearly shows long-term changes in temperature and precipitation superimposed on the natural year-to-year fluctuations of climate (NOAA NCDC 2012 and NASA GISS 2012). This trend over the past century is consistent with observations of long-term climate change in many other

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areas around the globe. This global-scale change of climate, which is almost certainly the consequence of human-induced changes in the Earth's atmosphere, is discussed in the next section of this chapter. Here, the focus is on describing changes observed over the last century within the United States. In most regions of our country, annual mean temperatures have increased significantly, though in the South and the Southeast the century-long linear trend shows regional cooling (Figure 1, top panel). Alaska has experienced the largest changes, but other northern and western regions have also warmed significantly. During the most recent decades, the cooling of the Southeast has slowed, particularly in the cold season, while northern and western warming has increased. New warm temperature records are becoming more common than record cold throughout the year, and winter snow cover has receded more quickly in spring.

Precipitation has also changed across the continent but exhibits significant fine-scale spatial variability. Much of the northwest, central and southern United States now receive more precipitation than 100 years ago, while other areas, such as parts of the Eastern Seaboard and the Rocky Mountains, and much of the Southwest, receive less (Figure 15, lower panel). These century-long trends are not continuous through time. Natural variability has led to substantial decadal fluctuations with distinct droughts (e.g., the 1930s Dust Bowl and subsequent droughts in western regions) and wet intervals.

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20^{th} Century U.S. Climate

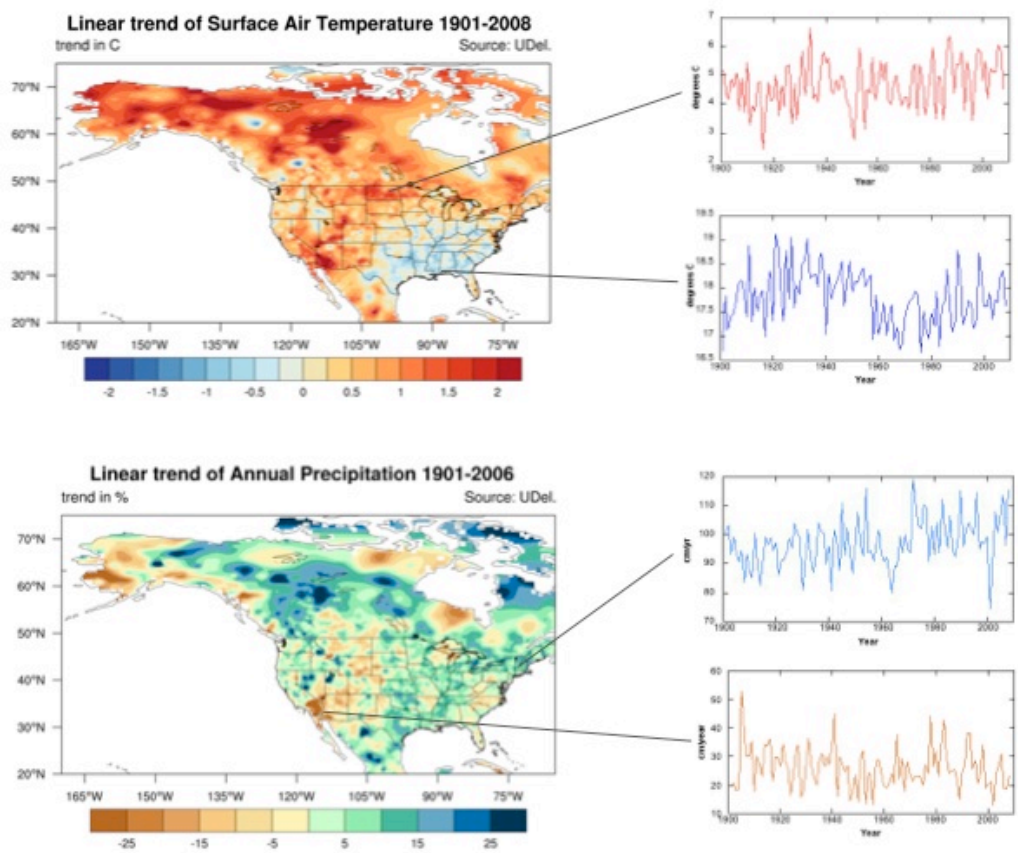

Figure 1. Linear 20^{th} Century (1901-2006) temperature and precipitation trends for North America. These data, which show the regional pattern of observed changes, are based on stations with complete, consistent, and high quality records of temperature and precipitation. Within the contiguous U.S., the density of stations allows for fine resolution. In sparser regions (e.g., Polar Regions), interpolation was applied to achieve the 0.5 degree (about 50 km) resolution. The right hand pullouts provide insight into detailed records for selected regions and show the variability within larger regional averages. Data courtesy of University of Delaware, Matsuura and Willmott, 2009, Version 2.01, based on augmented Global Historical Climatology Network, Version 2 (http://climate.geog.udel.edu/~climate/html_pages/download.html).

Precipitation intensity has also increased in most areas, even if some regions get less water overall. In many regions these trends are consistent with expected spatial structures of change in temperature and moisture availability. The fact that increases in total precipitation and precipitation intensity have been observed in much of the United States does not necessarily mean that more moisture is available for agriculture and other biological and ecological processes, however. Higher temperatures increase evapotranspiration losses to the atmosphere, and the relative balance of the two factors on average in the United States leads to less moisture in soils and reduced amounts of surface water.

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2.2 Global Climate Change

There is a broad scientific agreement that human activities are changing the Earth's climate.

Definitive observations show that burning of fossil fuels, deforestation, agricultural practices, and a variety of industrial processes are rapidly increasing the atmospheric concentrations of CO2 and other greenhouse gases (IPCC 2007c, pg. 10). These changes in atmospheric composition are increasing temperatures, altering the timing and

Greenhouse Gases

Gases that trap heat in the atmosphere are called greenhouse gases (GHGs). Some GHGs, such as carbon dioxide, may be emitted to or drawn from the atmosphere through natural processes or human activities. Other GHGs, such as certain fluorinated gaseous compounds, are created and emitted solely through human activities.

The principal GHGs that enter the atmosphere because of human activities are carbon dioxide (CO_2), water vapor (H_2O), methane (CH_4), nitrous oxide (N_2O), and fluorinated gases, such as hydrofluorocarbons, perfluorocarbons, and sulfur hexafluoride. (EPA 2011).

epa.gov/climatechange/emissions/index.html distribution of precipitation, and affecting terrestrial and marine ecosystems (IPCC AR4 WGI and WGII SPM's). Since the AR4's release, a series of new studies in the peer-reviewed scientific literature (see, e.g., The Copenhagen Diagnosis, Allison et al. 2009) and assessments by the U.S. Global Change Research Program, the U.S. National Research Council, and other scientific bodies have continued to refine our understanding and strengthen the evidence of ongoing changes in the Earth climate system. Among the noted changes:

- The global-average surface temperature increased by about 0.74°C (0.56-0.92°C) over the 20th century (IPCC 2007c, pg. 10).
- Long-term temperature records from ice sheets, glaciers, lake sediments, corals, tree rings, and historical documents demonstrate that every decade during the late 20th century was warmer than the previous (NOAA NDC, NASA GISS and UK CRU long-term temperature records).
- The most recent 50 years was likely the warmest such period worldwide in at least the last 1,300 years (IPCC 2007c, pg. 9), and 10 of the 11 warmest years on record have occurred since 2001 (NOAA NCDC, NASA GISS).
- Observations since 1961 show that the average temperature of the global ocean has increased to depths of at least 3,000 meters. This deep storage of heat is causing the ocean surface to warm more slowly than the land surface (IPCC 2007c, pg. 5).
- Global sea level increased by about 12-22 cm during the 20th century. Satellite records confirm that the rate of sea level rise has now almost doubled to about 3.4mm per year (IPCC 2007c, pp. 5 and 7; Allison et al. 2009).

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- Precipitation is highly variable and trends are more difficult to isolate. Overall precipitation and heavy precipitation events have increased in most regions, while at the same time the occurrence of drought has also been on the rise, notably since 1970 (IPCC 2007c, pg. 8; Allison et al. 2009).

- Mountain glaciers and ice caps, as well as snow cover, are receding in most areas of the world. Both the Greenland and Antarctic ice sheets are now losing mass at increasing rates. The extent and thickness (volume) of Arctic sea ice is declining, and lakes and rivers freeze later in the fall and melt earlier during the spring (IPCC 2007c; Allison et al. 2009).
- The growing season in the Northern Hemisphere has lengthened by about four to 16 days since 1970 (one to four days per decade) (EPA Climate Change Indicators 2010).
- Winter temperatures have increased more rapidly than summer temperatures, and nighttime minimum temperatures have warmed more than daytime maxima. Across the United States (and elsewhere), the observed number of record high temperatures is roughly three times higher than the number of record cold events (IPCC 2007c, pg. 8; Meehl et al. 2009).

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2.3 Projections of Future Global Climate

Human influences will continue to alter Earth's climate throughout the 21st century. Our current scientific understanding, supported by a large body of observational and modeling results (see IPCC AR4), indicates that continued changes in atmospheric composition will result in further increases in global average temperature, rising sea level, and continued declines of snow cover, land ice, and sea ice extent. The IPCC AR4 contains projections of the temperature increases that would result from many different emissions scenarios (IPCC SRES, Nakicenovic and et al. 2000). For this report, two alternatives are considered:

- A **low emissions scenario** for the 21^{st} century (IPCC SRES B1) could be achieved by continued improvements in technology, low or no growth in population, and effective action by individuals, corporations and governments to limit emissions. In such a scenario, atmospheric concentration of CO_2 would increase to about 550 parts per million (ppm), which would increase global average surface temperature by about 1.1-2.9°C in 2100.
- A **high emissions scenario** for the 21^{st} century (IPCC SRES A2) would result from a slowing of technological improvements, significant population growth, and less effective actions taken by individuals, corporations, and governments to limit emissions. For this scenario, atmospheric concentration of CO_2 would increase to about 800 ppm, which would increase global average surface temperature by about 2.0-5.4°C by 2100.

It is important to note that the average global surface temperature for each of the above scenarios would vary by region (see Figure 2). Polar areas will warm more than lower latitudes, land more than oceans, and continental interiors more than coastal areas.

Climate change in the 21st century will be largely driven by overall emissions of greenhouse gases and aerosols as well as the strength of feedbacks in the climate system. The lower the

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emissions during the next 100 years, the smaller the climate change experienced over this time and beyond. But it is important to note that the climate differences between high and low emissions scenarios will mainly occur in the latter half of the 21st century. This is largely because temperature and precipitation changes lag behind emission and concentration changes, due to the inertia of the climate system. The climate changes being experienced today are mainly the consequence of past emissions, and today's emissions will continue to cause climate change into the future. Even if atmospheric concentrations of greenhouse gases are stabilized, land surface temperatures will continue to rise for decades, and ocean surface temperatures and sea level will continue to rise for centuries (IPCC 2007c, pg. 5; Solomon et al. 2009).

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Climate Models and Climate Research

Scientists rely on computer models to better understand Earth's climate system because they cannot conduct large-scale experiments on the atmosphere itself. Climate studies rely largely on general circulation models, which use mathematical representations of physical, chemical, and biological processes that drive the Earth's climate. Climate models, like weather models, rely on a three-dimensional mesh that reaches high into the atmosphere and into the oceans. At regularly spaced intervals, or grid points, the models use laws of physics to compute atmospheric and environmental variables, simulating the exchanges among gases, particles, and energy across the atmosphere. To investigate possible future changes in climate, different scenarios of future greenhouse gas emissions are used as inputs for the model calculations that produce simulations of climate for the next century and beyond. Because most climate model experiments cover far longer periods than weather predictions, the focus is on large regional to global scales rather than local scales. This approach enables researchers to simulate global climate over years, decades, and millennia. Most current generation global models use grid points that are about 100-200 km apart. Scientists use global model results to drive finer scale models with grid spacing ranging from 2-50 km (similar to weather prediction models) for "small regional" and local-scale studies. There are also a number of statistical methods that downscale the global models based on available high-resolution observations to estimate finer scale change. A small number of climate modeling centers are experimenting with very high resolution global simulations, however such experiments require very large and expensive amounts of supercomputing time and produce very large data sets that are challenging to analyze.

There are about a dozen climate models worldwide that can be used to simulate the many components of Earth's climate system, including the oceans, atmosphere, sea ice, and land cover, along with a larger number of more simple global models that are used for less comprehensive simulation (e.g., oceans and atmosphere only). To verify the accuracy of these models, scientists typically simulate past conditions and then compare the model results to actual observations. Different modeling groups also perform common "control" experiments and compare the results across models to diagnose and evaluate model performance. This effort, known as the Coupled Model Intercomparison Project (CMIP, see http://www-pcmdi.llnl.gov/projects/cmip/), has been underway since 1995 and helps assure that high-quality, well-documented estimates of future climate change are available for use in research and scientific assessments, including those of the Intergovernmental Panel on Climate Change. CMIP-3 was completed in 2007 and was used in the IPCC 4th Assessment report. CMIP-3 results are also used for the vast majority of the analyses in this document. CMIP-4 focused on carbon cycle modeling. CMIP-5, which is currently underway and nearly complete, is producing a set of results that will soon be available for use by climate researchers and other interested users.

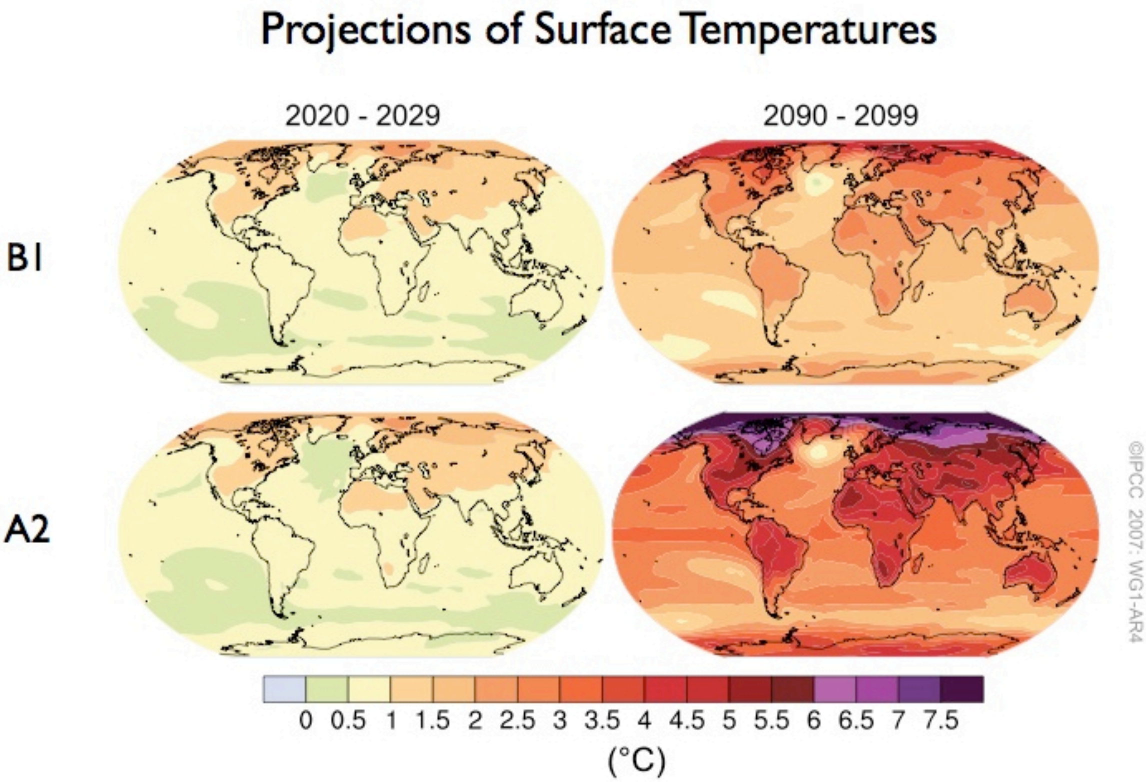

Figure 2. Projected global temperature changes for the 2020s (left side) and 2090s (right side) compared to 1980-1999 for a low emission (B1) and high emission (A2) scenario. The differences between scenarios get wider as time progresses. (IPCC 2007).

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2.4 Projections of U.S. Climate Change

It is very likely that U.S climate conditions will continue to change throughout the 21st century. For the purposes of this document, we have chosen to show projections for low and high emissions scenarios for the 2040s and the 2080s to illustrate how different choices about greenhouse gas emissions could affect future climate conditions for the United States. Just as in the global-scale analysis, the differences between high and low scenarios of future greenhouse gas emissions are much more noticeable near the end of the century than they are for coming decades. The results shown here (Figures 3-7), are based on multi-model ensemble averages of U.S. climate change, produced during the IPCC AR4, which have been downscaled to 12-km horizontal resolution in order to provide as much detail as possible about regional changes (Maurer 2007; Source: http://gdo-dcp.ucllnl.org/downscaled_cmip3_projections).

The entire United States is likely to warm substantially over the next 40 years, with an increase of one to two degrees over much of the country (Figure 3). This is a substantially greater rate of change than that observed over the last century, reflecting the accelerated rate of increase in greenhouse gas concentrations and temperatures observed during the last few decades. Both are now growing much more rapidly than they were during most of the 20th century.

Much of the interior U.S. is likely to see increases of two to three degrees, while the southeastern and western coastal areas experience about one to two degrees of warming. The cooling in the Southeast during the 20th century is projected to become warming in the 21st century.

Looking ahead to 2100, a low emissions scenario is likely to produce summertime warming of three to four degrees in much of the Interior West, with warming of two to three degrees almost everywhere else. A high emissions scenario is likely to result in warming of five to six degrees in much of the Interior West and Midwest, with warming of three to five degrees in the Southeast and far western regions, and significant increases in hot nights (see Figure 7).

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These temperature changes will lead to a further shift in the length of the growing season reaching the scale of a month or two, and the occurrence of frost days will also change significantly, particularly in the West (Figure 4).

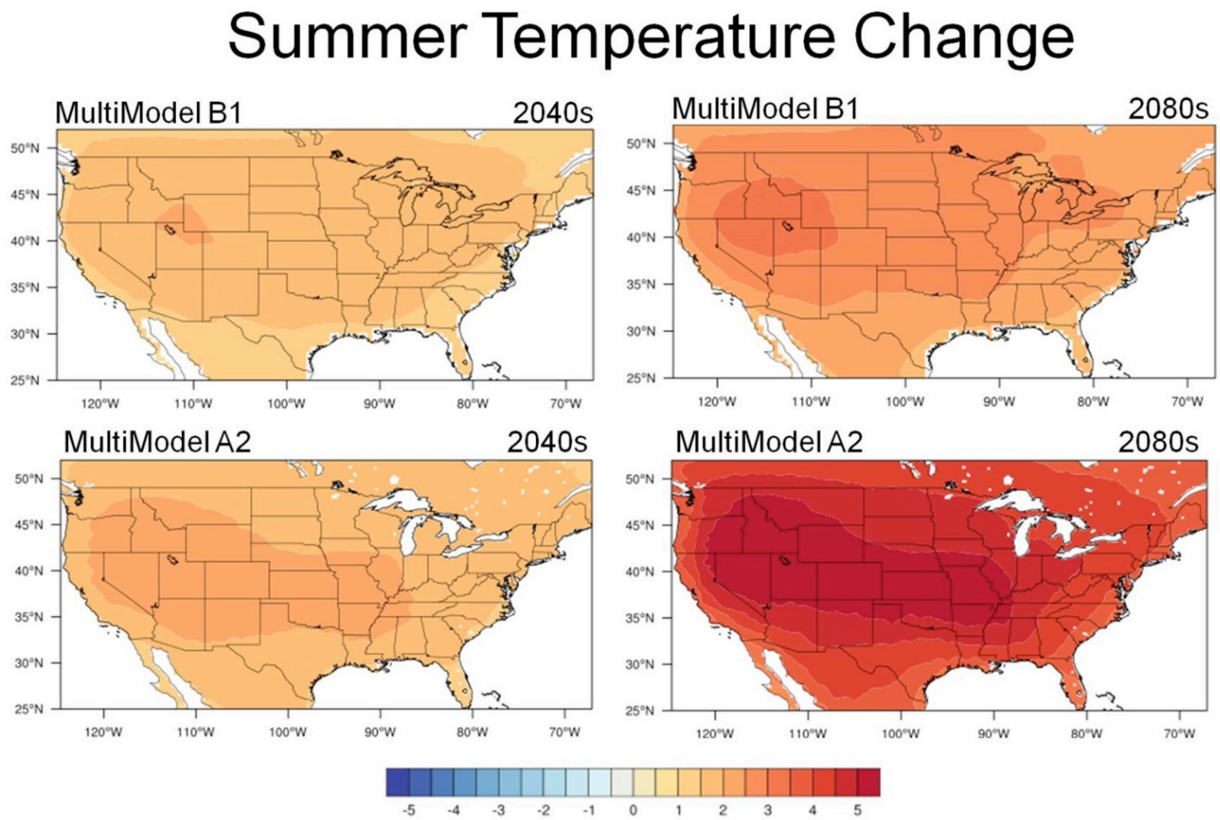

Figure 3. US summer surface temperature projections from a 16-model ensemble for a low emissions scenario (top panels) and a high emissions scenario (bottom panels). The near-term differences between scenarios (left panels showing the 2040s) are much smaller than the long-term differences (right panels showing the 2080s).

Growing Season and Frost Day Change

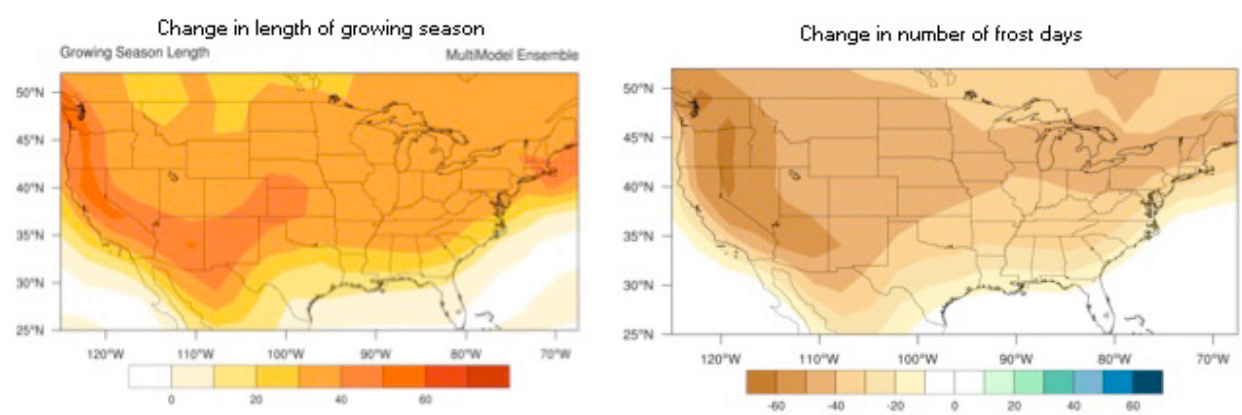

Figure 4. In a high emissions scenario, the U.S. growing season will lengthen by as much as 20-40 days by the end of the century (left panel). The number of frost days (days with minimum temperatures below freezing) will be reduced by 20-60 days in much of the United States. Both panels are produced from multi-model ensemble projections based on simulation results from CMIP-3.

Projected changes in precipitation are more uncertain because they are sensitive to both local conditions as well as shifts of the large-scale circulation. These uncertainties are probably larger in summer than in winter. Figure 5 shows projections of change in summer precipitation. Over the next 30-40 years, models agree that the Northwest is likely to become noticeably drier, with reductions of 15-25% in summertime precipitation. Much of the central South will likely sees decreases of about five percent, while some northern central and eastern U.S. regions are projected to experience increases of 5-15%.

Interestingly, the simulations for the low emissions scenario indicate that summer precipitation, after a clear change over the first part of the 21st century, might remain relatively stable during the second half. For the higher emissions scenario, where emissions continue to increase, the emerging summer precipitation pattern shows a substantially dryer Northwest and South, while a wet North and Northeast is likely to strengthen even further.

The seasonality of precipitation is also an important factor for agriculture, particularly in western regions that rely on winter accumulation of snow and gradual release of water stored in snowpack throughout the spring and summer. Figure 6 shows projected changes in U.S. winter precipitation.

Most regions of the northern and central U.S. are projected to see an increase of five to 15% in winter precipitation over the next 30-40 years; areas along the southern border will likely see decreases of five to 10%, with southern Texas possibly experiencing decreases of up to 15-20%. By 2100, again, the low-emission scenario produces little further change (possibly with increased drying in the SW and southern West Coast), while for the high emissions scenario the models produce substantially larger enhancement of the near-term trends with reduction in Texas and Florida of up to 20-25% and precipitation increases in the North of 20% or more.

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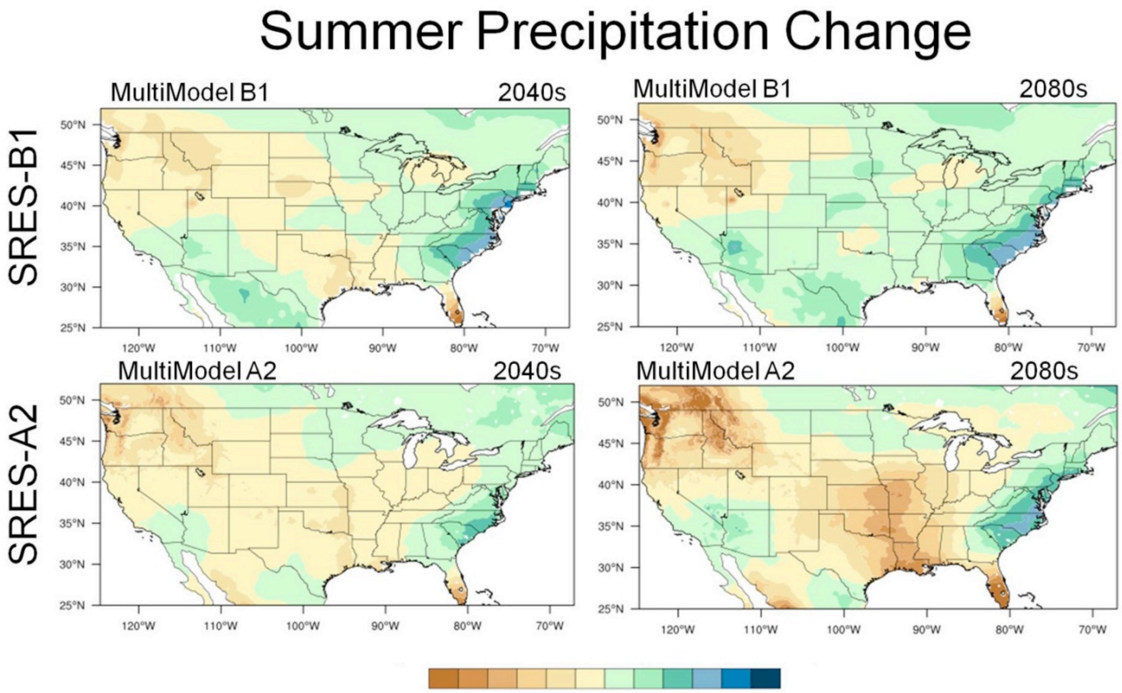

Figure 5. Summer precipitation projections for a low emissions scenario (upper panels) and a high emissions scenario (lower panels). Left panels show the changes for 2040s (averaged over 2025-2055), right panels are for 2080s (average of 2071-2100). Projections based on a 16-model ensemble of 21^{st} century climate change, statistically downscaled to 12 km resolution.

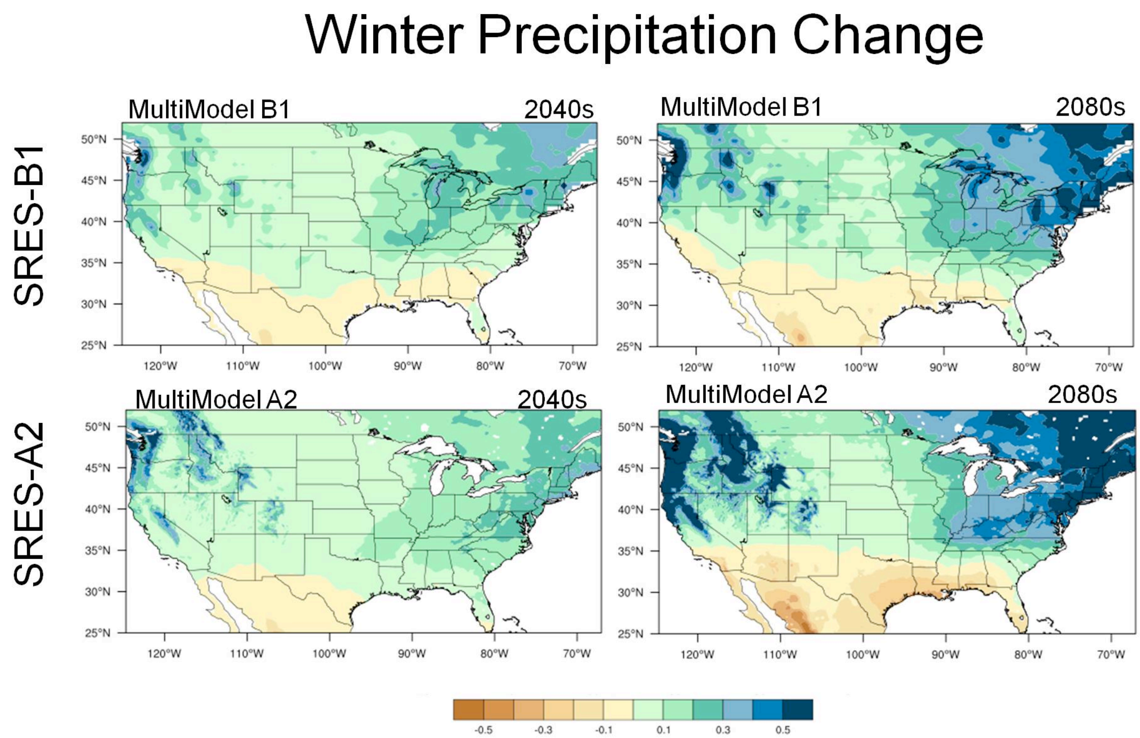

Figure 6. Winter precipitation projections for a low emissions scenario (upper panels) and a high emissions scenario (lower panels). Left panels show the changes for 2040s (averaged over 2025-2055), right panels are for 2080s (average of 2071-2100). Projections based on a 16-model ensemble of 21st century climate change, statistically downscaled to 12 km resolution.

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Although precipitation increases are anticipated for large areas of the United States in both the low and high scenarios, it is important to note this does not necessarily translate into more available moisture for agriculture at the time when the water is needed. Higher temperatures lead to both earlier melt and runoff of water stored in snow cover and to increase evapotranspiration losses to the atmosphere. More precipitation is projected to fall in shorter, more intense storms, leading to rapid runoff. These factors may offset the projected increase in mean precipitation amounts in the United States and thus lead to less available moisture in soils and less surface water for organisms or ecosystems.

2.5 Extreme Conditions

Average temperature and precipitation are not the only factors that affect agricultural systems. Extreme climate conditions, such as dry spells, sustained droughts, and heat waves can have large effects on crops and livestock. Changes in the incidence of these extreme events could thus have major effects on agricultural productivity and profitability. Although models are limited in their ability to accurately project the occurrence and timing of individual extreme events, observations indicate an emerging signal that is consistent with projections of an increase in areas experiencing droughts and periods of more intense precipitation (Alexander et al. 2006; IPCC 2007c; Zhang et al. 2007). Figure 21 shows how the number of very hot nights and the duration of very low (agriculturally insignificant) rainfall events are projected to change by the end of the 21st century under a high emissions scenario.

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Change in Dry Periods and Hot Nights

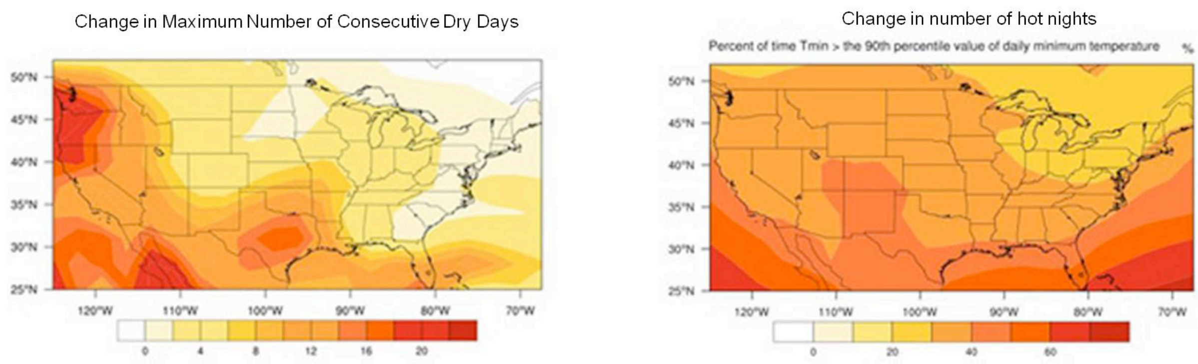

Figure 7. The left panel shows changes in dry periods. Under the high emissions scenario, by the end of the 21st century the longest continuous periods of less than 2 mm of rain per day are projected to lengthen by an additional 12 days compared to current conditions in large areas of the West. In some parts of the Northwest and south-central Texas, this increase could be as much as 2-3 weeks, mostly concentrated in the summer season. Some North Central, as well as the East and Southeast regions, are expected to experience little change. **The right panel shows i**ncreases in hot nights across the United States projected for the high emissions scenario by the end of the 21st century. By 2100 many parts of the United States could experience 30-40 additional hot nights, defined as nights with a minimum temperature warmer than 90% of the minimums between 1971 and 1990 (Source: CMIP-3).

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2.6 Summary and Conclusions

There is clear observational and modeling evidence, supported by current scientific understanding of the climate system, that human-induced climate change is underway. The United States, along with much of the rest of the world, has become warmer during the 20th century. Precipitation patterns have changed, with some areas receiving more rain and snow, while other regions receive less as atmospheric concentrations of greenhouse gases continue to rise. These trends are likely to continue during the next century.

Model simulations clearly indicate that if emissions of greenhouse gases are not reduced, then continuous, rapid warming is expected throughout the 21st century, along with higher incidence of heavy precipitation events and droughts. If emissions are reduced, the climate changes in the second half of the 21st century will be smaller. In both cases, the long-term climate change trend will remain superimposed on large natural variations, particularly at regional scales, which sometimes enhance and sometimes dampen the effects of greenhouse gases.

U.S. agriculture is a complicated system that includes important biophysical, economic, and cultural components. Climate change clearly poses risks to many aspects of this system. Increased levels of CO2 can stimulate plant growth, but increased levels of ozone and high temperature can inhibit productivity of plants and animals. Increased nighttime and winter

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temperatures are particularly problematic for some crops. A surplus or deficit of precipitation can cause serious direct problems for many crops and can also affect the water management and storage activities that are a critical component of the overall agricultural system. But even climate change beyond the United States can influence American agriculture as major changes in the productivity of agriculture in other nations can have large consequences for U.S. commodity prices and demand for U.S. crops.

Actions that reduce the amount of climate change experienced during the 21st century are very likely to have benefits for agriculture.

Adaptive actions also appear to hold significant potential for reducing the vulnerability of many parts of the agricultural system, but overall adaptive capacity is not yet well understood and may itself be affected by climate change, especially with regard to water management and availability.

The overall impact of climate change on the agricultural system will depend on the balance and effectiveness of emissions reduction and adaptation actions.

3. Climate Change Effects on Agriculture

3.1 General Considerations

Soil is often overlooked relative to climate change. Soil's fragile nature increases its vulnerability to changes in the climate. Increases in precipitation intensity will increase soil erosion and increase the rate of soil degradation, leading toward decreased plant productivity, unless there are adequate conservation practices in place to protect against these precipitation events. There is an increased risk of soil erosion because of increases in precipitation intensity and the shift toward more precipitation in the spring when the soil lacks cover of actively growing vegetation in many areas of the United States. Erosion decreases soil productivity, increases losses of soil organic carbon and other essential nutrients, and reduces soil fertility (Quine and Zhang 2002; Cruse and Herndl 2009).

Factors affecting soil erosion may be grouped into 1) erosivity of rainfall, irrigation, snowmelt, and wind, 2) plants, cropping and management, 3) soil erodibility; 4) conservation practices; and 4) topography. Factors affecting soil erosion may be grouped into 1) erosivity of rainfall, irrigation, snowmelt, and wind, 2) plants, cropping and management, 3) soil erodibility; 4) conservation practices; and 4) topography. Those factors most likely to be directly impacted by climate change include: 1) erosivity of rainfall, snowmelt, and wind, 2) plants, cropping, and management, and 3) soil erodibility; strategies for soil resource adaptation to climate change impacts generally are related to 4) conservation practices. Soil quality is related to the soil

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organic matter content and the level of soil biological activity. Soil quality is degraded when soil erosion causes a reduction in depth and when organic matter declines, causing deterioration of soil structure and loss of fertility. Input of roots into the soil through crop production is one method of introducing organic material into the soil profile and maintenance of crop residues protect the soil from erosion by reducing the raindrop energy from directly impacting the soil surface. Addition of crop residues provides the organic material necessary for soil formation by soil organic matter production.

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Climate change may increase or decrease crop production depending on the climate, crop species, and soil. Changes in the rate of soil organic matter production will be affected by direct climate effects through, for example, soil temperature, soil water availability, and the amount of organic matter input from plants; this latter is also dependent upon temperature and soil moisture availability. Protecting soil from the impacts of climate change-driven soil erosion will be necessary to preserve and enhance U.S. soil resources.

Water is one of the most critical factors to plant production and without adequate water during the growing season (drought) there is a decline in production. This applies to grain, forage, fruit, fiber, and vegetable production. Increasing variability in precipitation will alter the potential water availability to the crop and, when coupled increased atmospheric demand for water induced by warming temperatures, there is the likelihood for increased potential for water stress on plant production under climate change. Shifts to more spring precipitation and more intense precipitation events will mean less water availability to crops due to increased runoff and less storage within the soil profile.

A noted change in field practices affected by precipitation is a decrease in workable field days during spring caused by increasing precipitation. Over the past 10 years, workable field days in Iowa during April through May have decreased by three days, which limits the amount of time farmers have to prepare their soil and plant crops in the upper Midwest. Improvements in planting efficiency may enable this challenge to be overcome, but there is risk that delayed

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planting of crops could limit production, thus reducing benefits that might be expected from the observed lengthening of the growing season.

Air temperature is an important factor in planting and other crop decisions, but perhaps more important variables are soil heat status and water content. Soil water content and soil temperature are related; soil water content affects soil heat status as wet soils take longer to warm. As temperature increases, potential evapotranspiration and crop water use will increase, leading to soil water deficits. The relative changes in precipitation throughout the country are projected to vary by location. Some locations will see an increase in rainfall, others a decrease. Because of rising temperatures, it is expected that water requirements for agriculture will increase. This will be exacerbated by rainfall irregularities and increases in drought projected for some areas (notably western and northern Texas, and the southeastern United States). Due to earlier warming and higher winter temperatures snow accumulation has declined and runoff from snow melt is occurring earlier in the U.S. West (Knowles et al. 2006). Increased minimum temperatures have contributed to this effect. It is likely that this early runoff will reduce water available for irrigation later in the growing season.

While many research results are reported for increases in average temperatures, this change is created by a larger increase in minimum temperatures by climate change over large scales (Knowles et al. 2006). Maximum temperature impacts of climate change will be more variable and local in nature. Maximum temperatures are more affected by local conditions especially soil water content and evaporative heat loss when soil water evaporates (Alfaro et al., 2006).

Hence areas where rainfall is expected to increase, or where irrigation is predominant (Alfaro et al. 2006) or expanded are not likely to see increases in maximum temperatures as large as those in areas where drought is more likely. In some years, temperatures may not be as high as the maximum predicted. As minimum temperatures increase, years with low maximum temperatures, however, could be closer to the optimum temperature resulting in higher yields than seen today when temperatures are below the optimum.

3.2 Climate Change Effects on Crops

Plant response to climate change is dictated by a complex set of interactions to CO_2, temperature, solar radiation, and precipitation. Precipitation has indirect impacts impact because plants extract water from the soil profile for growth and also cool the leaves through from evaporation of the water at the leaf surface. One attribute of increasing soil organic matter is the increase in soil water holding capacity, which leads to more storage of precipitation and an increase in the amount of water available to the plant. One method to reduce the risk of drought in areas that rely on precipitation as the source of water for crop production is through improved soil management practices. Maintenance of crop residue reduces direct soil water evaporation from the soil surface, and also increases the amount of water available to growing crops. With the trend of increased precipitation event intensity and events less frequent precipitation events during the summer months, any strategy to increase soil water will reduce potential risks to crop production. Another change caused by the warming temperatures will be the increase in the atmospheric demand for water from the crop. This will increase the rate of water use by the crop and those soils with limited soil water holding capacity, which will increase increased risk of drought and potential crop failure. Improving soil management practices to increase the capacity of the soil to absorb and store precipitation or irrigation water will be critical to offsetting the effects of increased intensity and seasonality shifts of 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 in which they are exposed to temperatures best suited to their threshold values. As temperatures increase over the next century, shifts may occur in crop production areas because temperatures will no longer be in the range for optimal growth and yield of grain or fruit. In the Corn Belt, a rise in temperature of 0.8 °C, without altering the location of cropping, over the next 30 years is estimated to decrease corn yields by 2-3%, assuming no additional negative effects from soil water deficit (Hatfield et al. 2011). Decreases in crop yield of other species are expected due to increasing temperatures over the next 30 years. These effects do not include the potential harmful effects from extreme temperature events at critical phenological stages, e.g., flowering and pollination.

One critical period of exposure to temperatures is the pollination stage when pollen is released to fertilize the plant and trigger development of reproductive organs, for fruit, grain, or fiber (Hatfield et al. 2011). Pollination is one of the most sensitive stages to temperatures and exposure to high temperatures during this period can greatly reduce crop yields. Increases

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in the potential for high temperature extremes could place crops at risk for failure. Increasing temperatures cause plants to grow more quickly and complete their stages of development more quickly. This causes plants to become smaller and produce less growth, which leads

Wine Production and Climate Change

;e change will affect the U.S. wine industry, but the ultimate effects are not yet clear. National ınalysis has shown that United States premium wine grape production area could decline by up 6 by the late 21st century (White et al., 2006). White and colleagues found that increases in heat ıulation will likely shift wine production to warmer climate varieties and/or lower-quality wines ıat while frost constraints will be reduced, increases in the frequency of extreme hot days (>35°C) growing season are projected to completely eliminate wine grape production in many areas of ıited States. Grape and wine production will likely be restricted to a narrow West Coast region ıe Northwest and Northeast – areas where excess moisture is already problematic. However, results show significant regional variation within this broad picture.

ılysis of suitability for viticulture in the western United States (Jones et al., 2007d) examined five suitable regions across cool to hot climates, as well as the varieties that grow best in those ıs. The cooler region (I) includes higher elevation, more coastal, and more northerly areas (e.g., illamette Valley), while the warmest region (V) areas are mostly confined to the Central Valley rther south in California (e.g., the San Joaquin Valley). Based on the historical record, 34% of the rn United States falls into these regions, with 59% being too cold and 7% too hot. Using tions for average growing season temperatures from the Community Climate System Model I) of 1.0-3.0°C for 2049, Jones found that growing degree-days increased 15-30%. The 15% e increased the area suitable for viticulture from 34% to 39%, while the 25% change increased itable area to 43%. There was an overall reduction in the areas that are too cold from 59% to vhile the areas that are too hot increase from 7% to 16%. Four of the five regions increased in vhile one decreased, with an overall shift of regions toward the coast, especially in California, and ɾd in elevation (most notably in the Sierra Nevada Mountains).

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high temperatures will impact yield, although impacts will vary by region and crop because of varying temperature limits and optimal growth temperatures for individual species. Exposure to temperatures in the range of 1 to 4°C above optimal will moderately reduce yield, while and exposure to temperatures more than 5°C above optimal often leads to severe if not total production losses in vegetables. A notable example is the impact of warmer temperatures on apple production because exposure to warm temperatures during fruit development reduces fruit quality. Most crops and trees will exhibit a decline in production under warmer average climate, and in some cases fruit quality will decrease over the next 30 years as temperatures continue to increase. These temperature effects will be greater than the positive impacts offered by increased atmospheric CO_2 concentrations, and will be further complicated and increased if soil water availability is reduced at any of the growth stages.

Changing temperatures will affect specialty crops. The value of perennial specialty crops is derived from not only the tonnage but also the quality of the harvested product, such as the size of a peach, the red blush on an apple, the bouquet of a red wine produced from a particular vineyard. In contrast to annual agronomic crop production, perennial crop production is not as easily moved as the climatic nature of a region declines. Many socio-economic factors contribute to this reality, including: long re-establishment periods, nearness to processing plants, availability of labor, and accessible markets. Climate change complicates the problem of perennial food crop production. Modeling of past and future climate changes in the United States has demonstrated that warming in the historical record and future warming will affect perennial specialty cropping systems. Historically, apple mid-bloom dates in the

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northeastern United States have advanced 0.20 day/year (Wolfe et al. 2005), with a temperature rise of 0.25°C/decade (Hayhoe et al. 2007). According to Stöckle et al. (2010), apple bloom will occur approximately three days earlier by 2020 in eastern Washington state. From 1948-2002 in the main grape growing regions of California, Oregon, and Washington, growing seasons have warmed by 0.9°C (Jones et al. 2005). Under future climate scenarios, grape bloom time in the central valley of California declines 0.08 to 0.169 day/year (Gutierrez et al. 2006). Results of citrus production simulations, without including a CO_2-induced response (Rosenzweig et al. 1996; Tubiello et al. 2002), indicate that production may shift slightly northward in the southern states due to reduced frost frequency.

Increasing CO_2 in the atmosphere has a positive effect on plant growth and also decreases soil water use rates (Kimball 2011). There are differences among species in their response to CO_2 increases. C_3 plants (e.g., soybean, vegetables, wheat) are more responsive to increases in CO_2 than are C_4 plants (e.g., corn, millet) because of physiological differences; these differences also determine how plants respond to changes in climate. The decrease in soil water use is likely to be an advantage in areas with limited precipitation during the growing period because it will allow for greater water use efficiency (amount of plant material produced per unit water transpired), as well as reduce irrigation water requirements. Increases in CO_2 have a positive impact on vegetative growth of plants; Kimball (2011) summarized that overall increases in CO_2 would be expected to have a positive effect on crop yield of 10%. However, positive impacts on grain or fruit yield are not always evident across all species. In both forage and grain crops, exposure to increased CO_2 causes a reduction in grain and forage quality (Morgan et al. 2004).

This affects the nutritional quality of these products. In rangeland species, the implication of this change is that the number of animals that can graze on a given area of land will decrease unless feed supplements are added to offset this lack of protein in the forage. Similar changes have been noted in grain quality with reductions in protein content; this could affect the nutritional quality of grains for both animal and human consumption. Increasing CO_2 concentrations also contribute to more rapid growth of many invasive species (weeds) and increase the risk of crop loss from weed pressures in different production systems.

3.3 Climate Change Effects on Animal Agriculture

Climate impacts on animals are directly related to the ability to maintain a body temperature that is within the optimum range. Optimal environmental conditions for livestock production are comprised of a range of temperatures and other environmental conditions for which the animal does not need to significantly alter behavior or physiological functions to maintain a relatively constant core body temperature. Deviations from this optimum core temperature by 5-7°C can cause disruptions in performance, production, and fertility. An animal with a body temperature outside of these limits will either conserve heat (exposure to cold temperatures) or dissipate heat (exposure to high temperatures) through a variety of mechanisms. Onset of a thermal challenge often results in declines of physical activity and an associated decline in eating and grazing (for ruminants and other herbivores) activity. Hormonal changes, triggered by environmental stress, result in shifts in cardiac output, redistribution of blood flow to extremities, altered metabolic rates, and slowed digesta passage rate. These changes all affect animal performance and limit an animal's ability to produce meat, milk, or eggs.

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Losses from exposure to high temperature stresses are difficult to assess but may reach into billions of dollars each year of lost productivity and mortality. Even animals under confined production spaces may suffer from exposure to high temperatures. One approach to quantifying the climate regime for animals has been the thermal humidity index (THI), which relates temperature and relative humidity into an index related to animal performance. This index has been used to quantify stress on beef and dairy animals and employed as a management guideline for producers to begin to adjust management of animals to avoid stress. Utilization of this index has shown that high producing dairy cows used in current milk production systems have a lower THI value than previous herds.

Warming temperatures and increasing humidity are likely to increase the risk of lower production for beef, dairy and other agricultural animals unless new adaptation measures are successfully implemented. Increases of summer temperatures would create a more negative environment for animal production and in the southern United States these impacts could be large in terms of productivity and even mortality. For cattle that breed during spring and summer, exposure to high temperatures would have a negative impact on conception rates. Protection of animals against exposure to high temperatures and excessive THI values will require modification of shelter and perhaps even necessitate methods of increasing cooling through enhanced evaporation.

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For agricultural animals, climate change will also have indirect effects. Warmer, more humid conditions will promote insect growth and spread of disease. When coupled with reduced performance because of the direct effects of climate, the impacts of disease will be enhanced.

3.4 Climate Change Effects on Rangelands

It is likely that rising CO_2 concentrations over the last 150 years have increased productivity of pastures (Polley et al. 2003; Izaurralde et al. 2011). Based on simulation studies it is expected that the productivity of Great Plains native grasslands will continue to increase over the next 30 years as temperature and CO_2 increase (Parton et al. 2007; Izaurralde et al. 2011). Rangeland species encompass a wide variety of types of plants and include both C_3 and C_4 species. Their responses to increased temperature and CO_2 are similar to those of the major crops, though interactions among species are more important as rangelands consist of mixed species. Elevated CO_2 can increase the proportion of C_3 relative to C_4 species (Owensby et al., 1999). The mixed nature of pasture crops has important implications in terms of the relative response to water and nutrients under elevated temperatures and CO_2. (Owensby et al. 1999). In Texas, average biomass increased with CO_2 concentration and the increase ranged from 120 to 160 g m-2 per 100 ppm increase in CO_2 (Polley et al. 2003). Rangeland species will grow faster with higher temperatures and experience a longer growing season.

Future climatic conditions will likely enhance productivity on most rangelands over the next 30 years (Izaurralde et al. 2011). The magnitude varies by location and plant composition. There is evidence that climate changes over the past century and recently have been impacting pasture productivity and water use efficiency (Polley 1997; Izaurralde et al. 2011). Projected decreases in precipitation and shifts to earlier season rainfall may favor woody shrubs over herbaceous vegetation (Nielson, 1986). As a result, encroachment of woody plants into pastures may reduce the nutritive value for livestock and require more intense management. One management approach that has been suggested to help livestock production adapt to these changes is the adoption of integrated crop-livestock systems such as integration of grain crop production with pastures and livestock (Izaurralde et al. 2011). An analysis of cattle fecal chemistry over the past 14 years suggested that changes in pasture makeup and effects of increased temperature and decreased rainfall have resulted in a general decline in forage quality (Craine et al. 2010). This includes a decrease in dietary crude protein and digestible organic matter. It is likely that the livestock industry will have to provide increased supplemental feeds to pasture raised cattle in the future to prevent decreased cattle production (Craine et al. 2010).

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3.5 Climate Change Effects on Weeds, Invasive Species, and Insects

Changing temperatures, humidity levels, and precipitation patterns will affect insect, disease, and weed populations. The indirect effects of climate change on these pests will add pressure to the agricultural production system because of the more favorable conditions for insects and diseases to multiply and broaden their range; risk of economic loss in crop and animal production increases due to these climate change-induced changes to pest populations.

Similar to plants, insects have a range of critical temperatures. As long as upper critical limits are not exceeded, rising temperatures accelerate every aspect of an insect's life cycle, and warmer winters reduce winter mortality. Some insects with multiple generations per year have responded to longer growing seasons by producing greater numbers of generations in a single year (Tobin et al. 2008; Altermatt 2010). This, in addition to the effects on population growth, can lead to more rapid resistance to insecticides (May and Dobson 1986). Although increased summer temperatures also favor growth of insect populations, extension of the growing season has a proportionately greater effect on the demands (i.e., feeding) that insects make on host plants (Bradshaw and Holzapfel 2010).

Agriculture, in its simplest arrangement, can be characterized as a managed plant community that is composed of a desired plant species (the crop) and a set of undesired plant species (weeds). Weeds (both native and invasive species) compete with primary agricultural production and have long been rivals to crops in U.S. agro-ecosystems. Weeds cause the highest crop losses globally (34%), with insect pests and pathogens showing losses of 18% and 16%, respectively (Oerke 2006). Agronomic weeds reduce food production either directly through competition for light, nutrients and water, or indirectly by reducing production quality, increasing problems during harvest due to presence of weeds, or acting as hosts for other pest vectors.

Weeds are naturally occurring component of an agricultural system. They play a role in the successional evolution of the regional ecosystem. In contrast, invasive species are those plants

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that are not native to the agro-ecosystem (source http://www.invasivespeciesinfo.gov/plants/main.shtml). Invasive species are characterized by their adaptability; their vigor and lack of natural enemies mean they more easily capitalize on increases in resources, e.g., increased soil water, than do native plants (Daehler 2003; Pyšek and Richardson 2007; Blumenthal et al. 2009; González et al. 2010; Van Kleunen et al. 2010). Inherently fast-growing plants such as weeds respond particularly strongly to elevated CO_2 (Poorter and Navas 2003; Ziska 2003; Song et al. 2009). In controlled environment studies, these differences have not translated into consistently stronger CO_2 responses in invasive as compared to non-invasive plants (Dukes 2000), however, in field studies that incorporate competition with native plants, elevated CO_2 has been found to increase invasion in grasslands (see Williams et al. 2007; Dukes et al. 2011), desert (Smith et al. 2000), and forests (Hättenschwiler and Körner 2003; Belote et al. 2004). CO_2 also increases plant water use efficiency, and may be most likely to favor invasion in water-limited ecosystems (Dukes 2002), as seen in the Nevada desert (Smith et al. 2000).

Plant diseases are an important part of the agricultural system and plant pathogen responses to climate change must be considered within the context of the "disease triangle" involving the pathogen, the host, and the environment, all of which are intrinsically connected (Agrios 2005). However, with vector-borne pathogens, the vector must also be included making a "disease triangle" with the pathogen (viral, phytoplasmal, or bacterial), the host, and the vector in each of its corners, each interacting separately with the environment (e.g., Thresh 1983). In addition to the very basic components being conducive for plant disease to occur, plant pathogens and their vectors are influenced by multi-trophic interactions that make predictions regarding their movement, incidence, severity, and evolution very challenging (Van der Putten et al. 2010).

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The yield and quality losses caused by pathogen epidemics are influenced (i) by the direct consequences of climate change like increased greenhouse gas concentrations and temperature, altered rainfall patterns, drought and greater wind speeds, and (ii) indirectly by things like regional alterations in cropped areas and ranges of crops grown, and changes in vector activity. Particularly with viruses, these factors alter the geographic ranges and relative abundance of pathogens, their rates of spread, the effectiveness of host resistances, the physiology of host-pathogen interactions, their rates of evolution and host adaptation, and the effectiveness of control measures (Jones 2009). Effects of such changes on the frequency and duration of epidemics will vary depending on the pathogen involved and geographic location, thus it is difficult to generalize (Garrett et al. 2006). Extreme weather events predicted with climate change include strong winds and episodes of torrential rain in addition to heat waves and droughts – all of which impact plant pathogen epidemics. For example with drought, the combination of disease and drought stresses are additive, causing greater damage, as with *Beet yellows virus* and *Maize dwarf mosaic virus* (reviewed in Jones 2009). Also, the rate of spread of contact-transmitted viruses will be accelerated by plant wounding arising from intense storms with torrential rainfall, or hail and high winds.

Changes in climate will impact both the crop and the pathogen, and understanding these changes will be critical to avoid increased losses in crop productivity. Changes in individual host plant structure and shifts in range that impact whole crop populations result in significant alterations in microclimate, pathogen dynamics, and multi-trophic interactions (Pangga et al.

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2011), and these interactions have far-reaching consequences. Range expansion has been predicted for many pathogens, based on models that incorporate changes in crop distribution and requirements for pathogen survival and reproduction (Savary et al. 2011).

3.6 Conclusions

Climate change due to rising temperatures coupled with more extreme temperature events will impact all elements of the agricultural production system. However, effects will not be uniform across the United States. Temperature stresses on plants and animals will vary among years and locations, and producers will have to be aware of these impacts in order to implement management practices that alleviate or minimize these effects.

Increasing CO_2 in the atmosphere has positive and negative effects on plants. CO_2 has been shown to stimulate plant growth and decrease soil water use rates (Kimball 2011). But in forage and grain crops, exposure to increased CO_2 causes a reduction in grain and forage quality (Morgan et al. 2004). Increasing CO_2 concentrations also contribute to more rapid growth of many invasive species (weeds), and increase the risk of crop loss from weed pressures in different production systems.

The projected increase in variability of precipitation will further impact agricultural production because of the uncertainty in water availability within the growing season. The effect of variable precipitation will also impact water supplies used for irrigation because runoff

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from snowmelt or rainfall may become less reliable, requiring implementation of water-conserving practices and more efficient irrigation methods.

No simple solutions exist that will allow agriculture to avoid the effects of climate change. These effects will influence production levels and will have an economic impact due to reduced production and increased crop damage that will likely require greater use of crop insurance to assist producers in avoiding adverse economic impacts caused by changing climate. There has been an increase in crop insurance payments to producers over the past 10 years, and the expectation is that these will payments will continue to increase with the greater uncertainty of favorable growing conditions during the plant growth cycle.

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4. Economic Effects of Climate Change on U.S. Agriculture

4.1 General Considerations

The economic effects of climate change occur at a number of scales and have a complex array of feedback loops. ***While the biophysical effects of climate change play out locally through the stress factors described above, the economic implications are shaped by an array of local, national, and global institutions, from commodity markets to systems of research, development, education, communication, and transportation.*** These institutions define the opportunities and constraints within which stakeholders can adjust their behavior to minimize losses and take advantage of new opportunities for gain associated with changing climate conditions. Potential adaptive behavior can occur at any level in a highly diverse agricultural system, including consumption, production, education, and research. The aggregate impacts of climate change will therefore ultimately depend on a web of diffuse adaptive responses to local climate stressors, from farmers adjusting planting patterns in response to altered crop yields, to seed producers investing in drought tolerant varieties, to nations changing trade restrictions in response to food security concerns.

The biophysical effects of climate change on yields and production costs are regionally variable and have the potential to significantly alter patterns of agricultural productivity in the provision of food, feed, fiber, and fuel products worldwide. Because the agricultural economy is a complex, self-adjusting set of relationships, ultimately climate change impacts will depend on

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how production and consumption systems adjust – or adapt – in response to those biophysical impacts. Adaptation behaviors such as changing crops and crop varieties, adjusting planting and harvest dates, and modifying input use and tillage practices can lessen yield losses from climate change in some regions, and potentially increase yields in others where climate change creates expanded opportunities for production (Adams et al. 1998). The economic implications of climate change for the United States will therefore be sensitive to yield impacts and adaptation opportunities, as well as to constraints both within the United States and worldwide.

Several regional and national studies have predicted that U.S. cropland agriculture will be fairly resilient to climate change in the short term, with expansion of irrigated acreage, regional shifts in crop acreage, and other adjustments in inputs and outputs compensating for yield impacts caused by changing climate patterns (Adams et al. 1990; Mendelsohn et al. 1994). Adaptive behavior can significantly mitigate the potential effects of climate change on food production, farm income, and food security by moving agricultural production out of regions with newly reduced comparative advantage in specific production sectors and into areas with improved relative productivity (Rosenzweig and Parry 1994; Mendelsohn and Dinar 1999). Reilly et al (2007) find that with adaptation, the production effects of climate change are reduced to one-fifth to one-sixth of the initial yield impact.

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4.2 Estimating Economic Effects of Climate Change

Efforts to quantify economic impacts are sensitive to a number of research elements defining input assumptions as well as scale and scope of analysis, including:

- Climate and Yield Projections: Biophysical and economic impact assessment results are highly sensitive to the climate change model projection used and to the spatial resolution of those climate scenarios (Adams et al. 1990; Adams et al. 1995; Adams et al. 2003). Climate impact analyses that look farther into the future generally show greater impact on yields and economic indicators, though there is also greater uncertainty about future emissions trajectories, projected changes in climate variables, and available adaptive technologies. Treatment of CO_2 fertilization effects (i.e., whether and how potential yield-enhancing impacts of increased atmospheric CO_2 are included in the study) is also an important determinant of results (Adams et al. 1995; Sands and Edmonds 2005).

- Scope of the Assessment: Impact estimates are sensitive to the types of available adaptation options and whether the assessment includes consumer response and impact as well as that of producers, livestock, and forest production as well as cropland agriculture, and international interests as well as domestic interests (Sands and Edmonds 2005).

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- Treatment of Adaptation Constraints: Potential constraints to adaptation such as regional land and water availability, as well as constraints related to farm finances and viability, have received relatively little research attention, yet have been shown to significantly impact the results emerging from integrated assessments of climate change impacts (Adams et al. 1995; Darwin et al. 1995; Beach et al. 2010).

- Methodology Used and Model Specification. Methods used for climate change impact assessment include expert opinion, hedonic and production function approaches, and integrated assessment modeling (Schlenker et al. 2005).

4.3 Sensitivity of Economic Impact Estimates to Climate and Yield Projections

Projections suggesting that climate changes in temperate regions will increase yields in agriculturally important regions such as the Corn Belt are consistent with the IPCC (IPCC 2007b) assessment that "moderate climate change will likely increase yields of North American rain-fed agriculture," and its more general projection that crop productivity will increase slightly at mid to high latitudes for local mean temperature increases of up to 1 to 3°C. Economic analyses based on projected increases in yields have often resulted in net positive estimates of welfare change in the United States, though the net effects obscured underlying variability in regional and stakeholder impact (Adams et al. 1998; Adams et al. 2003; Reilly et al. 2003). Many such analyses estimate an increase in U.S. consumer welfare in response to climate change, because productivity increases result in price drops and reductions in consumer cost. However, producer welfare in the United States declines because the drop in

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prices offsets the producer benefits accruing from yield increases. Other studies suggest that the observed price effect may not fully erode the bump in producer returns arising from increased yields, so that both consumer and producer welfare increase in response to climate change in the near- to middle-term (Sands and Edmonds 2005). Regional variability in impact also exists; in the United States, for instance, research suggests that warming temperatures will cause a northerly shift in the comparative advantage of production regions, with producers in northern regions generally faring better under changing climate conditions than producers in the South (Adams et al. 1995; Darwin et al. 1995).

There is, however, no scientific consensus on the positive average U.S. yield projections upon which these economic impact studies are based. Other studies conclude that recent patterns of climate change have in fact already had adverse effects on U.S. corn and soybean production in agriculturally important regions (Lobell and Asner 2003; Kucharik and Serbin 2008; Ainsworth and Ort 2010). Deschenes and Greenstone (2007) found no statistically significant relationship between climate change and corn and soybean yields. Sands and Edmonds (2005) showed that climate change impacts vary substantially across climate projections. Furthermore, because the climate is projected to continue changing throughout the 21st century, yield and economic impact assessment results are sensitive to the time horizon used in the analysis, with greater impacts and damages occurring further in the future as temperatures continue to increase (Hitz and Smith 2004; IPCC 2007a; Tol 2009; Burke et al. 2011).

Projections may also miscalculate likely yield impacts because most analyses have not included a comprehensive treatment of the stress factors arising from climate change that can impact yields. Studies often focus on the impacts of a subset of direct stress factors, usually changes in average temperature and precipitation, but fail to consider the additional impacts of indirect stress factors, such as changes in pest, weed and disease pressure, arising from community-scale, agro-ecological adjustments to changing climate. Even when elements of climate change are not fully omitted, their impacts on crop yield can be highly uncertain. For instance, several researchers have called attention to the sensitivity of economic impact results to the treatment of the yield-enhancing effects of atmospheric CO_2 in estimating crop yield impacts (Adams et al. 1995; Long et al. 2005; Sands and Edmonds 2005; Tubiello et al. 2007; Gornall et al. 2010).

Uncertainty in climate projections is therefore a critical element of crop and economic impact uncertainty (Adams et al. 1995; Sands and Edmonds 2005). Nevertheless, both crop impact and economic assessment efforts have been slow to develop the tools necessary to accommodate climate uncertainty. Burke et al (2011) argue that although more than 20 climate models are regularly used by the climate change community, none have been determined to be more reliable than others for long-term climate projections; the median number of model projections used for economic, political, or social impact studies is only two. Greater attention to methods of quantifying and tracking multiple sources of uncertainty is required in climate change impact studies (Lobell and Burke 2008; Challinor et al. 2009; Winkler et al. 2010).

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4.4 Sensitivity of Economic Impact Estimates to Scope of Analysis

Domestic yield impacts alone are likely a poor predictor of domestic welfare impacts because domestic markets are highly interconnected with international markets, which will also be responding to yield and production changes worldwide (Adams et al. 1995; Hertel et al. 2010). Changes in *relative* productivity by region, and the price and trade effects arising in response, are therefore a critical determinant of the economic and welfare impacts of climate change (Reilly et al. 2007; Hertel et al. 2010; Winkler et al. 2010).

If global yield impacts are generally negative, it can drive global prices up despite potential domestic yield increases; the resulting price increases can benefit U.S. producers through increased return for their product, but U.S. consumer welfare is depressed by the global-market-mediated price increase (Reilly et al. 2003; Sands and Edmonds 2005). On the other hand, if net global yield impacts for a given crop are also positive, then world yield impacts can further lower world and domestic prices and push benefits associated with price changes even more in favor of consumers. In countries that experience yield declines, producer returns may therefore increase if rising global prices are sufficient to offset the adverse income effects of reduced yields (Reilly et al. 2007; Hertel et al. 2010). Consumers, however, always suffer welfare losses from reduced availability of food and increased prices associated with declining yields (Hertel et al. 2010); certain non-agricultural demographics, such as the urban labor strata and the non-agricultural self-employed, can be highly vulnerable to increased poverty arising from higher food prices (Hertel et al. 2010). Opposing dynamics would be expected if yields increase worldwide; domestic consumer welfare is improved by downward pressure on prices, while producer returns are pushed downward by the declining prices.

The scope of analysis is also defined by the number of sectors included in the impact analysis. Existing analyses of agricultural impacts have focused on climate change impacts on cropland agriculture, with some expansion – often in the case of simulation modeling efforts – to include the impacts of changing feed prices or competition for pasture land on the livestock sector (Reilly et al. 2003). Climate change will directly impact cropland, forestry, and livestock (as well as all the other sectors of the economy) simultaneously, however, and only a small subset of studies have looked at the impacts of changing relative productivity across sectors on decisions regarding land use and shifting patterns of crop, livestock, and timber products (Darwin et al. 1995; Alig et al. 2002; Sands and Edmonds 2005; Reilly et al. 2007).

4.5 Sensitivity of Economic Impact Estimates to Adaptation Constraints

Few economic impact analyses have incorporated potential constraints to adaptation related to farm financing and credit availability in the United States and elsewhere, though research suggests that such constraints may be significant (Antle et al. 2004; Wolfe et al. 2008; Knutson et al. 2011). In addition to 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 (Smit and Skinner 2002)).

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Regional capacity for expanding agriculture or irrigated production will depend on resource constraints such as the availability of land and water (Darwin et al. 1995). Large bands of uncertainty around future projections for regional precipitation change make it difficult to predict with precision regional changes in relative productivity, and estimates of net land brought into production as a result of climate change are mixed and highly sensitive to which models and climate assumptions or scenarios are used in the estimation (Zhang and Cai 2011). In general, however, studies estimate that arable land increases at the higher latitudes, including Canada, Russia, the northern U.S., and southern Argentina, and decreases in western Africa, central America, western Asia, the south-central United States, and northern South America (Ramankutty et al. 2002; Zhang and Cai 2011).

4.6 Sensitivity of Economic Impact Estimates to Estimation Methodology

Methods used for climate change impact assessment vary widely and have included expert opinion, statistical estimation using hedonic and production function approaches, and integrated assessment modeling (Schlenker et al. 2005). These assessment methodologies have differing capacities for reflecting adaptation options, allowing the adoption of adaptation technologies that don’t yet exist, capturing the effects of market responses such as changes in the prices of inputs and outputs, and accommodating scope and scale considerations like those described above.

Statistical estimation methods, for instance, estimate future impacts based on relationships observed in past data and cannot take into account the possibility of future technological

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changes that might fundamentally change production decisions and adaptation options. Such estimation methods are also highly sensitive to model structure. The structural approach employs integrated assessment models to measure the economic consequences of climate change (Adams et al. 1998). Over the past few decades, integrated assessment modeling efforts have used model ensembles from several different disciplines to tie together the dynamics of climate impacts at various scales for a broader picture of projected agricultural system response and impacts. These analyses allow for the introduction of a wide range of potential adaptation behaviors, though that flexibility is limited by the structure and scale of the component models, availability of good data, and by the need to specify for newly introduced adaptation options cost and benefit information that may be unknown or highly uncertain.

4.7 International Impacts of Climate Change and Food Security Implications

The impacts of climate change are generally projected to be more severe in poor developing countries than in the relatively more affluent developed countries (Winters et al. 1998; Mertz et al. 2009). Productivity may be more negatively impacted because many developing countries are already at the upper end of their temperature ranges, and precipitation is not expected to increase as is expected to occur in many temperate regions (IPCC 2007b; Mertz et al. 2009). Overall economic impacts may be more severe because developing countries rely on agriculture for a much greater proportion of their national income and employment than do developed countries (Mertz et al. 2009). As with economic impacts, the food security implications of climate change are also significantly different across regions (Funk and Brown 2009; Acevedo 2011).

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Studies have consistently suggested that climate change is not a significant food security risk for the United States and other developed countries in the near to medium term (Adams et al. 1995; Cline 2007; UNDP 2007). Concerns about food security are more acute for other regions of the world, however. Regional differences in yield impacts, and adaptation capacity, are expected to result in regional differences in vulnerability to hunger and poverty impacts, with particularly severe implications for tropical semi-arid developing countries (Fischer et al. 2005). Almost 90% of world hunger is concentrated in Asia, the Pacific, and Sub-Saharan Africa—regions that are particularly vulnerable to climate change (Battisti and Naylor 2009; Acevedo 2011). Several studies project negative impacts of climate change on productivity and food security in Africa and South Asia (Challinor et al. 2007; IPCC 2007a; Lobell and Burke 2008; Funk and Brown 2009; Schlenker and Lobell 2010; Hare et al. 2011).

While developing countries may be particularly vulnerable to climate change impacts, substantial gaps between crop yield potential and actual yields ("yield gaps") in those countries may represent an opportunity to offset negative climate change impacts through investments that narrow those yield gaps on existing croplands (Lobell et al. 2009). Furthermore, Tilman et al (2011) suggest that "strategic intensification" of agriculture that targets yield gaps and elevates yields on existing croplands of under-yielding nations can significantly reduce the potential environmental impacts associated with meeting 2050 global crop demands.

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4.8 Conclusions

In the short term, existing adaptation strategies will likely provide substantial adaptive capacity, mitigating the impacts of climate change on domestic producers and consumers. Some economic impact estimates point to initial benefits of a modest increase in temperature, followed by losses as temperatures increase further. Impacts of climate change on international food security, however, may be significant even in the shorter term. Even future climate scenarios with mild to inconsequential net global impacts of climate change may result in severe implications for the food security of the world's poorest and most vulnerable populations.

A failure to consider the management costs associated with changing biotic stresses, the impacts of variability and extreme weather events on crop yields, and potential credit and resource constraints may overstate farms' financial viability in the face of changing climate conditions. Many impact analyses do not consider potential constraints to farmers' adaptive behavior or the full range of emerging stressors on crop growth and yield.

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5. ADAPTATION

5.1 Introduction

Modern agriculture represents a path of continual human adaptation to a wide range of factors driving change both from within and outside of agricultural systems. Through the ages, agriculturalists have selected and developed crops, livestock, and management practices that reduce production risks by adapting to local climate and resource constraints. Utilizing drought- and pest-resistant crops, making planting date adjustments to avoid seasonal extremes in temperature and precipitation, planting longer season crops, and managing water availability through irrigation and the control of surface runoff and drainage are a few examples of adaptive agricultural practices in wide use today in the United States. While current climate change impacts are challenging, the changes predicted over the next century have the potential to transform U.S. agriculture. With effective adaptive action, this transformation could capitalize on the opportunities presented by climate change while minimizing the costs and risks.

Agricultural productivity is determined by a diverse set of biophysical, social, economic, and technological drivers operating across multiple dimensions of time and space. These drivers of change create opportunity and present risk to the successful production of crops and livestock. In particular, agriculture is highly sensitive to weather impacts with climate variations, soil type, biotic stressors, and management being the dominant drivers of

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production variability in many regions (Howden et al. 2007; Hatfield et al. 2011; Lal 2011). As climate change intensifies, Howden et al. (2007) suggests that “climate risk” is likely to be added to the risks commonly managed by farmers, such as those related to production, marketing, finances, regulation, and personal health and safety (Harwood et al. 1999).

Key drivers of agricultural adaptation to climate change at the farm level are likely to include: personal experience of direct and indirect effects of change (Field et al. 2007; Knutson et al. 2011; Spence et al. 2011), market signals (Antle 2009; Antle and Capalbo 2010), current and proposed policies (Batie 2009), institutional strategies (Preston et al. 2011), farmer perceptions and preferences (Blackstock et al. 2010; Nelson et al. 2010; Arbuckle 2011; Weber and Stern 2011), issues awareness (for example, food security) (Godfray et al. 2010), and information sources and types, and how these are interpreted (Malka et al. 2009).

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5.2 Agricultural Systems and Adaptation

A recent report by the National Research Council, *Toward Sustainable Agricultural Systems in the 21st Century* (NRC 2010), identifies climate change as a major challenge to the sustainability of U.S. agriculture in this century. The report, which offers a concise synthesis of the key biophysical impacts likely to challenge agricultural production in the United States, argues that current and predicted climate change increases the importance of developing robust farming systems capable of coping with these impacts. A major outcome would be to understand the farming system characteristics – economic, environmental and social – that increase resilience and adaptive capacity in the face of global changes, including those likely to occur in a changing climate.

Agricultural adaptation to climate change is challenged by the increasing pace of this change, the diversity and complexity of agricultural social-ecological system (SES) response to climate change impacts, and the complexity of the adaptation process (Easterling et al. 2007). All SESs exist and function at multiple scales of space, time, and social organization and the interactions across scales are fundamentally important in determining the dynamics of the system at any particular focal scale (Gunderson and Holling 2002). Because human actions dominate in SESs (though constrained by ecosystem capacity), the adaptive capacity of the system is mainly a function of the social component, that is, the individuals and groups acting to manage it (Walker et al. 2004; Easterling et al. 2007).

The concepts of adaptation, adaptive capacity, vulnerability, and resilience are well-developed in the global change literature (synthesized in Smit and Wandel 2006, Adger et al 2007); however, the methodological development needed to apply these concepts to adaptation planning and assessment lags behind, particularly in developed countries (Moser et al. 2008; Kenny 2011). Efforts to identify key factors contributing to system vulnerability or adaptive capacity, to address issues of uncertainty, scale, and multidimensional system interactions, and to develop effective integrated indices of vulnerability or adaptive capacity, typify methodological research (for example, Adger and Vincent 2005; Brooks et al. 2005;

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Alberini et al. 2006; Eakin and Bojórquez-Tapia 2008) and participatory research methods are increasingly employed (for example, Petheram et al. 2010; Krishnamurthy et al. 2011).

Agroecology may emerge as a key knowledge base to inform the development of effective adaptation strategies in agriculture. Tomich et al (2011) argue that agroecology offers an integrative knowledge framework that is well suited to innovative agricultural research and development strategies. Agroecologists have established the contribution of agrobiodiversity to agricultural resilience and offer key insights on practical approaches to assess and enhance the adaptive capacity of agriculture and food systems. In a recent review of agroecology from a global change perspective, Tomich et al (2011) suggest that agroecology has the conceptual and methodological capacity needed to integrate the technical, scientific, economic, social and cultural aspects of adapting agriculture to climate change.

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5.3 Conclusions

The sustainable management of soil and water resources is a key adaptation strategy for U.S. agriculture. Soil conservation practices like cover cropping, diversifying annual cropping systems, inclusion of perennial crops in rotations, changing from annual to perennial crops, organic soil amendments, grazing management, conversion of cropland to pasture, agroforestry and natural areas, and wetland restoration contribute to climate change adaptation in agriculture. The ability of healthy soils to regulate water resource dynamics at the farm and watershed scales is widely recognized and is particularly critical for the maintenance of crop and livestock productivity under conditions of variable and extreme weather events. In the United States, agricultural producers are very aware of soil and water vulnerabilities and have access to a variety of best management practices (BMPs) and incentive programs to address these on-farm and off-farm risks (Prokopy et al. 2008; Morton 2011). Research on producer adoption rates of conservation BMPs (Hua et al. 2004; Valentin et al. 2004; McCown 2005; Smith et al. 2007; Prokopy et al. 2008) provide insights on the willingness and capacities of producers to put in place adaptive management practices in response to changing climate conditions.

Although agriculture has a long history of successful adaptation to climate change and variability, the current pace of climate changes and the intensity of projected climate change represent a novel and unprecedented challenge to the sustainability of U.S. agriculture.

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Meeting this grand societal challenge requires new methods of scientific inquiry and technological development and a transformational approach to problem-solving utilizing transdisciplinary teams that co-create the knowledge needed to sustain a productive and profitable agriculture in a changing climate.

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6. Overall Conclusions

Agriculture across the United States is a complex system comprised of many different commodities and production practices, and has exhibited the ability to adapt to changing environmental, economic, and policy environments.

Climate change across the United States will present challenges to agriculture because of the increasing variability in temperature and precipitation. These changes will not exert themselves with the same degree of impact across all agricultural production systems because of regional and seasonal variations in temperature and precipitation.

The effects of climate change on agriculture are a combination of the direct impacts on production systems and the indirect effects through insects, diseases, and weeds.

The effects of increasing temperatures on plants and animals will vary among species and production systems, with one of the more noticeable impacts on perennial crops, which may suffer reductions in product quality and production.

Animals exposed to high temperatures will suffer stress; modifications to production practices will be necessary to overcome these problems.

Water availability is crucial to agriculture, and variation in precipitation will impact water supplies for all agricultural sectors. When water stress is coupled with temperature stresses the result will be larger impacts on production.

The economic consequences of the changes described above are projected to alter prices for commodities; however, producer income may increase as a result of higher prices.

Actions that reduce the amount of climate change experienced during the 21st century are very likely to have benefits for agriculture.

Adaptive actions appear to hold significant potential for reducing the vulnerability of many parts of the agricultural system, but overall adaptive capacity is not yet well understood and may itself be affected by climate change, especially with regard to water management and availability.

The overall effects of climate change on the agricultural system will depend on the balance of regional effects and **the** effectiveness of adaptation actions.

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