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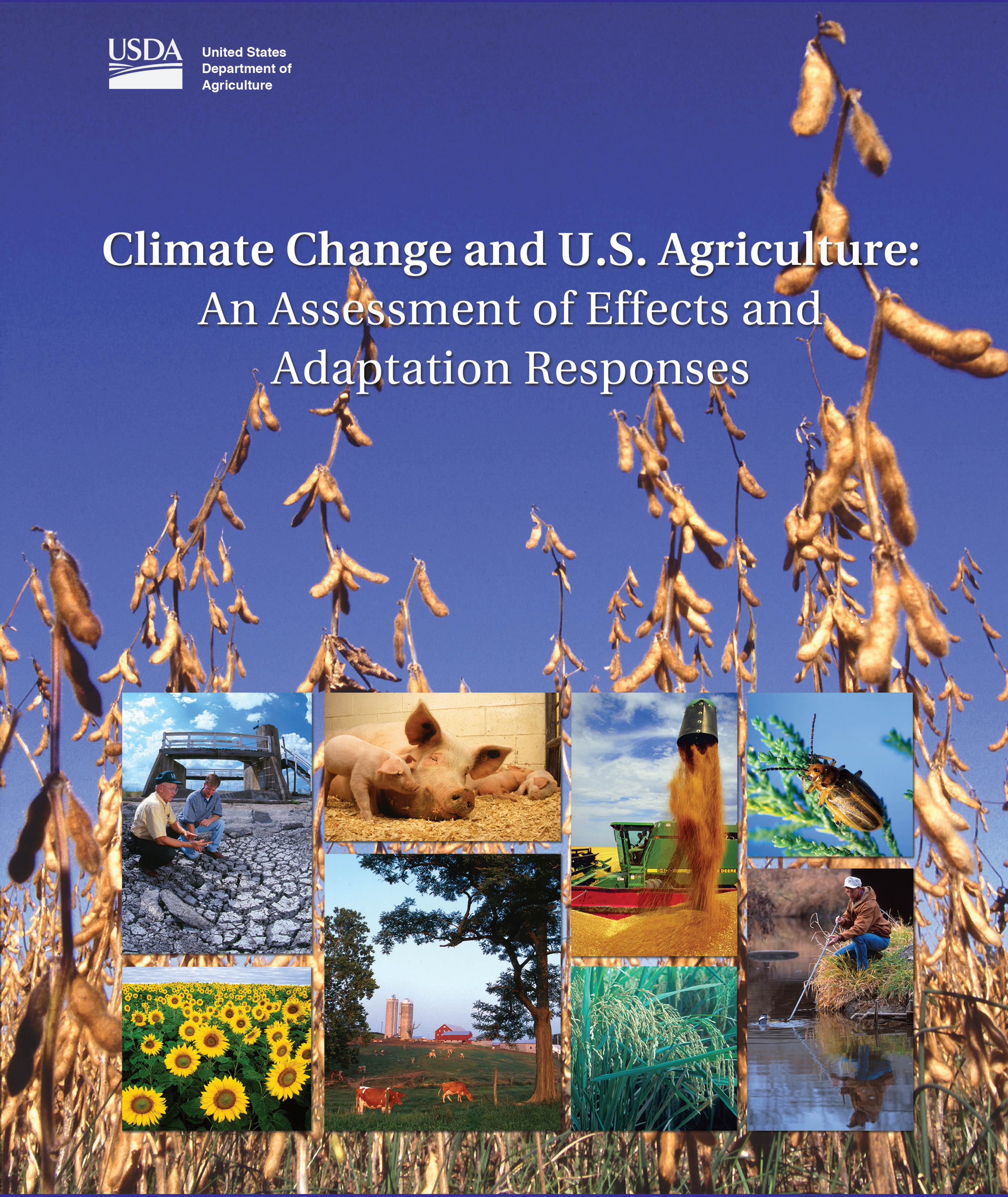
Climate Change and U.S. Agriculture: An Assessment of Effects and Adaptation Responses



Climate Change and U.S. Agriculture:
An Assessment of Effects and Adaptation Responses

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This report is available on the Web at: http://www.usda.gov/oce/climate_change/effects_2012/effects_agriculture.htm

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Preface

To present a current understanding of how climate change might affect aspects of the U.S. agroecosystem over both the short (up to 25 years) and long term (into the next century), the U.S. Department of Agriculture (USDA) released a technical report, *Climate Change and Agriculture in the United States: Effects and Adaptation, Technical Bulletin 1935.*[1] The technical bulletin offers extensive information on the state of U.S. agriculture and climate science, and details the effects of climate change on agricultural production, the economics of these effects, and potential adaptation strategies. *USDA Technical Bulletin 1935* sums up the latest understanding of climate change effects on U.S. agriculture and explores the potential for adaptation strategies to minimize the costs and capitalize on the opportunities presented by a changing climate.

This report, *Climate Change and U.S. Agriculture: An Assessment of Effects and Adaptation Responses,*[2] is a summary of the technical bulletin. This summary reviews the existing vulnerabilities of U.S agriculture to climate change and explores adaptive actions that may reduce those vulnerabilities.

The document begins with a summary of the past and current state of U.S. agriculture, followed by an overview of projected future climate conditions in the United States. The next section merges the ideas of the first two sections, taking a detailed look at how climate is affecting U.S. agriculture today, considering both direct effects (e.g., changes in precipitation and temperature) and indirect effects (e.g. weeds, diseases, and insects) that influence agricultural production. In addition to information on agronomic and atmospheric science, this summary offers insights on the latest research related to the economic impacts of climate change and explores the possible repercussions of such change on both the United States and, to a lesser degree, the global agricultural system.

Critical to the study of climate change and its effects on U.S. agriculture are considerations of adaptive strategies intended to enhance the resilience of the agroecosystem to climate change and variability, whereby agricultural producers, agribusiness, government personnel, and consumers make choices that both reduce costs related to climate change, as well as take advantage of any benefits presented by climate change. This summary concludes with some of the major findings of the *USDA Technical Bulletin 1935* and suggests areas where additional study will enable development of a more robust U.S. agricultural system. It is the intent of this summary to provide up-to-date scientific analysis to assist those working within the U.S. agricultural system to continue the nation's long history of innovating and adapting to change.

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[1] See http://www.usda.gov/oce/climate_change/effects_2012/effects_agriculture.htm for full report.

[2] Citations are not included in this document. Please refer to *Climate Change and Agriculture in the United States: Effects and Adaptation, Technical Bulletin 1935* for the full list of research references.

Key Messages from USDA Technical Bulletin 1935

Projections for crops and livestock production systems reveal that climate change effects over the next 25 years will be mixed. Beyond midcentury, however, changes in climate are expected to have overall detrimental effects on most crops and livestock.

Increases of atmospheric carbon dioxide (CO_2), rising temperatures, and altered precipitation patterns are affecting agricultural productivity and will continue to do so. Increases in temperature coupled with more variable precipitation reduce crop productivity and, over the longer-term, these effects will likely outweigh the benefits of increasing CO_2. Effects vary among annual and perennial crops, and between regions; however, all production systems will be affected to some degree by climate change. Because agricultural systems depend upon reliable water sources, and because the pattern and potential magnitude of precipitation change are not well understood, there is considerable uncertainty in climate change assessment efforts.

The predicted higher incidence of extreme weather events will have an increasing influence on agricultural productivity. Extremes matter because agricultural productivity is driven largely by environmental conditions during critical threshold periods of crop and livestock development. Improved assessment of climate change effects on agricultural productivity and profitability requires greater integration of the timing and magnitude of extreme events into crop and economic models.

Livestock production systems are vulnerable to temperature stresses. An animal's ability to adjust its metabolic rate to cope with temperature extremes can lead to reduced productivity and in extreme cases, death. Prolonged exposure to extreme temperatures will also further increase production costs and productivity losses associated with all animal products, e.g., meat, eggs, and milk.

Climate change exacerbates indirect biotic stresses on agricultural plants and animals. Changing pressures associated with weeds, diseases, and insect pests, together with potential changes in timing and coincidence of pollinator lifecycles, will affect growth and yields. The potential magnitude of these effects is not yet well understood. For example, while some pest insects will thrive under increasing air temperatures, warming temperatures may force others out of their current geographical ranges. Several weeds have shown a greater response to CO_2 relative to crops; understanding these physiological and genetic responses may help guide future enhancements to weed management.

Multiple stressors, including climate change, increasingly compromise the ability of ecosystems to provide key ecosystem services. Agriculture is dependent on a wide range of ecosystem processes that support productivity, including maintenance of soil quality and regulation of water quality and quantity. Key near-term climate change effects on agricultural soil and water resources include the potential for increased soil erosion through extreme precipitation events, as well as regional and seasonal changes in the availability of water resources for both rain-fed and irrigated agriculture.

The vulnerability of agriculture to climate change depends upon the responses taken by people to mitigate greenhouse gas emissions and adapt to changing climate. Mitigation efforts that slow the pace and intensity of climate change will reduce agricultural exposure to these changes, while effective adaptation increases agroecosystem resilience through actions that reduce sensitivity to climatic effects and increase production systems' adaptive capacity.

I. Introduction

Agriculture in the United States is a dynamic, self-adjusting system that responds to changes or fluctuations in environmental conditions, trade, policy, markets, and technology. Since 1900, farms have grown larger, more mechanized, less labor intensive, and more specialized. Across the United States, the total area of land in agriculture has remained fairly constant and the number of farms has decreased, while production and productivity have continued to increase. Agriculture is a major economic sector that includes more than two million farms, covers about 900 million acres in cultivated, range, and pasture lands, and generates gross annual farm income between $300-350 billion.

Across the United States more than 200 different agricultural goods are produced; of this total, livestock and livestock products account 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. Changes in key climate variables (e.g., seasonal mean temperatures or precipitation patterns) can result in potentially significant shifts in the mix of commodities produced within a region and the systems and technologies that agricultural producers employ to generate these commodities. Agriculture and its related industries have a long history of successful innovation to changing environmental and social conditions and have become much more productive over time. For example, in 1910 U.S. agricultural producers cultivated 330 million acres and supplied food and fiber to a population of 92.2 million. In 2006, agricultural producers supplied food and fiber to 297.5 million people on the same cultivated land area.

However, evidence shows that U.S. climate has changed substantially since 1900, that this change is accelerating, and that even larger change will 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 greenhouse gases, which 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 (1.4°F) since 1900 and is projected to warm another 1.9-5°C (3.4-9°F) over the next century, depending on the amount of greenhouse gases emitted during this period.

Crops and livestock production systems, two fundamental elements of the U.S. agricultural system, function within a complex web of environmental, economic, and social interactions that extend from local to global scales (Figure 1). This web of interconnections means that change in one part of the U.S. agricultural system can drive changes that ripple across the system as a whole. Changing climate will affect all aspects of the U.S. agricultural system, including water and soil resources, the pests and diseases that affect plants and animals, the productivity of crops and livestock, the distribution of welfare of consumers and producers of agricultural goods, and the prices, production and trade patterns that characterize agricultural markets. Changing climate is already influencing agricultural system performance, and research indicates that U.S. agriculture will experience even greater disturbance due to the effects of climate change in the coming years and decades.

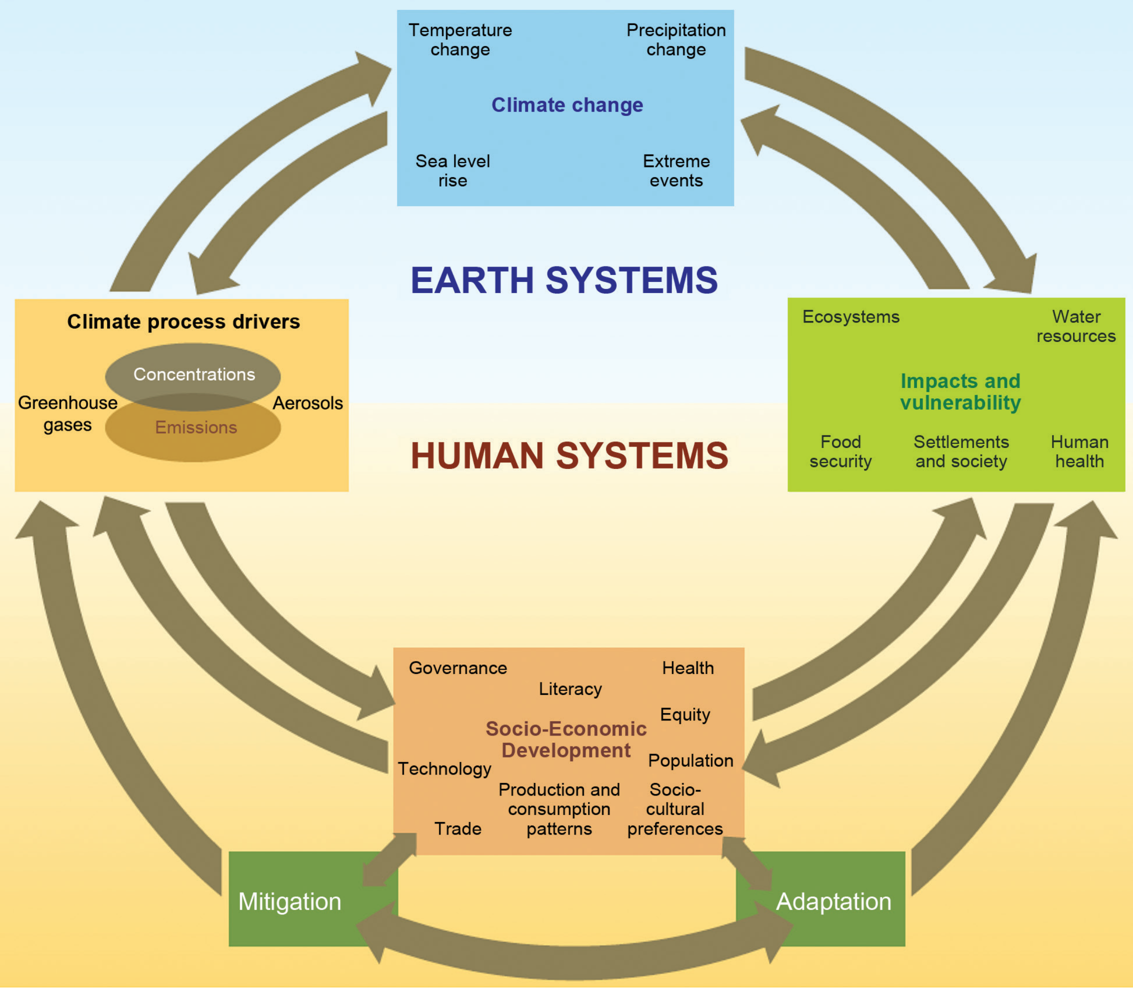
The State of U.S. Agriculture

A large part of the success of U.S. agriculture results from the dynamic, self-adjusting characteristics of the system, which respond to changes or fluctuations in environmental conditions, trade, policy, markets, and technology. This capacity to react and adapt to shifting circumstances is valuable in the face of changing climate. Agricultural production is vulnerable to climate change through direct effects of changing climate conditions on crop and livestock development and yield, as well as through the indirect effects arising from changes in the severity of pest pressures, availability of pollination services, and performance of other ecosystem services that affect agricultural productivity.

Complicating the issue and ability to respond to change is the pace and intensity of projected climatic changes, which present novel challenges to U.S. agriculture. Until recently, producers and land managers could often turn to historical knowledge for a time-tested response when challenged by a climatic or weather anomaly. However, for many of the projected changes, such experience-based adaptation will likely become insufficient; as weather and climate conditions break out of historical ranges, planning for and responding to change will become much more difficult.

The U.S. agricultural system is expected to be fairly resilient to climate change in the short term due to the system's flexibility to engage in adaptive behaviors such as expansion of irrigated acreage, regional shifts in acreage for specific crops, crop rotations, changes to management decisions such as choice and timing of inputs and cultivation practices, and altered trade patterns compensating for yield changes caused by changing climate patterns. By midcentury, when temperature increases are expected to exceed 1-3°C (1.8-5.4°F) and precipitation extremes intensify, yields of major U.S. crops are projected to decline and production risk and variability of returns are projected to increase for many U.S. producers. However, these projections should be interpreted with caution. The climate model simulation studies underlying such projections do not incorporate production constraints created by interactions between direct and indirect climate effects, effects on ecosystem services, or conditions that limit adaptation, all of which can significantly increase production costs and yield losses.

Figure 1. *A schematic framework representing key linkages between the anthropogenic drivers of climate change and the global climate system. An assessment of the interactions between key components of this system may inform the development of adaptation options to reduce future climate change effects on the U.S. agricultural system.*



II. Climate Science: An Overview of the Changing Climate

There is a strong scientific consensus that human activities are changing the Earth's climate. Emissions of CO_2 and other greenhouse gases, primarily resulting from combustion of fossil fuels and deforestation, have grown steadily since the beginning of the industrial revolution in the late 1700s, significantly increasing the concentrations of these gases in the atmosphere. This change in atmospheric composition has increased the ability of the Earth system to retain heat, leading to global-scale warming of the atmosphere and oceans and changes in patterns of precipitation that are in turn affecting terrestrial and marine ecosystems. The Earth's global average surface temperature has increased by about 0.74°C (1.4°F) since 1900. Precipitation and heavy precipitation events have increased in most regions of the world while at the same time occurrence of drought has also been on the rise, in particular since 1970. The rise in greenhouse gas concentrations and temperatures has accelerated during recent decades. Global average temperature increased by about 0.55°C (1°F) since 1979, and CO_2 concentrations recently surpassed 400 parts per million (ppm). This is about 120 ppm more than pre-industrial levels and higher than any level measured in the last 800,000 years.

Projections of Global Climate Change

Human influences will continue to alter Earth's climate throughout the 21st century. Current scientific understanding, supported by a large body of observational and modeling results (including the Intergovernmental Panel on Climate Change Fourth Assessment Report (IPCC AR4)), indicates that continued changes in atmospheric composition will result in further increases in global average temperature, rising sea level, and continued declines in 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. To illustrate the climate implications of these emissions scenarios, this report focuses on two alternatives:

- **A low emissions scenario** for the 21st 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 ppm, which would increase global average surface temperature by about 1.1-2.9°C (2-5.2°F) in 2100.

- **A high emissions scenario** for the 21st century (IPCC SRES A2) would result from a slowing in technological improvement, significant population growth, and less effective actions taken by individuals, corporations, and governments to limit emissions. In 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 (3.6-9.7°F) by 2100.

The average global surface temperature for each of these scenarios will vary by region (Figure 2). Polar areas will warm more than lower latitudes, land will warm more than oceans, and continental interiors will warm more than coastal areas. The differences between high and low emissions scenarios become much more noticeable near the end of the century.

Projections of Change in U.S. Temperatures

U.S climate conditions will also continue to change throughout the 21st century. In the figures below, U.S. projections are shown for the low and high emissions scenarios for the 2040s and 2080s. These illustrate how different choices about greenhouse gas emissions could affect future U.S. climate conditions. Similar to global-scale projections, the differences between high and low scenarios of future greenhouse gas emissions are much more noticeable near the end of the century. The entire United States is projected to warm substantially over the next 30 years, with an increase of 1-2°C (1.8-3.6°F) over much of the country (Figure 3). This is a substantially greater rate of change than observed

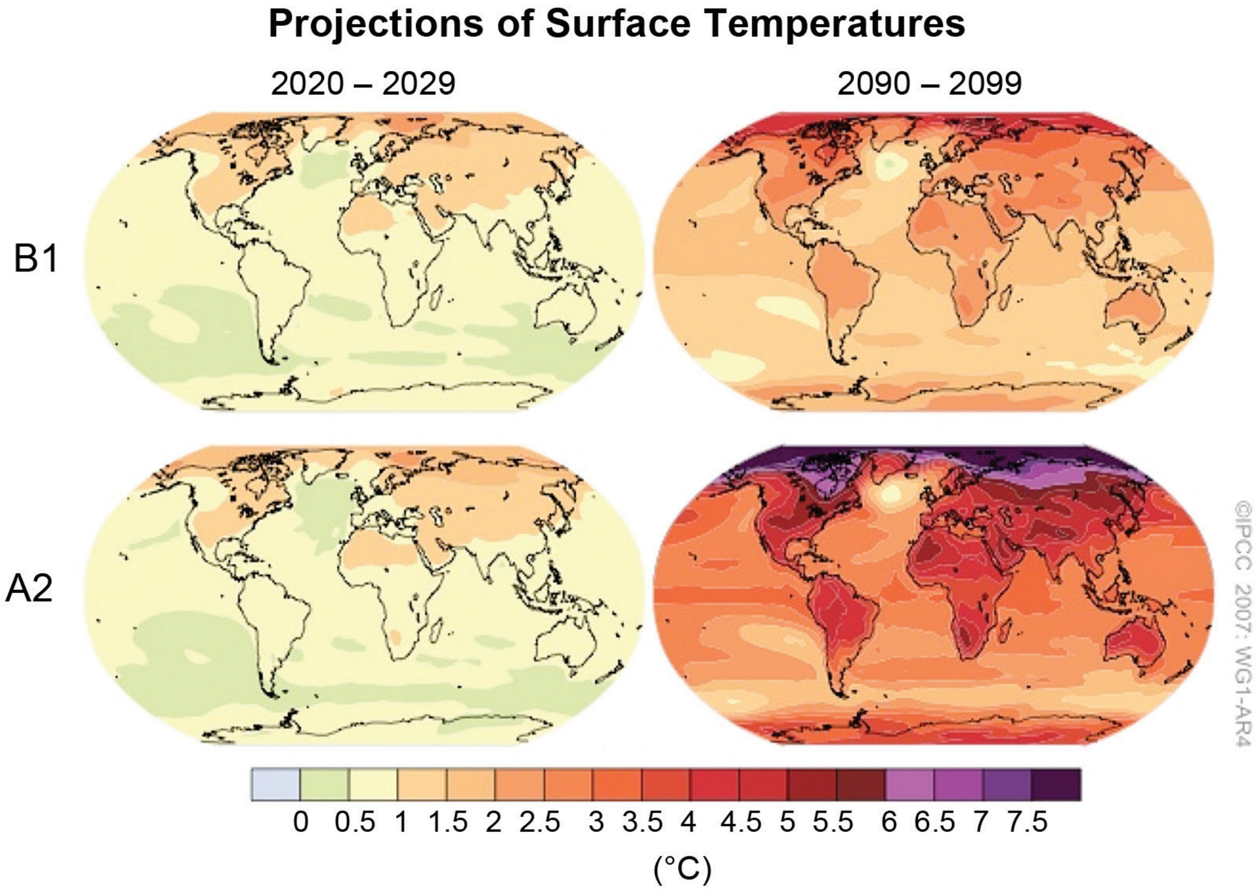


Figure 2. *Projected global temperature changes for the 2020s (left side) and 2090s (right side) compared to 1980-1999 for low-emissions (B1) and a high-emissions (A2) scenario.*

over the 20th century, reflecting the accelerated rate of increase in greenhouse gas concentrations and temperatures observed during the last few decades. By the 2080s, a low emissions scenario is projected to produce summertime warming of 3-4°C (5.4-7.2°F) in much of the Interior West, with warming of 2-3°C (3.6-5.4°F) almost everywhere else. A high emissions scenario is projected to result in warming of 5-6°C (9-10.8°F) in much of the Interior West and Midwest, with warming of 3-5°C (5.4-9°F) degrees in the Southeast and far western regions.

Projected Changes in U.S. Precipitation

Projected changes in precipitation are more uncertain because they are sensitive to both local conditions and shifts in the large-scale circulation of the atmosphere, which influence the distribution of storms. These uncertainties are probably larger in summer than in winter; Figure 4 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 (Figure 4). Much of the central South will likely see decreases of about 5%, while some northern central and eastern U.S. regions are projected to experience increases of 5-15%. The seasonality of precipitation is also an important factor for agriculture, particularly in western regions that rely on winter snow accumulation and gradual release of water stored in snowpack throughout the spring and summer.

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 increased 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.

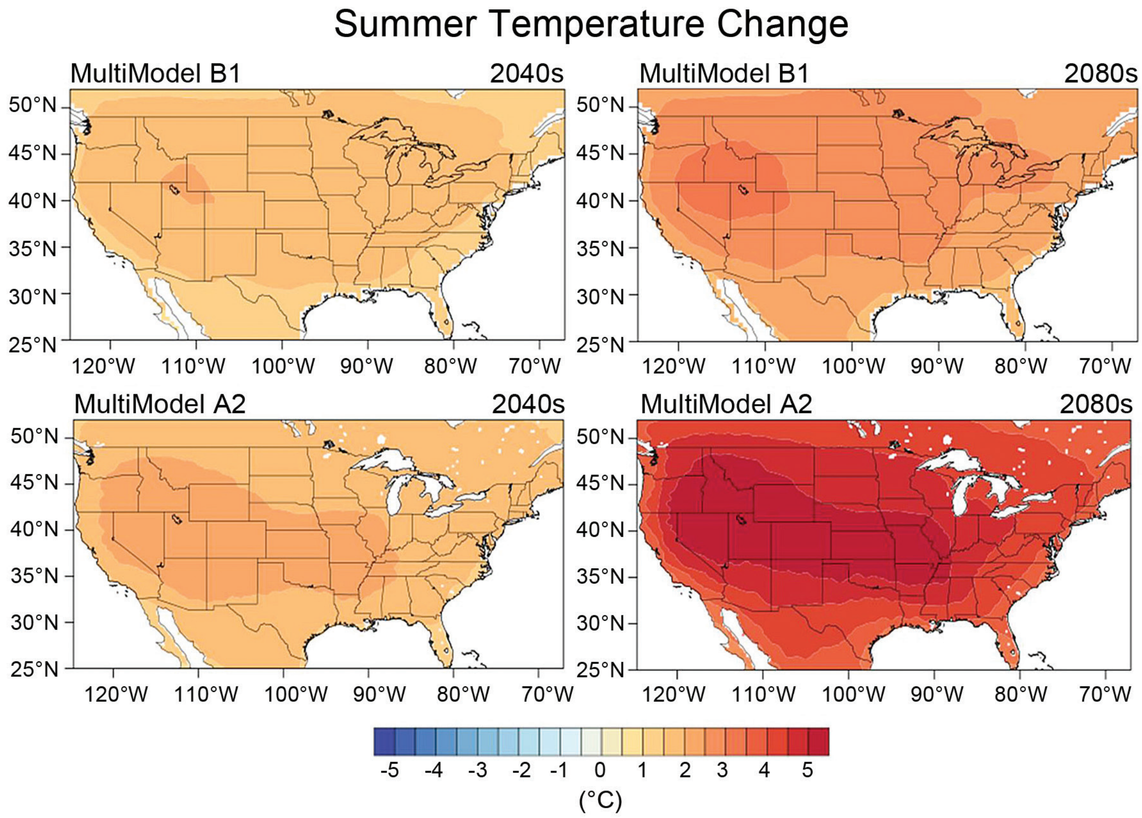


Figure 3. *Summer surface temperature projections for a low-emissions scenario (top panels) and a high-emissions scenario (bottom panels). Left panels show the changes for 2040s (averaged over 2025-2055), right panels are for 2080s (average of 2071-2100). Projections are based on a 16-model ensemble of 21st century climate change, statistically downscaled to 12-km resolution.*

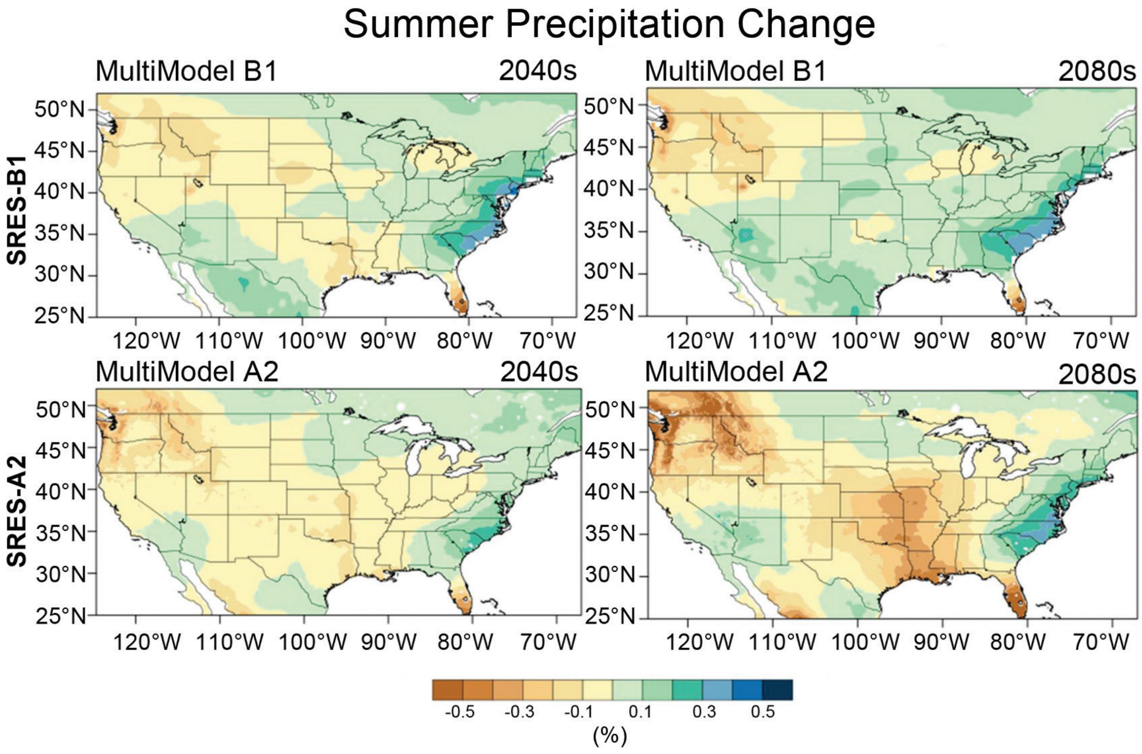


Figure 4. *Summer precipitation projections for a low-emissions scenario (upper panels) and a high-emissions scenario (lower panels). Left panels show the changes for 2040s (averaged over 2025-2055), right panels are for 2080s (average of 2071-2100). Projections are based on a 16-model ensemble of 21st century climate change, statistically downscaled to 12-km resolution.*

Projections for Future U.S. Hot Nights and Frost Days

There are many aspects of climate in addition to average precipitation and temperature that are important for agriculture. In a high emissions scenario, many areas of the United States are projected to see large increases in the length of the growing season by the 2080s, ranging from an extension of about 20 days through much of the upper Midwest to as much as 40 days in much of the Southwest and central California. Under this scenario, changes in mean temperatures will very likely be accompanied by significant increases in hot nights, with many parts of the United States potentially experiencing 30-40 additional hot nights by 2100 (Figure 5, bottom). In addition to a longer growing season and a greater number of warm nights, large decreases are projected in the number of frost days throughout our nation (Figure 5, top). Much of the Southeast is projected to have 10-20 fewer frost days per year, much of the Midwest 30-40 fewer frost days, and decreases of 40-50 frost days are projected for large areas of the Intermountain West.

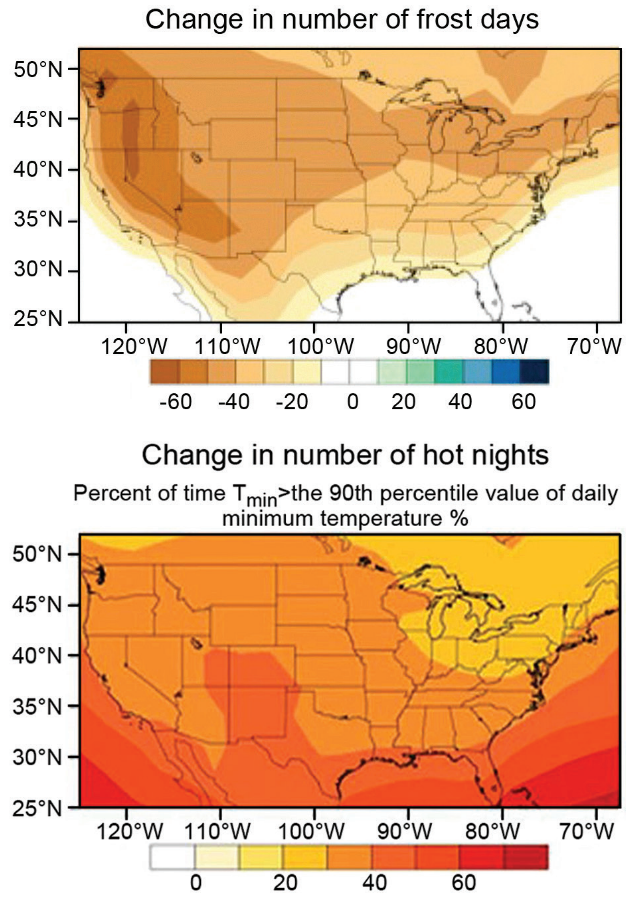


Figure 5. *Changing Numbers of Frost Days and Hot Nights: The top panel shows that the number of frost days (days with minimum temperatures below freezing) will be reduced by 20-60 days in much of the United States. The bottom panel shows increases in hot nights across the United States projected for the high-emissions scenario by the end of the 21st century; by 2100 many parts of the U.S. could experience 30-40 additional hot nights, defined as nights with a minimum temperature warmer than 90% of the minimums between 1971 and 1990.*

III. Climate Change Effects on the U.S. Agricultural System

Agricultural production systems will be affected by climate change, with effects varying across agricultural production types and regions of the United States. Rising air temperatures, changing precipitation patterns, and rising concentrations of atmospheric CO_2 are critical factors affecting growth of crops, forage, livestock, and other agricultural products. Together, these factors comprise direct effects of climate change. Equally important are indirect effects of climate change, including the consequences of changing air temperature and precipitation on non-crop species found in agroecosystems, such as insects, weeds, pathogens (microorganisms that cause disease in a host), and invasive species, as well as impacts on soils and the availability and quality of other inputs such as irrigation water. The complexity of the agricultural system's response to both direct and indirect effects of climate change makes projecting the net outcome of climate change effects challenging. Some of the current science describing direct and indirect climate effects on agriculture is presented below.

Direct Effects of Climate Change: Temperature, Precipitation, and CO_2

Temperature

Projected temperature increases in the contiguous United States will almost inevitably affect agricultural production, as all plants have minimum, maximum, and optimum temperatures that define their relationship between growth and temperature. Beyond a threshold, higher air temperatures adversely affect plant growth, pollination, and reproductive processes. This relationship is nonlinear; as air temperatures rise beyond the optimum, instead of falling at a rate commensurate with the temperature increase, negative effects on growth and grain production accelerate. Although research tends to focus on the effects of average air temperature changes on crops, changes in minimum air temperature may have greater effect because minimum temperatures are more likely to increase due to climate change over broad geographic scales. Minimum air temperatures affect nighttime plant respiration

Table 1. *This table shows the cardinal base- and optimum-temperatures (°C) for vegetative development and reproductive development, the optimum temperature for vegetative biomass, the optimum temperature for maximum grain yield, and the failure (ceiling) temperature at which grain yield fails to zero yield, for economically important crops. The optimum temperatures for vegetative production, reproductive (grain) yield, and failure point temperatures represent mean temperatures from studies where diurnal temperature range was up to 10°C.*

Crop	Base Temperature Vegetation	Optimal Temperature Vegetation	Base Temperature Reproduction	Optimal Temperature Reproduction	Optimal Temperature Range Vegetative Production	Optimal Temperature Range Reproduction Yield	Failure Temperature Reproduction Yield
Corn	8[1]	34[1]	8[1]	34[1]		18-22[2]	35[3]
Sorghum	8[16]	34[16]	8[16]	31[17]	26-34[18]	25[17,19]	35[17]
Bean					23[28]	23-24[28,29]	32[28]
Cotton	14[20]	37[20]	14[20]	28-30[20]	34[21]	25-26[22]	35[23]
Peanut	10[24]						
Rice	8[12]	36[13]	8[12]	33[12]	33[14]	23-26[13,15]	35-36[13]
Soybean	7[4]	30[4]	6[5]	26[5]	25-37[6]	22-24[6]	39[7]
Wheat	0[8]	26[8]	1[8]	26[8]	20-30[9]	15[10]	34[11]

rate, and higher minimum temperatures can reduce biomass accumulation and crop yield. However, such effects are sensitive to the natural variability of weather cycles; as minimum average temperatures increase, years with low maximum temperatures may more frequently approach the temperature optimum, which will result in higher yields than is the case today during years when average temperatures are below the optimum.

Within the range of temperature exposures during the growth cycle, one critical period of exposure to temperature extremes is the pollination stage, when pollen is released to fertilize the plant and trigger development of reproductive organs, for fruit, grain, or fiber. Exposure to high temperatures during this period can greatly reduce crop yields and increase risk of total crop failure. Plants exposed to warm nighttime temperatures during grain, fiber, or fruit production also experience lower productivity and reduced quality. Increasing temperatures cause plants to mature and complete their stages of development faster, which may create smaller plants, because soil may not be able to supply water or nutrients at required rates, thereby reducing grain, forage, fruit, or fiber production. Increasing temperatures may also increase the rate of water use by plants, causing more water stress in areas with variable precipitation.

For vegetables, exposure to temperatures in the range of 1-4°C (1.8°-7.2°F) above optimal for biomass growth moderately reduces yield; exposure to temperatures more than 5-7°C (9- 12.6°F) above optimal often leads to severe, if not total, production losses. While many agricultural enterprises have the option to respond to climate changes by shifting crop selection, development of new cultivars in perennial specialty crops commonly requires 15 to 30 or more years, greatly limiting that sector's opportunity to adapt unless cultivars can be introduced from other areas.

An increase in winter temperatures also affects perennial cropping systems through interactions with plant-chilling requirements. All perennial specialty crops have a winter chilling requirement (typically expressed as hours below 10°C (50°F) and above 0°C (32°F)), ranging from 200 to 2,000 cumulative hours. Yields will decline if the chilling requirement is not completely satisfied because flower emergence and viability will be low. Projected air temperature increases for California, for example, may fail to satisfy the chilling requirements for fruit and nut trees by the middle to end of the 21st century. For most of the U.S. Northeast, perennial crops having a lower-than-400-hour chilling requirement will continue to have these conditions met through the 21st century, but crops with prolonged cold requirements (i.e., 1,000 or more hours) could demonstrate reduced yields, particularly in southern sections of the Northeast. Climate change will also affect winter temperature variability; mid-winter warming can lead to early bud-burst or bloom of some perennial plants, resulting in frost damage if cold winter temperatures return.

Precipitation

Precipitation has a direct influence on agriculture and is projected to increase for some areas of the United States and decrease for others. Changes in the timing, intensity, and amount of rain/snow mix for a location are expected to increase the management challenge of delivering water to crops at the right time through irrigation systems and practices. Excess precipitation can lead to increased incidence of flooding events, greater erosion, and decreased soil quality, and can be as damaging to crops as too little precipitation. Temperature-induced increases in evapotranspiration can result in greater water demand by crops, leading to increased water stress even in areas where precipitation amounts increase, particularly on soils with limited soil water holding capacity. Timing of these stressors is critical; excess water during corn's early growth stages, for example, may cause a reduction in growth or even death, while soil water deficit may lead to less growth and lower yields if the stress occurs during the grain filling period of growth

The increased intensity of rainfall events projected to accompany climate change may result in disproportionately large increases in erosion through increases in rainfall's erosive power. Effects of changing climate on plant biomass will also affect rainfall-driven erosion. The mechanisms by which climate change affects biomass, and by which biomass changes affect runoff and erosion will vary across the United States due to differences in annual growth characteristics and rainfall distribution within and among years. Furthermore, climate change may be associated with regional shifts from snowfall to rainfall events. There is a general lack of knowledge about the rates of soil erosion associated with snowmelt or rain-on-thawing-soil erosion on a regional or national basis; an enhanced understanding of these process dynamics will be important to estimating the potential erosion effects of changing climate conditions and to understanding the long-term implications for soil quality and crop productivity.

As is the case with regional temperature increases, climate change effects on the intensification of the hydrologic cycle will have consequences for agricultural production and soil conservation across many U.S. regions. Many regions are projected to have increases in precipitation amounts, along with increased intensity and frequency of extreme events. Drought frequency and severity will increase, rain-free periods will lengthen, and individual precipitation events will become more erratic and intense, leading to more runoff. Rising temperatures and shifting precipitation patterns will alter crop-water requirements, crop-water availability, crop productivity, and costs of water access, resulting in differential effects across the agricultural landscape. The resulting shift in crop competitiveness, in turn, will drive changes in cropland allocations and production systems. Regional production effects will depend on climate-induced changes to hydrologic systems and on the sensitivity of current cropping systems to changes in water requirements and water availability.

Carbon Dioxide Concentrations

Carbon dioxide concentrations in the atmosphere have increased rapidly since measurements began in 1958. The effects of enhanced atmospheric CO_2 concentrations on crop growth are complex and variable across species. Higher CO_2 levels typically increase growth, but due to differences in photosynthetic biochemistry, plants with the C_3 photosynthetic pathway (about 95% of all plant species) are likely to respond more strongly than plants possessing the C_4 photosynthetic pathway. In addition to production quantity, quality of agricultural products may be altered by elevated CO_2. Where elevated CO_2 results in reduced nitrogen content, for instance, grain products may yield reduced quality feed stocks or forage.

Controlled experiments show that elevated CO_2 concentrations can increase plant growth while decreasing soil water-use rates. The magnitude of the growth stimulation effect of elevated CO_2 concentrations under field conditions, however, in conjunction with changing water and nutrient constraints, is uncertain. The effects of elevated CO_2 on water-use efficiency may be an advantage for areas with limited precipitation, with other changing climate conditions potentially offsetting or complementing such effects. Warming temperatures, for instance, will act to increase crop water demand and reducing available soil moisture through evaporation from the surface, reducing the moisture available for growth, even with improved water-use efficiencies.

The projected benefits of rising CO_2 on crop yields may be overly optimistic if they are based on models that do not include other important confounding factors. Ground level ozone, for instance, is a pollutant that is generally produced in cities but that can be transported hundreds of miles into rural areas and that has a well-documented negative impact on crop yields. Changes in ground-level ozone may offset some of the yield gains associated with elevated CO_2 concentrations, though some research suggests that increases of atmospheric CO_2 may also lessen ozone injury (the interaction becomes less effective as ozone concentrations increase). While not a direct consequence of climate change, changes in ground-level ozone concentrations are one important air quality consideration in long-term crop yield projections.

Indirect Climate Change Effects: Weeds, Invasive Species, and Insects

Changes in temperature, precipitation, and CO_2 also have indirect effects on agricultural productivity as a result of changes in disease occurrence and in insect and weed populations. Conditions favorable to the growth in population and range of these pests may add pressure to the agricultural production system, potentially increasing economic losses in crop and animal production.

Weeds (both native and invasive species) compete with primary agricultural crop and livestock production and have long been rivals in U.S. agroecosystems. Weeds cause the highest crop losses globally (34%), with insect pests and pathogens showing losses of 18% and 16%, respectively. Weeds can reduce crop yield through competition for light, nutrients, and water; by reducing production quality; by increasing problems during harvest; or acting as hosts for other pest vectors. Crop productivity and costs of production will therefore be significantly affected by adjustments in the relationship between crop and weeds under changing climate conditions. Research has documented cases where elevated atmospheric levels favor the growth of weeds over the growth of the crop species with which they compete, resulting in increased pest pressure (Table 2).

Non-native weeds (invasive species) are characterized by high vigor and fast growth and may be particularly suited to capitalizing on the changes in growing conditions arising from climate change. Fast-growing weeds, for instance, respond particularly strongly to elevated CO_2. Controlled studies have not consistently demonstrated a stronger CO_2 response in invasive compared to non-invasive plants; however, in field studies that incorporate competition with native plants, elevated CO_2 has been found to increase invasion in grasslands, desert, and forests. CO_2 also increases plant water use efficiency, and may be most likely to favor invasion in water-limited ecosystems, as seen in the Nevada desert.

Table 2. *Summary of studies examining whether weed or crops grown in competition were "favored" as a function of elevated concentrations of CO_2. "Favored" indicates whether elevated CO_2 concentrations – i.e., $[CO_2]$ – produced significantly more crop or weed biomass.*

Crop	Weed	Increasing $[CO_2]$ Favors	Environment
A. C_4 Crops / C_4 Weeds			
Sorghum	*Amaranthus retroflexus*	Weed	Field
B. C_4 Crops / C_3 Weeds			
Sorghum	*Xanthium strumarium*	Weed	Glasshouse
Sorghum	*Albutilon theophrasti*	Weed	Field
C. C_3 Crops / C_3 Weeds			
Soybean	*Cirsium arvense*	Weed	Field
Soybean	*Chenopodium album*	Weed	Field
Lucerne	*Taraxacum officinale*	Weed	Field
Pasture	*Taraxacum and Plantago*	Weed	Field
Pasture	*Plantago lanceolate*	Weed	Chamber
D. C_3 Crops / C_4 Weeds			
Fescue	*Sorghum halapense*	Crop	Glasshouse
Soybean	*Sorghum halapense*	Crop	Chamber
Rice	*Echinochloa glabrescens*	Crop	Glasshouse
Soybean	*A. retroflexus*	Crop	Field

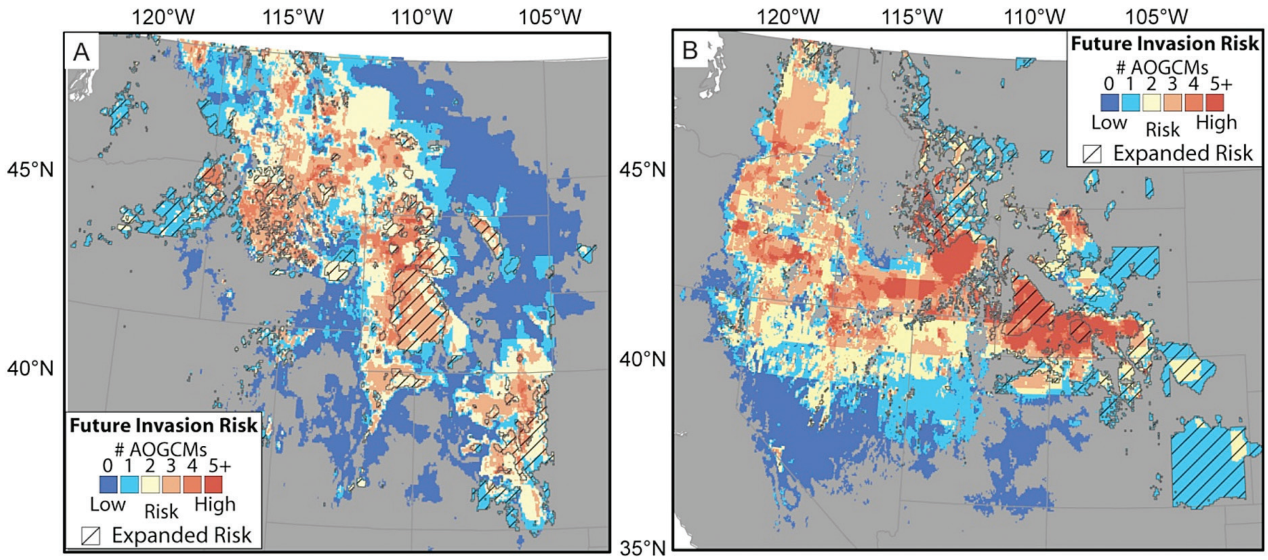


Figure 6. *Biogeographical models project range shifts in invasive plant distribution, creating both areas of increased and decreased risk. Colors show future climatically suitable regions for invasive plant species according to climate projections for the year 2100 from 10 Atmosphere-Ocean General Circulation Models (AOGCMs) under the IPCC A1B future climate scenario. Warmer colors represent greater overlap of AOGCM projections, increasing confidence in future risk. Hatched areas show regions that are currently unsuitable, but become suitable in at least one projection.*

Plant diseases are an important part of the agricultural system, and plant pathogen responses to climate change must be considered together with effects on the host, the environment, and disease vectors, where pathogens are vector borne. Changes in climate will affect both crops and their pathogens, for instance, and understanding these changes will be critical to avoiding increased losses in crop productivity. Plant pathogens and their vectors are influenced by a web of interactions that make predictions regarding their movement, incidence, severity, and evolution in response to climate change very complex. Nevertheless, range expansion has been predicted for many crop pathogens based on models that incorporate changes in crop distribution and requirements for pathogen survival and reproduction.

Yield and quality losses caused by pathogen epidemics are influenced by increased CO_2 concentrations, increased temperatures, altered rainfall patterns, drought, regional changes in cropped areas and ranges, and changes in vector activity. 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. The effects of such changes on the frequency and duration of outbreaks will vary depending on the pathogen involved and geographic location. 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 affect plant pathogen epidemics. When occurring in combination, these events may not simply be additive, but may amplify the effects of climate change on agroecosystems. For example, under changing climate the rate of spread of contact-transmitted viruses may be accelerated to a greater degree than would otherwise be the case in the event of plant damage arising from intense storms with torrential rainfall, or hail and high winds.

Insects also have a range of critical temperatures for survival, reproduction, and range expansion. 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. This, in addition to the effects on population growth, leads to more rapid resistance to insecticides. The extension of the growing season has a strong effect on the demands (i.e., feeding pressure) that insects make on host plants.

Often overlooked are the effects of climate on the quality of agricultural products; effects of elevated CO_2

on grain and fruit yield and quality, for example, are mixed. Exposure to high temperatures often affects crop quality; when examining potential adaptation strategies, such effects must be addressed along with the other effects on growth and development (i.e., yield quantity).

Crops will continue to be subjected to increasing temperatures, increasing CO_2, and more variable water availability. These factors interact in their effect on plant growth and yield. A balanced understanding of the consequences of management actions and genetic responses to these factors will form the basis for more resilient production systems to climate change. Due to the complexities of these relationships, integrated research and development of management practices, plant genetics, hydrometeorology, socio-economics, and agronomy are necessary to enable successful agricultural adaptation to climate change.

Climate Change and Animal Agriculture

Equally important are the direct and indirect effects that changing climate will have on animals, which make up half of the total production value of U.S. agriculture. Shifts in climatic conditions affect animal agriculture in four primary ways, through change in 1) feed-grain production, availability, and price, 2) pastures and forage crop production and quality, 3) animal health, growth, and reproduction, and 4) disease and pest distributions. Implications for potential adaptive responses to climate change include utilization of different species and genotypes of animals and forages, changes in facilities utilized for care and management of livestock, and a redistribution of livestock in a region. Greater concerns exist with regard to climate change on animals managed in unsheltered environments. The majority of American domestic livestock managed in extensive outdoor facilities are ruminants (goats, sheep, and beef cattle). Within limits, these animals can adapt to and cope with gradual thermal challenges. However, the rate at which environmental conditions are projected to change, the extent to which animals are exposed to extreme conditions, and the inability of animals to adequately adapt to sudden and/or dramatic environmental changes are a concern. Lack of prior conditioning to rapidly changing or adverse weather events often results in catastrophic deaths in domestic livestock and losses of productivity in surviving animals. Animal phenotypic and genetic variation, management factors (facilities, stocking rates, and nutrition), physiological status (stage of pregnancy, stage of lactation, growth rate), age, and previous exposure to environmental conditions influence the effects of adverse environmental conditions. In addition, reduced nitrogen and protein content observed in some nitrogen-fixing plants causes a reduction in grain and forage quality because the growth rate exceeds the plant's ability to extract nitrogen from the soil. This reduces the ability of pasture and rangeland to support grazing livestock.

The 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. Ambient environmental conditions directly affect mechanisms and rates of heat gain or loss by all animals. In many species, 5-7ºC (9-12.6°F) deviations from core body temperature can cause significant reductions in productive performance and may lead to death.

IV. Climate Change Effects on the Economics of U.S. Agriculture

The biophysical effects of climate change on yields and production costs vary by region and have the potential to significantly alter patterns of agricultural productivity in the provision of food, feed, fiber, and fuel products worldwide. The economic implications of those shifts will be 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.

Agricultural production is chronically vulnerable to stress factors like dry spells, weed competition, insect damage, and disease outbreaks. Local farm production patterns and practices have evolved in response to weather conditions and stress factors that have historically prevailed for that region. As growing conditions and stress factors change, so will farm production decisions. 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 other regions where climate change creates expanded opportunities for production.

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. Changing patterns of comparative advantage in response to climate change will occur both regionally within the United States and

globally across nations. U.S. and global agricultural markets are highly interconnected; trade therefore links the production impacts and decisions made domestically to those made around the world. As a result, the economic implications of climate change for the United States will be sensitive to yield effects and adaptation opportunities and constraints both within the United States and worldwide.

A wide array of stakeholders feels the economic impacts of climate change. Farmers are affected by initial yield and production cost effects, which they respond to through adaptive strategies; they are further impacted by price effects emerging from market adjustments made in response to widespread changes in productivity and adaptive behaviors. Consumers are affected by market price changes and also have adaptation options, including changing consumption patterns to substitute relatively lower priced products for products that have become higher priced due to the effects of changing climate.

Several studies of climate change effects within the United States have suggested that, in the short term, moderate levels of climate change will increase crop yields on average, resulting in net positive estimates of welfare change in the United States. Such aggregate impact estimates often mask considerable variability across demographics and regions, both within the United States and worldwide. In fact, the net effects of climate change on average U.S. yields will vary by crop and region and be sensitive to regional shifts in crop acreage and irrigation practices that arise through market adjustments, such as price and demand effects. Economic impact assessments are also highly sensitive to the emissions and climate projection selected; use of more extreme climate model projections of regional temperature and precipitation changes, even those associated with moderate emissions assumptions may result in declines in annual net returns to crop production in agriculturally important regions like the Corn Belt and, in aggregate, at the national level.

Furthermore, existing assessment research does not fully capture potential crop-yield effects of climate change, even in the short term. Most studies incorporate the effects of average temperature and precipitation (or the highly uncertain impacts of CO_2 fertilization), while excluding the potential effects on yield from factors such as ozone exposure and solar radiation. In addition, assessments rarely consider effects of indirect stress factors, such as changes in pest, weed, and disease pressure, arising from community-scale, agro-ecological adjustments to changing climate. Such uncertainty about effects on crops translates into substantial uncertainty about economic impacts as well.

Economic impact estimates are also sensitive to the scope of the economic analysis, including:

- Whether research considers interactions among sectors (such as agriculture and forestry) in estimating the impact and response to climate change;
- Whether international climate change effects and farmer or consumer behavior changes are included;
- The extent to which potential adaptation responses (or constraints to those responses) are estimated; or
- Whether adjustment and transition costs are included as part of impact estimates.

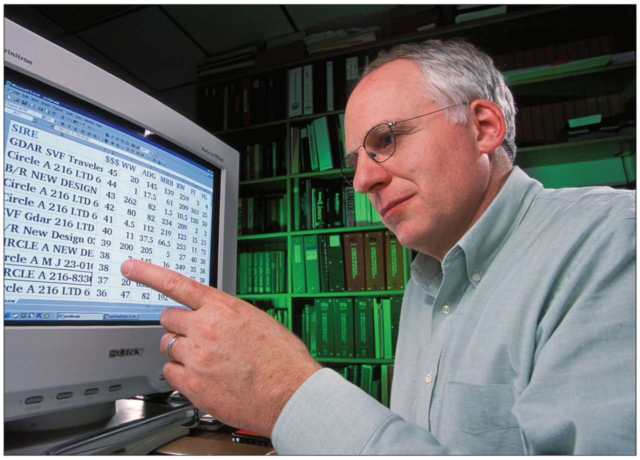
For instance, the migration of crop production in response to climate change has been recognized as a likely adaptation mechanism since the early days of integrated assessment modeling. Nevertheless, constraints on the regional capacity for expanding agriculture or irrigated production – such as the availability of land and water – have been recognized but not widely incorporated into impact estimates. Furthermore, most existing sector-level impact assessments fail to take into account the costs associated with transitioning from the current agriculture structure to a future one induced by changing climate conditions – including, for instance, the costs of developing the transportation, distribution, and irrigation infrastructure necessary to support new patterns of agricultural production. However, it has been argued that adjustment costs are likely to be a large element of cost in response to climate change.

Due to data and model limitations, economic impact studies generally do an inadequate job of addressing induced impacts of climate change such as changes in the environmental impact of agricultural production. Potential environmental effects are associated with both intensification of agriculture and expansion of cropland that may occur in response to changing patterns of productivity. Identifying and incentivizing the adoption of management practices that deal effectively with climate change-related challenges, such as shifting diseases and pests and increased incidence of flooding and other extreme events, will be a critical and challenging element of a sustainable agricultural adaptation strategy for climate change. Environmental effects may also be reduced through adaptation and technological or agronomic advancements that result in increased yields per acre.

While much of the existing research on climate change effects explores changes in seasonal or monthly averages of growing conditions, attention is increasingly turning in both biophysical and economic research arenas to the potential impacts of changes in the timing and variability of climate conditions, with particular attention to the incidence of extreme events such as drought or flooding. The regions affected by extreme events vary across the years both in economic impact and spatial extent, but some evidence exists that the United States is already experiencing an increased incidence of extreme weather events. A compilation of the economic impact of extreme events with an economic impact in excess of $1 billion shows an increase in estimated economic damage from such extreme events over the last 30 years.

For example, an analysis of crop insurance payments from Iowa suggests a recent increase in the relative fraction of payments due to excessive wetness/flood and drought; such changes may be an indicator that Iowa is already experiencing changes in frequency of extreme wet and dry periods with implications for agricultural production. Other patterns observed in Iowa, such as a decline in workable field days during the planting season and a rapid increase in soil erosion as daily rainfall exceeds critical thresholds, provide a glimpse into additional implications of the increased incidence of extreme events for agriculture and its impacts. More intense rainfall events are likely to cause more erosion events unless improved conservation practices (e.g., residue cover, reduced tillage, installed waterway conduits) are adopted to reduce rain energy, protect soil, and reduce runoff. Some estimates suggest that under climate change, losses to corn production in the United States from precipitation extremes are expected to increase substantially and by 2030 could total $3 billion per year. Such events may represent critical economic thresholds for farming operations and compromise their ability – and the ability of the agriculture sector as a whole – to engage in long-term adaptation.

Developing economic-impact estimates for climate change requires input from disciplines as diverse as climate, crop, and soil science, as well as the tools and data to represent a wide variety of potential adaptive and economic behaviors. While research is advancing, there remains a high degree of uncertainty in estimating the economic impacts of climate change. Estimates of aggregate economic impacts of climate changes often mask considerable variability across demographics and regions, both within the United States and worldwide. While studies have consistently suggested that climate change is not a food security risk for the United States and other developed countries in the near to medium term, concerns are more acute for other regions of the world. 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. Even in the short-term, climate change will likely increase the incidence of global hunger through effects on the world's poorest and most at-risk populations.



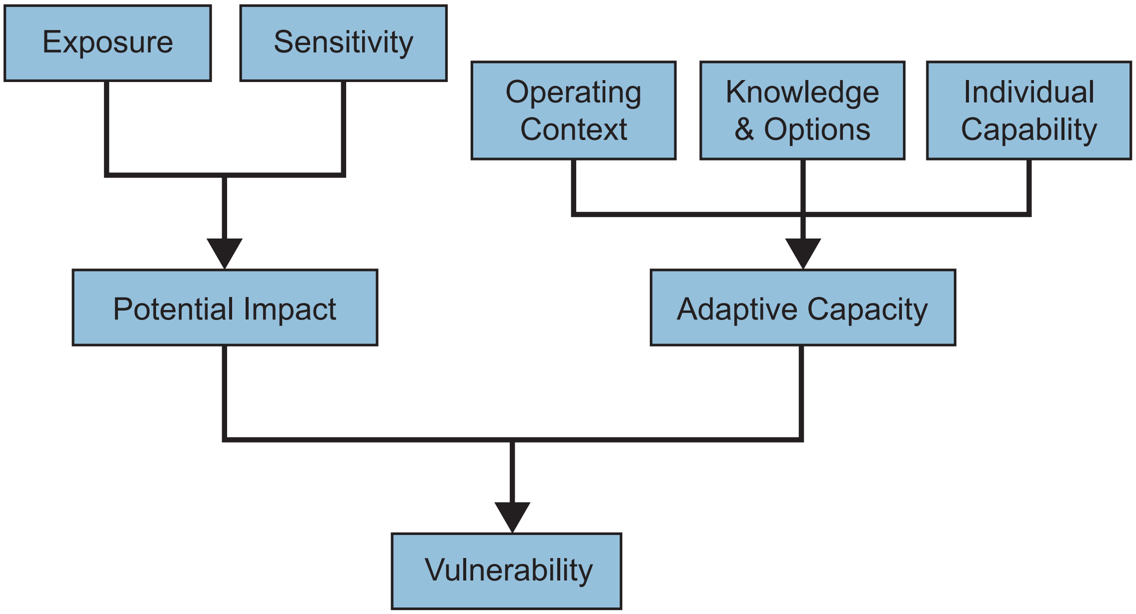
In the longer term, continuing changes in climate conditions are likely to affect the ability of the U.S. agricultural system to adapt using existing technologies without significant disruptions to elements of the agricultural system such as producer welfare, consumer welfare, or the ecosystem services that support – and are affected by – agricultural production. Agricultural adaptation to climate change is challenged by the increasing pace of change, the complex interactions between the global climate system and the agricultural system, and the complexity of adaptation processes. Strengthening adaptive capacity at multiple levels within the agricultural sector will be necessary to address the challenges of climate change.

V. Adapting Agriculture to Climate Change

U.S. agriculture has demonstrated a remarkable adaptive capacity over the last 150 years. Crop and livestock production systems expanded across a diversity of growing conditions and responded to dynamic changes in agricultural knowledge, technology, markets, and, most recently, public demands for sustainable production of agricultural products. This adaptive capacity has been supported in large part by public sector investment in agricultural research, development, and extension activities made during a period of climatic stability and abundant technical, financial, and natural resource availability. Adaptive behaviors can occur within different sectors of the U.S. agricultural system. Adaptation at the enterprise level may involve, expansion or intensification of production or a change in the kinds of crops or livestock produced. Broader scale adaptation may occur at the market level through changing patterns of trade and consumption, and at the policy level through programs that spread risk and support adaptive responses by agricultural stakeholders.

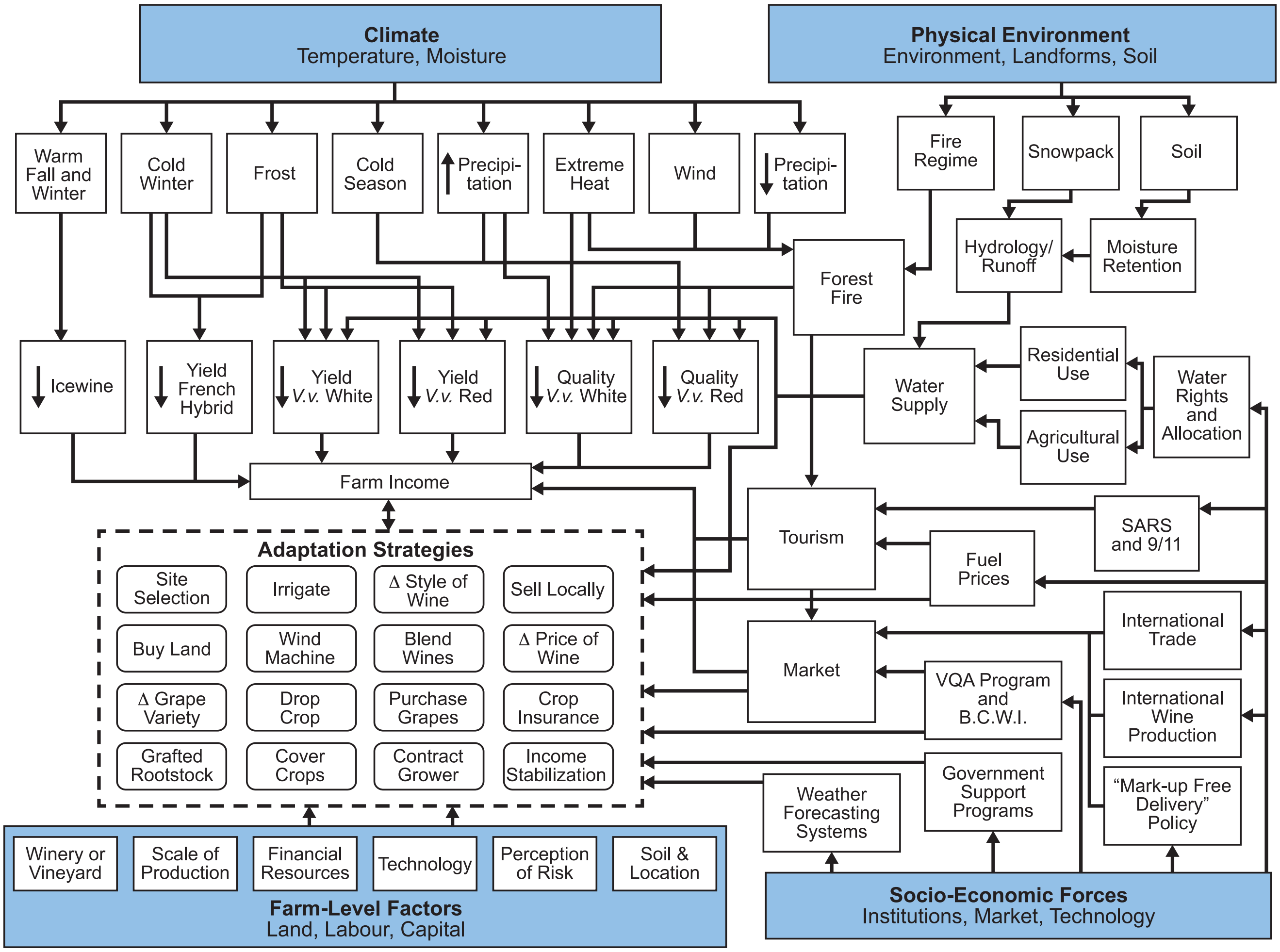
Climate change presents an unprecedented challenge to the adaptive capacity of U.S. agriculture. Current climate change effects are increasing the complexity and uncertainty of agricultural management. Projected climate changes over the next century may require major adjustments to production practices, particularly for production systems operating at their marginal limits of climate. Because agricultural systems are human-dominated ecosystems, the vulnerability of agriculture to climatic change is strongly dependent not just on the biophysical effects of climate change, but also on the responses taken by humans to moderate those effects within the United States and worldwide. Effective adaptive action taken by decision makers operating throughout the U.S. agricultural system – on farms and ranches, in agribusiness, and in government – offer the potential to minimize the cost and capitalize on the opportunities presented by a changing climate.

Figure 7. *Linked human and biophysical factors that determine the ultimate vulnerability of agriculture systems to climate change.*



Vulnerability and adaptive capacity, characteristics of human and natural systems, are dynamic and multidimensional, and are influenced by complex multiscale interactions among social, economic, and environmental factors. The vulnerability of a system to climate change is defined by two key characteristics of the system: the potential effects on the system and the system's adaptive capacity (Figure 7). The potential influence of climate on the system is a function of the exposure to climate effects and the sensitivity of the system to those effects. Adaptive capacity describes the ability of the system to cope, adapt, or recover from the effects of climate change. The adaptive capacity of a system is shaped by the operating context within which decisions are made (for example, existing natural resource quality and non-climate stressors, government policy and programs), access to effective adaptation options, and the individual capability to take adaptive action. Taking adaptive action requires stakeholders to make decisions about the system under their management despite the novel uncertainties created by climate change. The place-based nature of adaptation adds additional complexities to adaptive responses and suggests the development of local, context-specific adaptive options rather than prescriptive solutions (Figure 8). Research and development of adaptation planning in agriculture aims to provide agricultural decision-makers with effective methods to assess the vulnerability of the systems under their management, to guide the selection and implementation of adaptation options, and to manage dynamic systems in a complex decision environment.

Figure 8. *A schematic framework of the multiscale factors influencing production-level vulnerability to climate change of grape growers and winery operators in the Okanagan Valley of Canada. This framework provides specific examples of the socio-economic forces interacting with local climate, landscape and enterprise level factors to drive adaptation responses in the agricultural system.*



An emerging approach to adaptation planning employs a spectrum of management intention and action – resistance, resilience, and transformation – that describes a successively greater change in the adaptive capacity of the agricultural system. Resistance strategies seek to maintain the status quo in the near term through management actions that resist climate change disturbance but do not increase the adaptive capacity of the system. Resistance strategies can be costly, will likely increase in cost and difficulty over time, and may ultimately fail as climate change effects intensify. Resilience strategies are typically actions that increase the adaptive capacity of the agroecosystem. These strategies seek to manage climate-related disturbances by enhancing the ability of the agroecosystem to moderate climate effects and to return to a healthy condition after a disturbance, either through natural processes or with minimal management intervention. Transformation strategies facilitate the transition of the existing agroecosystem to a new agroecosystem with a different structure and function better suited to sustained production under rapidly changing climate conditions.

This resistance-resilience-transformation framework is applied to climate risk management in U.S. national forests, defines adaptation options in the National Fish, Wildlife, and Plants Climate Adaptation Strategy, and has been recommended for use as an ecosystem-based approach to agricultural adaptation to climate change. Research and programmatic efforts to better understand and manage agricultural ecosystem resilience and stability in the face of climate change are explicit in the strategic goals and climate change adaptation planning effort at multiple agencies within USDA.

Adaptation strategies in use today by U.S. farmers coping with current changes in weather variability and a lengthening growing season include changing cultivar selection or timing of field operations, and increased use of pesticides to control higher pest pressures. Adaptation options for managing novel crop pest management challenges may involve new strategies for preventing rapid evolution of pest resistance to chemical control agents, the development of new pesticide products and improved pest and disease forecasting. Adaptation options that increase the resilience of agricultural systems to increased pest pressures include crop diversification and the management of biodiversity at both field and landscape scale to suppress pest outbreaks and pathogen transmission. Research on adaptation planning to increase the resilience of agriculture in California's Central Valley found that an integrated set of changes in crop mix, irrigation methods, fertilization practices, tillage practices, and land management was the most effective approach to managing projected climate risks in the near term. Given the projected effects of climate change, some U.S. agricultural systems, such as those currently operating at their southern marginal limit or those that currently depend on irrigation, will have to undergo more transformative changes to remain productive and profitable. These changes would involve a shift to a new product mix requiring substantial adjustments in management skills, field equipment, farm infrastructure, and/or marketing requirements.

Adaptation measures such as developing crop and livestock production systems robust to drought, pest, and heat stress, diversifying crop rotations, integrating livestock with crop production systems, improving soil quality, minimizing off-farm flow of nutrients and pesticides, and other practices typically associated with sustainable agriculture may increase the capacity of the agricultural system to remain productive under climate change. For example, drought and heat stress-resistant crops and livestock may improve the ability of farmers and ranchers to cope with the increases in variability of temperature and precipitation projected through mid-century. Similarly, production practices that enhance the ability of healthy soils to regulate water resource dynamics at the farm and watershed scales will be particularly critical for the maintenance of crop and livestock productivity under conditions of variable and extreme weather events. Enhancing the resilience of agriculture to climate change through adaptation strategies that promote the development of sustainable agriculture is a common multiple-benefit recommendation for agricultural adaptation planning.

National Agricultural Adaptation Planning

National agricultural adaptation planning has begun in the United States and elsewhere. Broad policy measures that may enhance the adaptive capacity of agriculture include strengthening climate-sensitive assets, integrating adaptation into relevant government policies, and addressing non-climate stressors that degrade adaptive capacity. Because of the uncertainties associated with climate change effects on agriculture and the complexity of adaptation processes, adaptive management strategies that facilitate the regular evaluation and revision of adaptation plans will help to ensure that agricultural systems remain productive under climate change. The need to move ahead with adaptation planning despite many uncertainties has driven research to develop robust adaptation strategies. Among these strategies, "no-regrets" adaptations may be of particular utility to agriculture. These are adaptations that are both cost effective under current climate conditions and are likely to reduce specific risks associated with projected climate change effects. Synergies between mitigation and adaptation planning are also possible through the use of coherent climate policy frameworks that link issues such as carbon sequestration, greenhouse gas emissions, land-use change, regional water management, and the long-term sustainability of agricultural production systems.

High adaptive capacity does not guarantee successful adaptation to climate change. The limits and barriers to adaptation – some ecological and natural resource-based, others arising from social and cultural considerations that complicate adaptation efforts – add uncertainty to the adaptation process. As a result of these limits, the capacity for adaptation and the processes by which it occurs vary greatly within and across economic sectors, communities, regions, and countries. Differential capacity for adaptation, together with the variable effects of climate change on agroecosystem function, creates significant concerns about agricultural productivity and food security.

VI. Research Needs

Agricultural research has contributed greatly to the success of U.S. agriculture, providing producers and scientists with a better understanding of the effects of change on the agroecosystem and helping foster the system's adaptive capacity. *USDA Technical Bulletin 1935* explores research needs in detail, addressing specific actions that would serve to improve understanding and management of the exposure, sensitivity, and adaptive capacity of U.S. agriculture to climate change. Focus on these research needs would enhance the ability of the U.S. agriculture sector to anticipate and respond to the challenges presented by changing climate conditions. Among the high-level research requirements identified that might aid decision making and improve existing understanding of the effects of climate change on the U.S. agricultural system are:

- Improvements to projections of future climate conditions for time scales of seasons to multiple decades at a regional level, including more precise information about changes of average and extreme temperatures, precipitation, and related variables (e.g., evapotranspiration, soil moisture);

- Improved treatment of yield and return variability and risk assessment in economic impact analysis;

- Improved understanding of the potential costs, constraints, and obstacles to adaptation, including technology, finance, information, natural, and other resource limitations;

- Evaluations of the sensitivity of diverse plant and animal production systems to key direct and indirect climate change effects and their interactions;

- Development and application of the knowledge, management strategies and tools needed by U.S. agricultural stakeholders to enhance the adaptive capacity of plant and animal production systems to climate variability and extremes.

VII. Conclusions

Agriculture in the United States has followed a path of continual adaptation to a wide range of factors driving change both from within and outside of agricultural systems. As a result, agriculture in the United States over the past century has steadily increased its productivity and integration into world markets. However, observational evidence, supported by an improved understanding of the climate system, shows that human-induced climate change is underway.

The United States, along with much 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 over the next century. Expected increases in frequency, duration, and intensity of weather events driven by changing climate present novel and unprecedented challenges to U.S. agriculture.

Climate and climate change affect agriculture directly through the immediate effects of temperature, precipitation, and CO_2. The growth and development of crops, rangelands, and livestock are also influenced indirectly by climate change, through its effects on incidence of disease and range and vigor of weed and insect populations, together with climate effects on the natural resources, such as soil and water, upon which agriculture depends. These variables interact with one another to further influence agricultural outcomes.

Over the short term, the existing adaptive capacity of the U.S. agricultural system will likely enable it to respond to climate changes in ways that partially offset the damaging effects of climate change, while taking advantage of new opportunities that may arise through changing climate conditions. Economic impact research suggesting that domestic agricultural markets and producer and consumer welfare will remain relatively stable in the short-term despite changing climate conditions usually assumes that producers take successful adaptive actions, such as those described in the preceding sections of this report, and in greater detail in *USDA Technical Bulletin 1935*. While such studies can be interpreted to suggest that the United States has a couple of decades – a “buffer period” – before the effects of climate change will be sufficiently intense to create large disruptions in the agricultural system, such results must be interpreted in the context of recognized limits to their analyses. Most existing climate change impact studies, for instance, are limited in scope, relying on an assessment of only one or two direct yield effects, while excluding indirect effects and interactions between effects, such as changes in pest and disease pressures that can significantly decrease productivity and increase management costs in crops and livestock.

Moreover, an inherent disconnect exists between U.S. agricultural producers and managers' needs related to climate-driven problems and the information that research offers them. In the past, agricultural research into climate change effects has largely focused on mean values of precipitation and temperature. Today's management requirements, however, often demand immediate response on shorter time scales to address abrupt, often novel needs. Further complicating this reality, future decisions will likely require even greater emphasis on managing under increasing levels of uncertainty, and planning for and adjusting to the extremes. Research must better address these emerging issues for the relevant timescales and parameters in order to allow the formulation of improved and resilient management strategies that apply to a future in which past experience has become less applicable.

Extension of climate knowledge through education has been proposed as a core adaptation strategy in agriculture as well as many other economic sectors. Extending climate knowledge improves adaptive capacity of the agricultural system by ensuring that land managers, technical advisors, researchers, private businesspeople, government program managers, and policymakers are aware of current and projected effects of climate change and can access best management practices to reduce risks and capture opportunities. Taking such a comprehensive climate risk management approach to agricultural adaptation offers great potential to promote effective adaptive action by decision makers throughout the multiple dimensions of U.S. agriculture. A climate-ready U.S. agricultural system requires easy access to useable climate knowledge and technical resources, improved climate risk management strategies, new processes to support effective adaptive actions, and the development of sustainable production systems resilient to climate effects.