CHAPTER 13

CLIMATE CHANGE AND AGRICULTURE IN THE UNITED STATES

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CHAPTER SUMMARY

It is likely that climate changes and atmospheric CO_2 levels,as defined by the scenarios examined in this Assessment,will not imperil crop production in the US during the 21st century. The Assessment found that,at the national level,productivity of many major crops increased. Crops showing generally positive results include cotton,corn for grain and silage,soybeans,sorghum,barley, sugar beets, and citrus fruits. Pastures also showed increased productivity. For other crops including wheat, rice, oats,hay, sugar cane,potatoes,and tomatoes,yields are projected to increase under some conditions and decline under others.

Not all agricultural regions of the United States were affected to the same degree or in the same direction by the climates simulated in the scenarios. In general the findings were that climate change favored northern areas. The Midwest (especially the northern half), West,and Pacific Northwest exhibited large gains in yields for most crops in the 2030 and 2090 timeframes for both of the two major climate scenarios used in this Assessment,Hadley and Canadian. Crop production changes in other regions varied,some positive and some negative, depending on the climate scenario and time period. Yields reductions were quite large for some sites, particularly in the South and Plains States, for climate scenarios with declines in precipitation and substantial warming in these regions.

Crop models such as those used in this Assessment have been used at local, regional,and global scales to systematically assess impacts on yields and adaptation strategies in agricultural systems,as climate and/or other factors change. The simulation results depend on the general assumptions that soil nutrients are not limiting,and that pests,insects,diseases, and weeds,pose no threat to crop growth and yield. One important consequence of these assumptions is that positive crop responses to elevated CO_2, which account for one-third to one-half of the yield increases simulated in the Assessment studies, should be regarded as upper limits to actual responses in the field. One additional limitation that applies to this study is the models'inability to predict the negative effects of excess water conditions on crop yields. Given the "wet"nature of the scenarios employed,the positive responses projected in this study for rainfed crops,under both the Hadley and Canadian scenarios,may be overestimated.

Under climate change simulated in the two climate scenarios,consumers benefited from lower prices while producers'profits declined. For the Canadian scenario,these opposite effects were nearly balanced, resulting in a small net effect on the national economy. The estimated $4-5 billion (in year 2000 dollars unless indicated) reduction in producers' profits represents a 13-17% loss of income,while the savings of $3-6 billion to consumers represent less than a 1% reduction in the consumers food and fiber expenditures. Under the Hadley scenario,producers'profits are reduced by up to $3 billion (10%) while consumers save $9-12 billion (in the range of 1%). The major difference between the model outputs is that under the Hadley scenario, productivity increases were substantially greater than under the Canadian, resulting in lower food prices to the consumers'benefit and the producers' detriment.

At the national level,the models used in this Assessment found that irrigated agriculture's need for water declined approximately 5-10% for 2030 and 30-40% for 2090 in the context of the two primary climate scenarios,without adaptation due to increased precipitation and shortened crop-growing periods.

A case study of agriculture in the drainage basin of the Chesapeake Bay was undertaken to analyze the effects of climate change on surface-water quality. In simulations for this Assessment,under the two climate scenarios for 2030,loading of excess nitrogen into the Bay due to corn production increased by 17-31% compared with the current situation.

Pests are currently a major problem in US agriculture. The Assessment investigated the relationship between pesticide use and climate for crops that require relatively large amounts of pesticides. Pesticide use is projected to increase for most crops studied and in most states under the climate scenarios considered. Increased need for pesticide application varied by crop – increases for corn were generally in the range of 10-20%; for potatoes,5-15%;and for soybeans and cotton,2-5%. The results for wheat varied widely by state and climate scenario showing changes ranging from approximately

–15 to +15%. The increase in pesticide use results in slightly poorer overall economic performance, but this effect is quite small because pesticide expenditures are in many cases a relatively small share of production costs.

The Assessment did not consider increased crop losses due to pests, implicitly assuming that all additional losses were eliminated through increased pest control measures. This could possibly result in underestimates of losses due to pests associated with climate change. In addition, this Assessment did not consider the environmental consequences of increased pesticide use.

Ultimately, the consequences of climate change for US agriculture hinge on changes in climate variability and extreme events. Changes in the frequency and intensity of droughts, flooding, and storm damage are likely to have significant consequences. Such events cause erosion, waterlogging, and leaching of animal wastes, pesticides, fertilizers, and other chemicals into surface and groundwater.

One major source of weather variability is the El Niño/Southern Oscillation (ENSO). ENSO effects vary widely across the country. Better prediction of these events would allow farmers to plan ahead, altering their choices of which crops to plant and when to plant them. The value of improved forecasts of ENSO events has been estimated at approximately $500 million per year. As climate warms, ENSO is likely to be affected. Some models project that El Niño events and their impacts on US weather are likely to be more intense. There is also a chance that La Niña events and their impacts will be stronger. The potential impacts of a change in frequency and strength of ENSO conditions on agriculture were modeled. An increase in these ENSO conditions was found to cost US farmers on average about $320 million per year if forecasts of these events were available and farmers used them to plan for the growing season. The increase in cost was estimated to be greater if accurate forecasts were not available or not used.

CLIMATE CHANGE AND AGRICULTURE IN THE UNITED STATES

INTRODUCTION

Both weather and climate affect virtually every aspect of agriculture,from the production of crops and livestock,to the transportation of agricultural products to market. Agricultural crop production is likely to be significantly affected by the projected changes in climate and atmospheric CO_2 (Rosenzweig and Hillel,1998). While elevated CO_2 increases plant photosynthesis and thus crop yields (Kimball,1983),the projected changes in temperature and precipitation have the potential to affect crop yields either positively or negatively. The negative effects are associated with some climate changes that result in more rapid plant development,and modification of water and nutrient budgets in the field (Long,1991).

The net effects of increased CO_2 and climate change on crop yields will ultimately depend on local conditions. For example,higher spring and summer air temperatures might be beneficial to crop production at northern temperate latitude sites,where the length of the growing season would increase. However, higher temperatures might have negative effects during crop maturity in those regions where summer temperature and water stress already limit crop production (Rosenzweig and Tubiello,1997).

The response of agricultural systems to future climate change will additionally depend on management practices,such as the levels of water and nutrient applied. Water limitation tends to enhance the positive crop response to elevated CO_2, compared to well-watered conditions (Chaudhuri et al.,1990;Kimball et al.,1995). The opposite is true for nitrogen limitation: well-fertilized crops respond more positively to CO_2 than less fertilized ones (Sionit et al.,1981;Mitchell et al.,1993).

This Assessment is intended to present our latest understanding of the potential impacts of climate change on the agricultural sector. The Assessment relies on two sources of information:the relevant scientific literature,and new quantitative and qualitative analyses done specifically as part of the Assessment. Complete documentation of the work of the Agriculture Assessment Team is given in their Sector Report (Reilly et al.,2000;http://www.nacc.usgcrp.gov). This Foundation document,while a standalone statement,summarizes the report of the Agriculture Assessment Team.

In this document, we review the major activities undertaken in this Assessment. First, we present a summary of the key findings of the national and international assessments of climate change and agriculture that have been undertaken during the past two decades. Second, we briefly report results of new simulation modeling,done for this Assessment,that considers the consequences of two different climate-change scenarios on crop yield and the economics of agriculture in the US. Third, we set out the essential findings of new analyses on how the impacts of climate change on agriculture may, in turn,affect resources such as water and other aspects of the environment. And finally, we discuss the highlights of a new analysis of climate variability on agriculture.

The agriculture sector Assessment considered crop agriculture, grazing,livestock and environmental effects of agriculture. The focus here is primarily on crop agriculture,which was studied most intensely in the Assessment. Grain production is a major concern,with attention given to vegetables and fruit crops.

The approach used to assess the effects of climate change on crop agriculture involved an “end-to-end” analysis that linked climate-change scenarios for the future derived from general circulation models,with crop models designed to consider the effects of climate change and elevated atmospheric CO_2 on crop yields. The outputs of the crop models were inputs to an economic model that was then used to analyze the economic consequences of changed crop yields on farmers and consumers.

SOCIOECONOMIC CONTEXT

The US is a major supplier of food and fiber for the world,accounting for more than 25% of the total global trade in wheat,corn,soybeans,and cotton.

Cropland currently occupies about 400 million acres, or 17% of the total US land area. In addition, grasslands and permanent grazing and pasturelands,occupy almost 600 million acres,another 26% of US land area. The value of agricultural commodities (food and fiber) exceeds $165 billion at the farm level and over $500 billion,approaching 10% of GDP, after processing and marketing.

Economic viability and competitiveness are major concerns for producers trying to maintain profitability as real commodity prices have fallen by about two-thirds over the last 50 years. Agricultural productivity has improved at over 1% per year since 1950, resulting in a decline in both production costs and prices. This trend maintains intense pressure on individual producers to continue to increase the productivity of their farms and to reduce costs of production. In this competitive economic environment, producers see anything that might increase costs or limit their markets as a threat to their viability. Issues of concern include regulatory actions that might increase costs,such as efforts to control the off-site consequences of soil erosion, agricultural chemicals, and livestock wastes; growing resistance to and restrictions on the use of genetically-modified crops; new pests;and the development of pest resistance to existing pest-control strategies. Future changes in climate will interact with all of these factors.

CLIMATE CONTEXT

This Assessment of climate change is based on climate scenarios derived from climate models developed at the Canadian Centre for Climate Modelling and Analysis and the Hadley Centre in the United Kingdom. While the physical principles driving these models are similar, they differ in how they represent the effects of some important processes. Therefore,these two primary models paint different views of the future. On average over the 21st century the Canadian model projects a greater temperature increase than does the Hadley model,while the Hadley model projects a much wetter climate than does the Canadian model. By using these two models,a plausible range of future temperature conditions is captured,with one model being near the lower end and the other near the upper end of projected temperature changes over the US. Both models project much wetter conditions,compared to present, over many agricultural areas in the US.

Temperature. Average warming in the US is projected to be somewhat greater than for the globe as a whole over the 21st century. In the Canadian model scenario,increases in annual average temperature of 9˚F (5˚C) by the year 2100 are common across the central US,with changes about half this large along the East and West coasts. Seasonal patterns indicate that projected changes will be particularly large in winter, especially at night. Large increases in temperature are projected over much of the South in summer. In the Hadley model scenario,the eastern US has temperature increases of 3-5˚F (2-3˚C) by 2100,while the rest of the nation warms more,up to 7˚F (4˚C),depending on the region.

In both models,Alaska is projected to experience more intense warming than the lower 48 states,and in fact,this warming is already well underway. In contrast,Hawaii,the other Pacific islands,and the Caribbean islands are likely to experience less warming than the continental US,because they are at lower latitudes and are surrounded by ocean, which warms more slowly than land.

Precipitation. At this time, climate scientists have less confidence in climate model projections of regional precipitation than of regional temperature. For the 21st century, the Canadian model projects the percentage increases in precipitation will be largest in the Southwest and California,while east of the Rocky Mountains,the southern half of the nation is projected to experience a decrease in precipitation. The percentage decreases are projected to be particularly large in eastern Colorado and western Kansas,and across an arc running form Louisiana to Virginia. Projected decreases in precipitation are most evident in the Great Plains during the summer and in the East during both winter and summer. The increases in precipitation projected to occur in the West,and the smaller increases in the Northwest,are likely to occur mainly in winter.

In the Hadley model,the largest percentage increases in precipitation are projected to be in the Southwest and Southern California,but the increases are smaller than those projected by the Canadian model. In the Hadley model,the entire US is projected to have increases in precipitation,with the exception of small areas along the Gulf Coast and in the Pacific Northwest. Precipitation is projected to increase in the eastern half of the nation and in southern California and parts of Nevada and Arizona in summer, and in every region during the winter, except the Gulf States and northern Washington and Idaho.

In both the Hadley and Canadian models,most regions are projected to experience an increase in the frequency of heavy precipitation events. This is especially notable in the Hadley model,but the Canadian model shows the same characteristic.

PREVIOUS ASSESSMENTS – A BRIEF OVERVIEW

Several conclusions are shared among assessments conducted over the past quarter century. Here these are briefly reviewed and a more complete synopsis of some of the important previous assessments is given in the Appendix.

Over the next 100 years and probably beyond, human-induced climate change as currently modeled will not seriously imperil overall food and fiber production in the US, nor will it greatly increase the aggregate cost of agricultural production. Most assessments have looked at multiple climate scenarios. About one-half of the scenarios in any given assessment have shown small losses for the US (increased cost of production) and about one-half have shown gains for the US (decreased cost of production). However, no assessment has adequately included the potential impacts of extreme events,such as flooding, drought,and prolonged heat waves,and the potential effects of increased ranges of pests, diseases,and insects. The result of including these factors could require a reevaluation of this finding.

There are likely to be strong regional production effects within the US, with some areas suffering significant loss of comparative advantage (if not absolute advantage) relative to other regions of the country. With very competitive economic markets,it matters little if a particular region gains or loses absolutely in terms of yield,but rather how it fares relative to other regions. The southern region of the US is persistently found to lose both relative to other regions and absolutely. The likely effects of climate change on other regions within the US are less certain. While warming can lengthen the growing seasons in the northern half of the country, the full effect depends on precipitation,notoriously poorly projected by climate models.

Global market effects and trade dominate in terms of net economic effect on the US economy. Just as climate's effects on regional comparative advantage are important,the relevant concerns are the overall effects on global production and prices and how US producers fare relative to their global competitors or potential competitors. The worst outcome for the US would be severe climate effects on production in most areas of the world, with particularly severe effects on US producers. Consumers would suffer from high food prices, producers would have little to sell,and agricultural exports would dwindle. While an unlikely outcome based on newer climate scenarios,some early scenarios that featured particularly severe drying in the mid-continental US with milder conditions in Russia,Canada,and the northern half of Europe produced a moderate version of this scenario. The US and the world could gain most if climate changes were generally beneficial to production worldwide,but particularly beneficial to US producing areas. Consumers in the US and around the world would benefit from falling prices and US producers would also gain because the improving climate would lower their production costs even more than prices fell,thus increasing their export competitiveness. In fact,most scenarios come close to the middle,with relatively modest effects on world prices. The larger gainers in terms of production are the more northern areas of Canada,Russia,and Northern Europe. Tropical areas are more likely to suffer production losses. The US as a whole straddles a set of climate zones that include gainers (the northern areas) and losers (southern areas).

Effects on producers and consumers often are in opposite directions and this is often responsible for the small net effect on the economy. This result is a near certainty without trade,and reflects the fact that demand is not very responsive to price so that anything that restricts supply (e.g.,acreage reduction programs,environmental constraints, climate change) leads to price increases that more than make up for the reduced output. Once trade is factored in,this result depends on what happens to production abroad as discussed above.

US agriculture is a competitive, adaptive, and responsive industry and will likely adapt to climate change;all assessments reviewed have factored adaptation into their analyses. The final effect on producers and the economy after consideration of adaptation may be either negative or positive. The evidence for adaptation is drawn from analogous situations such as the response of production to changes in commodity and input prices, regional shifts in production as economic conditions change,and the adoption of new technologies and farming practices.

KEY ISSUES

Here, we briefly report results of new simulation modeling done for this Assessment that considers the consequences of two different climate change scenarios on crop yield and the economics of agriculture in the US. In addition, we set out the essential findings of new analyses on how the impacts of climate change on agriculture may, in turn,affect resources such as water and other aspects of the environment. And finally, we discuss the highlights of new analyses of climate variability on agriculture.

Four key issues were identified:
- Crop Yield Changes
- Changes in Economic Impacts
- Resource and Environmental Effects
    - Changing water demands for irrigation
    - Surface water quality
    - Increasing pesticide use
- Climate Variability

1. Crop Yield Changes

Approach

The agriculture-sector team investigated the effects of climate change on US crop production,using future climate scenarios generated by two climate models,the Hadley and Canadian models,as input into a family of dynamic crop-growth models. The DSSAT family of models was used extensively in this study to simulate wheat,corn,potato,soybean, sorghum, rice,and tomato (Tsuji et al.,1994). The CENTURY model was used to simulate grassland and hay production (Parton et al.,1994). Finally, the model of Ben Mechlia and Carrol (1989) was used to simulate citrus production.The models were run to simulate yields at 45 sites across the US. These sites were chosen using USDA national and state-level statistics to be in areas of major production.

All models employed have been used extensively to assess crop yields across the US under current conditions as well as under climate change (e.g., Rosenzweig et al.,1995; Parton et al.,1994,Tubiello et al.,1999). Apart from CENTURY, which runs with a monthly time-step,all other models use daily inputs of solar radiation,minimum and maximum temperature,and precipitation to calculate plant phenological development from planting to harvest, photosynthesis and growth,and carbon allocation to grain or fruit. All models use a soil component to calculate water and nitrogen movement,and are thus able to assess the effects of different management practices on crop growth. The simulations performed for this study considered:1) rainfed production;and 2) optimal irrigation,defined as re-filling of the soil water profile whenever water levels fall below 50% of capacity at 30 cm depth. Fertilizer applications were assumed to be optimal at all sites. Atmospheric concentrations of CO_2 assumed in the core analysis were as follows:350 parts per million by volume (ppmv) for the base,445 ppmv for the year 2030,and 660 ppmv for 2090. The crop models assumed that crops such as wheat, rice,barley, oats,potatoes,and most vegetable crops,tend to respond favorably to increased CO_2, with a doubling of CO_2 leading to yield increases in the range of 15-20%. Other crops including corn,sorghum,sugar cane,and many tropical grasses, were assumed to be less responsive to CO_2, with a doubling of the gas leading to yield increases of about 5%.

In addition to current practices at each site,simulations were done that included different adaptation techniques. These consisted largely of testing the effects of early planting,a realistic scenario at many northern sites under climate change;and of testing the performance of cultivars better adapted to warmer climates,using currently available genetic stock. In general,early planting was considered for spring crops,to avoid heat and drought stress in the late summer months,while taking advantage of warmer spring conditions. New, better-adapted cultivars were tested for winter crops,such as wheat, to increase the time to maturity (shortened under climate change scenarios) and to increase yield potential.

Two other groups in the US developed additional analyses,independent from the core study described above. Specifically, researchers at the Pacific Northwest National Laboratories (PNNL) developed national-level analyses for corn,winter wheat,alfalfa, and soybean,using climate projections from the Hadley model (Izarraulde et al.,1999). Another group,co-located at Indiana University and Purdue University, focused on corn,soybeans,and wheat, developing a regional analysis for the Midwest, including the states of Indiana,Illinois,Ohio, Wisconsin,and Michigan,using Hadley model projections (Southworth et al.,2000).

In the PNNL study, the baseline climate data were obtained from national records for the period 1961–1990. The scenario runs were constructed for two future periods (2025–2034 and 2090–2099). The Erosion Productivity Impact Calculator (EPIC) was used to simulate the behavior of 204 farms with considerations of soil-climate-management combinations under the baseline climate,the two future periods,and their combinations with two levels of atmospheric CO_2 concentrations (365 and 560 ppmv).

In an independent study by Indiana University and Purdue University, a baseline climate was defined using the period 1961-1990. Several future scenarios were analyzed for the decade of 2050,with atmospheric CO_2 concentration set at 555 ppmv. Crop yields were simulated with the DSSAT model at 10 representative farms in the Corn Belt and Lake States. Adaptations studied included change of planting dates,as well as the use of cultivars with different maturity groups. These results were not included in the economic modeling but provide another source of information.

Although specific differences in time horizons,CO_2 concentrations,and simulation methodologies complicate the comparison of these additional analyses to the work discussed herein,model findings were overall in general agreement with results of the core study.

Dominant Land Uses, 1992

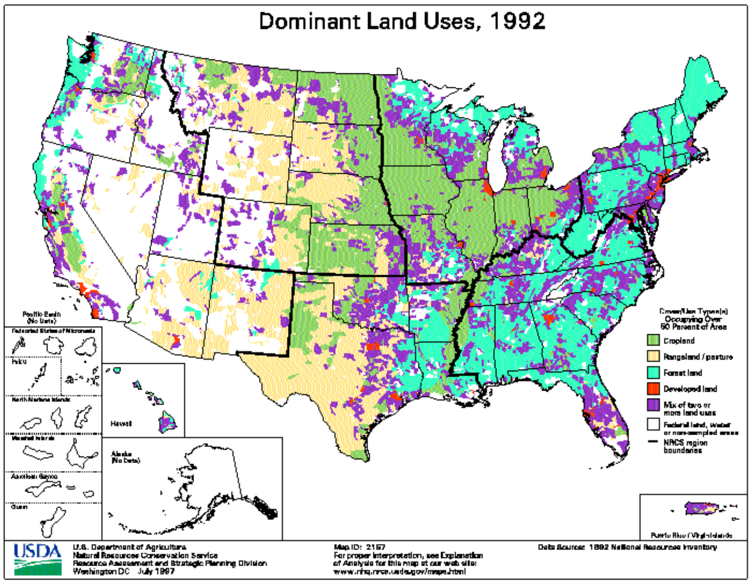


Figure 2. Agriculture Sector Model (ASM) Regions with USDA Regions Overlaid. (ASM regions follow state boundaries except where further disaggregated). The economic analysis in the Assessment is summarized for the 10 USDA regions outlined in the map. Source: Changing Climate and Changing Agriculture: Report of the Agricultural Sector Assessment Team, 2000. See Color Plate Appendix

Results

Here we present the results from the models for several major crops. The DSSAT analyses for wheat, corn,alfalfa,and soybean, were integrated with results from two additional independent studies. The national average changes in yields for dryland and irrigated crops with and without adaptation are given in Figures 1a-d. The national averages were calculated by summing regional estimates for the coterminous United States (Figure 2) that are specified in Agriculture Sector Model (ASM). The regional estimates were derived by using crop-model outputs for sites in the region and harvested acreage in each ASM region based on data from the 1992 National Resource Inventory.

Yield Changes for Major Crops

A summary of the changes in simulated crop yields under the Canadian and Hadley scenarios relative to present yields is given below.

Winter wheat. Even with adaptation, rainfed production was reduced by an average of 9% in the 2030 time period under the Canadian scenario. Adaptation techniques helped to counterbalance yield losses in the Northern Plains,but not in the Southern Plains where losses were more severe and due to reductions in precipitation. Yields increased an average of 23% under the Hadley scenario for the 2030 period. Average dryland yields increased under both climate scenarios for the 2090 period, up to 59% in the case of the Hadley scenario. Irrigated wheat production increased under both climate scenarios by up to 16% on average by the end of the 21st century when adaptation strategies were used.

Spring wheat. Dryland production of spring wheat yields increased under both scenarios,either with or without adaptation. Adaptation techniques, including early planting and new cultivars,helped to improve yields under both scenarios,up to 59% for the Hadley scenario in 2090. Irrigated yields were reduced slightly under the Canadian scenario and increased slightly under the Hadley scenario.

Corn. Dryland corn production increased at most sites due to increases in precipitation under both climate scenarios. Average yields were up by between 15 to 40% by the end of the 21st century in much of the Corn Belt region. Larger yield gains were simulated in the Northern Great Plains and in the Northern Lakes Region,where higher tempera-

Figure 1a - Dryland Yields Without Adaptation

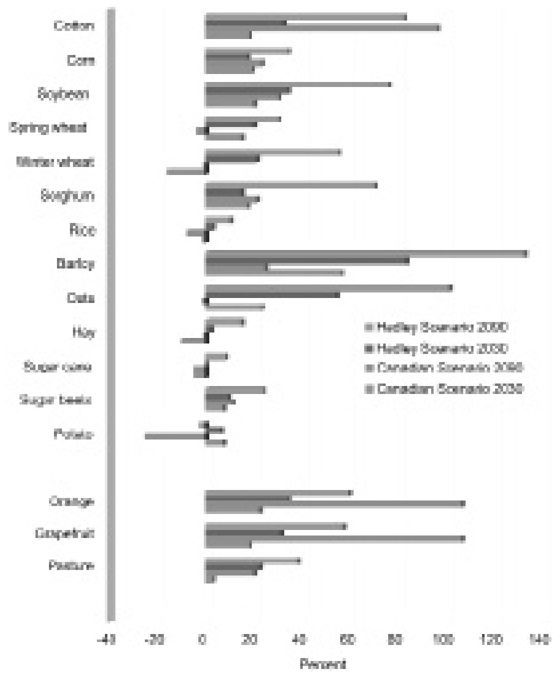


Figure 1b - Dryland Yields With Adaptation

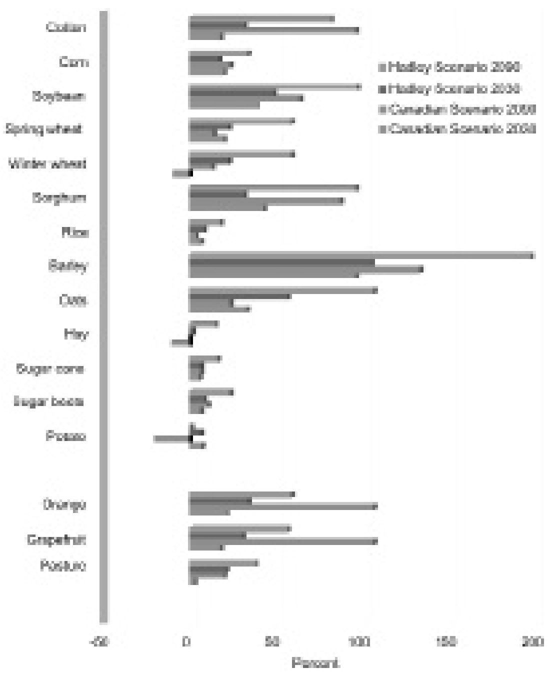


Figure 1c - Irrigated Yields Without Adaptation

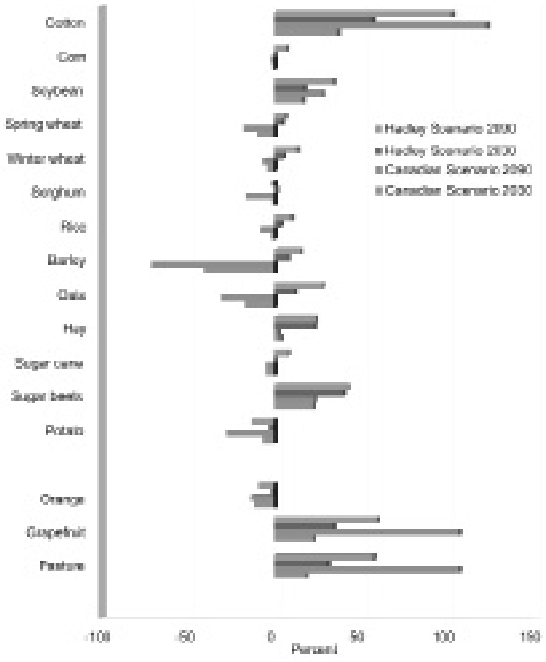


Figure 1d - Irrigated Yields With Adaptation

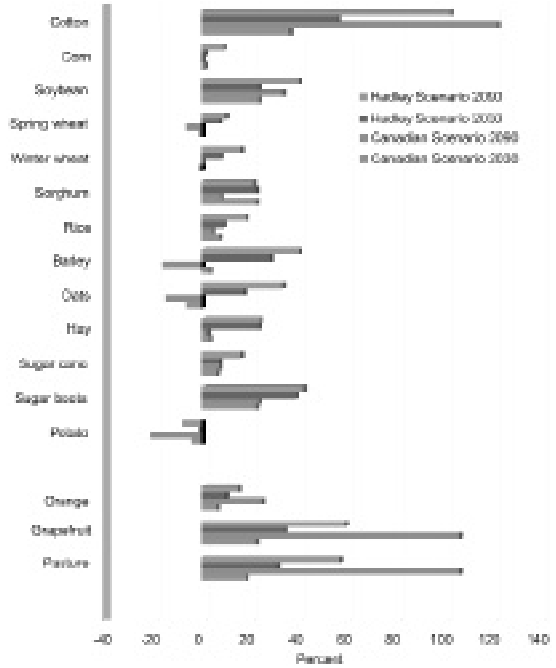


Figure 1a-d. Relative changes (% change relative to present) in crop yield for two time periods, 2030s and 2090s, under the Canadian and Hadley Scenarios. 0 = no change. Under the two climate scenarios, most crops showed substantial yield increase, even without adaptation, under dryland conditions. Irrigated yields increased less or decreased. (Source: Changing Climate and Changing Agriculture: Report of the Agricultural Sector Assessment Team, 2000) See Color Plate Appendix

tures were also beneficial to production. Irrigated corn production was not greatly affected at most sites.

Potato. Potato production decreased across many sites analyzed. While major production areas in the northern US experienced either small increases or small decreases,at some other sites potato yields decreased up to 50% from current levels. At these sites,there was little room for cultivar adaptation, because the projected higher fall and winter temperatures negatively affected tuber formation. Adaptation of planting dates mitigated only some of the projected losses.

Citrus. Production largely benefited from the higher temperatures projected under all scenarios. Simulated fruit yield increased in the range of 60 to 100%,while irrigation water use decreased. Crop losses due to freezing diminished by 65% in 2030, and by 80% in 2090.

Soybean. Soybean production increased at most sites analyzed,in the range 20 to 40% for sites of current major production. Larger gains were simulated at northern sites where cold temperatures currently limit crop growth. The Southeast sites considered in this study experienced large reductions under the Canadian scenario. Losses were reduced by adaptation techniques involving the use of cultivars with different maturity classes. (For regional details see the Southeast chapter).

Sorghum. Sorghum production,especially with adaptation, generally increased under rainfed conditions,due to the increased precipitation projected under the two scenarios considered. Higher temperatures at northern sites further increased rainfed grain yields. By contrast,irrigated production without adaptation was reduced almost everywhere, because of negative effects of higher temperatures on crop development and yield.

Rice. Rice production increased slightly under the Hadley scenario,with the increases in the range 1-10%. Under the Canadian scenario, rice production was 10-20% lower than current levels at sites in California and in the Delta region.

Tomato. Without adaptation,irrigated tomato production decreased at most of the simulated sites due to increased temperatures. Noted exceptions were the northern locations where production is currently limited by low temperatures and by short growing seasons. Reductions were in the 10 to 15% range under the Canadian scenario. Under the Hadley scenario, reductions in tomato yields were in the 5% range. Adaptation strategies resulted in increased yields of tomatoes under the two climate scenarios.

Even without adaptation,the weighted average yield impact for many crops grown under dryland conditions across the entire US was positive under both the Canadian and Hadley scenarios. In many cases,yields under the 2030 climate conditions improved compared with the control yields under current climate,and improved further under the 2090 climate conditions. These generally positive yield results were observed for cotton,corn for grain and silage,soybean,sorghum,barley, sugar beet,and citrus fruit. The yield results were mixed for other crops (wheat, rice,oats,hay, sugar cane, and potatoes) showing yield increases under some conditions and declines other conditions.

Changes in irrigated yields,particularly for the grain crops, were more often negative or less positive than dryland yields. This reflected the fact that under these climate scenarios precipitation increases were substantial. The precipitation increases provided no yield benefit to irrigated crops because they face no water stress under current conditions since all the water needed is provided through irrigation. Higher temperatures sped development of crops and reduced the grain filling period,thereby reducing yields. For dryland crops, the positive effect of more moisture and CO_2 fertilization counterbalanced the negative effect of higher temperatures.

Water demand by irrigated crops dropped substantially for most crops. The faster development of crops due to higher temperatures reduced the growing period and thereby reduced water demand,more than offsetting increased evapotranspiration due to higher temperatures while the crops were growing. To a large extent,the reduced water use thus reflected the reduced yields on irrigated crops. Increased precipitation also reduced the need for irrigation water.

Adaptations examined in the crop modeling studies contributed small additional gains in yields of dryland crops,particularly for those with large yield increases due to climate change. Adaptation options examined,including shifts in planting times and choice of cultivars adapted to new climatic conditions. For the most part,however, these adaptations had little additional benefit where yields increased from climate change. This suggests that adaptation may be able to partly offset changes in comparative advantage across the US that may result under these scenarios. Other strategies for adaptation, such as whether or not to switch crops or to irrigate, were options available in the economic model. The decisions to undertake these strategies are driven by economic considerations; that is, whether they are profitable under market conditions simulated in the scenario. Adaptations for several crops were not considered because the options available, such as changing planting date, were not applicable to many perennial and tree fruit crops. Adaptation studies were conducted for only a subset of sites considered in the study and these results were extrapolated to other sites.

Adaptation contributed greater yield gains for irrigated crops. Shifts in planting dates were able to reduce some of the heat-related yield losses. With higher yields than in the no-adaptation cases, water demand declines were not as substantial. Again, this reflected the fact that the adaptations considered extended the growing (and grain-filling period) and this extension meant longer periods over which irrigation water was required.

The factors responsible for the positive results of this Assessment varied, but can generally be traced to aspects of the climate scenarios. First, increased precipitation in these transient climate scenarios is an important factor contributing to the more positive effects for dryland crops and explains the difference between dryland and irrigated crop results. The benefits of increased precipitation outweighed the negative effects of higher temperatures for dryland crops, whereas increased precipitation had little yield benefits for irrigated crops because water stress is not a concern for crops already irrigated. In fact, where the climate scenarios projected both higher temperatures and decreases in precipitation, such as for the Central Plains regions of Kansas and Oklahoma, rainfed cereal production, notably winter wheat, was negatively affected.

As noted for the Central Plains, not all agricultural regions of the United States are affected to the same degree or direction by the climates in the scenarios. In general, climate change as projected in the two climate scenarios favored northern areas. The Midwest (especially northern areas), West, and Pacific Northwest exhibited large gains in yields for most crops with both climate scenarios in the 2030 and 2090 time frames. Yield changes in other regions were mixed, depending on the climate scenario and time period. For example in the Southeast, simulated yields for most crops increased under the Hadley scenario in both the 2030 and 2090 time frames. Yield estimates varied widely among crops under the Canadian scenario. Citrus yields increased slightly by 2030, and dramatically by 2090. Dryland soybean yields decreased in the range of 10-30 % in about 2030, and by up to 80 % in about 2090. And rice yields decreased on the order of 5 to 10 % for both time periods

The potential for within-region differences was highlighted in the Indiana University/Purdue University study of the Midwest. In this study, decreases were found in corn yields across the southern portion of the region's southern states — Indiana, Illinois, and Ohio. In addition, decreases, or only small increases in yields, were found for soybean and wheat across these same southern locations. In the region's northern states, Wisconsin and Michigan, there were simulated increases in yield for all the crops studied, with soybean showing the most dramatic increases. In addition, a variability analysis indicated that a doubling of current climate variability in association with climate change would produce the most detrimental climate conditions for crop growth across this region (Southworth et al., 1999).

Crop models such as those used in this Assessment have been used at local, regional, and global scales to systematically assess impacts on yields and adaptation strategies in agricultural systems, as climate and/or other factors change. The simulation results depend on the general assumption that soil nutrients are not limiting, and that pests, insects, diseases, and weeds pose no threat to crop growth and yield (Patterson et al., 1999; Rosenzweig and Hillel, 1998; Rosenzweig et al., 2000; Strzepek et al., 1999; Tubiello et al., 1999; Walker et al., 1996). One important consequence of these assumptions is that positive crop responses to elevated CO_2, responsible for one-third to one-half of the yield increases simulated in the Assessment studies, should be regarded as upper limits to actual responses in the field. One additional limitation that applies to this study is the models' inability to predict the negative effects of excess water conditions on crop yields. Given the "wet" nature of the scenarios employed, the positive responses projected in this study for rainfed crops, under both the Hadley and Canadian scenarios, may be overestimated.

2. Economic Impacts

Approach

The crop results were combined with impacts on water supply, livestock, pesticide use, and shifts in international production to estimate impacts on the US economy. This allowed the estimation of regional production shifts and resource use in response to changing relative comparative advantage among crops and producing regions. These changes were estimated using a US national agricultural sector model (ASM) (Adams et al., 1990, 1997) that is linked to a global trade model.

The ASM is based on the work of Baumes (1978) which was later modified and expanded by Burton and Martin (1987); Adams et al. (1986); Chang et al. (1992) and Lambert et al. (1995). Conceptually, ASM is a price endogenous, mathematical programming model of the type described in McCarl and Spreen (1980). Constant elasticity curves are used to represent domestic consumption and export demands as well as input and import supplies. Elasticities were assembled from a number of sources including USDA through the USMP modeling team (House, 1987) and prior model versions. ASM is designed to simulate the effects of various changes in agricultural resource usage or resources available on agricultural prices, quantities produced, consumers' and producers' welfare, exports, imports and food processing. In calculating these effects, the model considers production, processing, domestic consumption, imports, exports and input procurement.

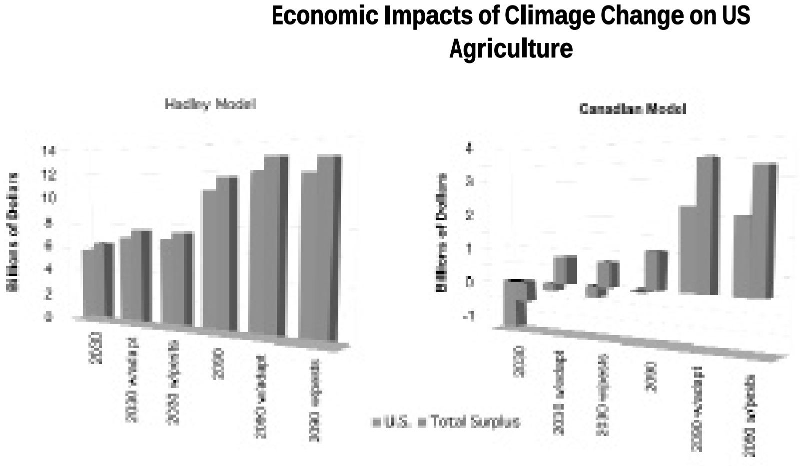

Economic Impacts of Climage Change on US Agriculture

Figure 3a and b. The economic index is change in welfare expressed as the sum of producer and consumer surplus in billions of dollars. There were net economic benefits for the US under most of the scenarios examined in the Assessment. Foreign consumers also gained from lower commodity prices on international markets. Source: Changing Climate and Changing Agriculture: Report of the Agricultural Sector Assessment Team, 2000. See Color Plate Appendix

The model distinguishes between primary and secondary commodities, with primary commodities being those directly produced by the farms and secondary commodities being those involving processing. Within ASM, the US is disaggregated into 63 geographical production subregions. Each subregion possesses different endowments of land, labor and water as well as crop yields. Agricultural production is described by a set of regional budgets for crops and livestock. Marketing and other costs are added to the budgets following the procedure described in Fajardo et al. (1981) such that the marginal cost of each budget equals marginal revenue. ASM also contains a set of national processing budgets which uses crop and livestock commodities as inputs (USDA, 1982). There are also import supply functions from the rest of the world for a number of commodities. The demand sector of the model consists of the intermediate use of all the primary and secondary commodities, domestic consumption use and exports.

There are 33 primary crop and livestock commodities in the model. The primary commodities depict the majority of agricultural production, land use and economic value. The model incorporates processing of the primary commodities. There are 37 secondary commodities that are processed in the model. These commodities are chosen based on their linkages to agriculture. Some primary commodities are inputs to the processing activities yielding these secondary commodities and certain secondary products (feeds and by-products) are in turn inputs to production of primary commodities. Three land types (crop land, pasture land, and land for grazing on an animal unit month basis) are specified for each region. Land is available according to a regional price elastic supply schedule with a rental rate as reported in USDA farm real estate statistics. The labor input includes family and hired labor. A region-specific reservation wage and maximum amount of family labor available reflect the supply of family labor. The supply of hired labor consists of a minimum inducement wage rate and a subsequent price elastic supply. Water comes from surface and pumped ground water sources. Surface water is available at a constant price, but pumped water is supplied according to a price elastic supply schedule.

US agricultural sector models typically only deal with aggregate exports and imports facing the total

US without regional trading detail. The ASM includes foreign regions,and shipment among foreign regions modeled as 6 spatial equilibrium models for the major traded commodities (Takayama and Judge,1971). To portray US regional effects,US markets are grouped into the ten regional definitions used by the USDA. We also added variables for shipment among US regions,and shipment between US regions and foreign regions. The commodities subject to explicit treatment via the spatial equilibrium world trade model components are hard red spring wheat (HRSW),hard red winter wheat (HRWW),soft red winter wheat (SOFT),durum wheat (DURW)), corn,soybeans and sorghum.These commodities are selected based on their importance as US exports. The rest of the world is aggregated into 28 countries/regions. Transportation cost,trade quantity, price and elasticity were obtained from Fellin and Fuller (1998),USDA (1987) statistical sources and the USDA SWOPSIM model (Roningen,1986).

In the base results, climatic effects on crops and livestock in the rest of the world were assumed to be neutral,that is,no climate change effects on agriculture in the rest of the world were assumed. To test how sensitive the results were to this assumption three scenarios of climate impacts on agriculture in the rest of the world were used. These were developed from previous work reported in Reilly et al.(1993;1994),and based on a global analysis using a Hadley Centre climate scenario and a global agricultural model developed by Darwin et al.(1995). These climate scenarios were not completely consistent with the new scenarios used for the US,but provide a good test of the sensitivity of US economic results to impacts in the rest of the world.

Results

The net economic effect on the US economy was generally positive, reflecting the generally positive yield effects (Figures 3a,b). The exceptions were simulations under the Canadian climate scenario in 2030,particularly in the absence of adaptation.

Foreign consumers gained in all the scenarios as a result of lower prices for US export commodities. The total effects (net effect on US producers and consumers plus foreign gains) ranged from a $0.5 billion loss to a $12.5 billion gain.

This Assessment found that producers and consumers were affected in opposite ways by climate change (Figures 4a,b). Producers'incomes generally fell due to lower prices. Producer reductions ranged from about $0.1 up to 5 billion. The largest reductions were under the Canadian scenario. Under the Hadley scenario,producers suffered from lower prices,but enjoyed considerable increases in exports such that the net effect was for only very small reductions. Economic gains accrued to consumers through lower prices in all scenarios. Gains to consumers ranged from $2.5 to 13 billion.

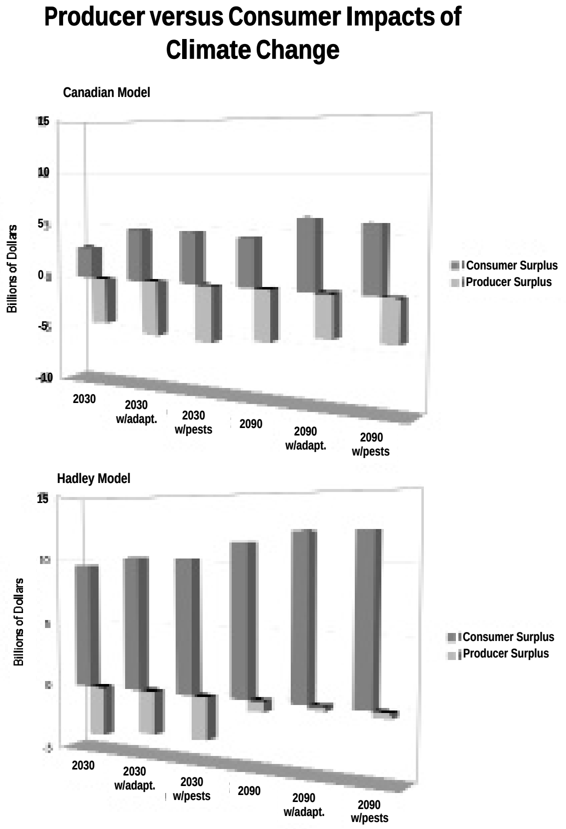


Figure 4a and b. In the model simulations consumers generally benefited from climate change while producers experienced lower income due to lower prices for commodities resulting from increased yields and supply. Source: Changing Climate and Changing Agriculture: Report of the Agricultural Sector Assessment Team, 2000. See Color Plate Appendix

Different scenarios of the effect of climate change on agriculture abroad did not change the net impact on the US very much,but redistributed changes between producers and consumers. The direction depended on the direction of effect on world prices. Lower prices increased producer losses and added to consumer benefits. Higher prices reduced producer losses and consumer benefits.

Modeled projections of livestock production and prices were mixed. Increased temperatures directly reduced productivity, but improvements in pasture and grazing and reductions in feed prices due to lower crop prices counter these losses. (For additional comments on livestock,see the Great Plains chapter).

Regional Production Changes Relative to Current Production

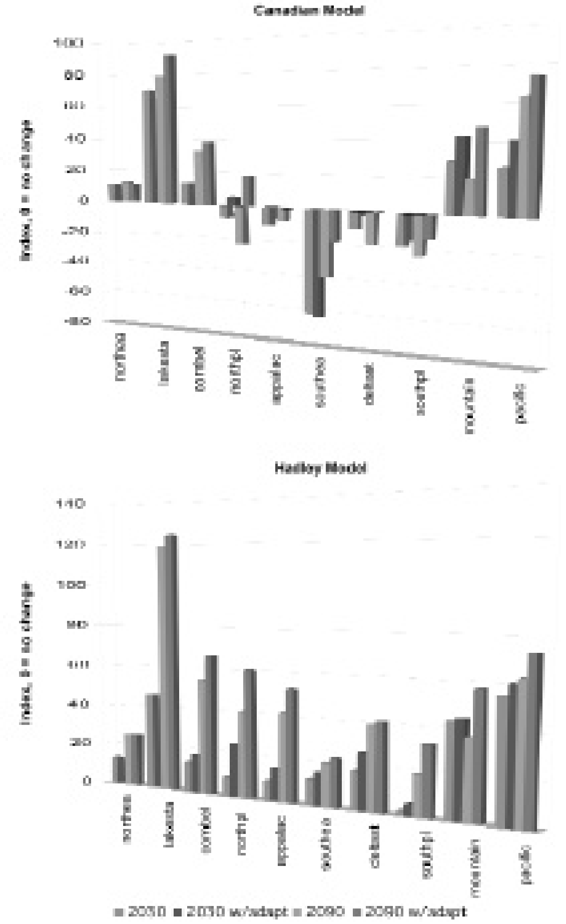


Figure 5a and b. In the model simulations production increased in northern regions as a result of longer growing seasons, and in western regions due to increased precipitation. Higher temperatures and increased drought conditions contributed to production declines or smaller increases in southern and plains regions. Source: Changing Climate and Changing Agriculture: Report of the Agricultural Sector Assessment Team, 2000. See Color Plate Appendix

Aggregate regional production changes (Figures 5a, b) were positive for all regions in both the 2030 and 2090 time frames under the Hadley scenario. Adaptation measures had a small additional positive effect. In contrast, aggregate production changes differed among regions under the Canadian scenario in both the 2030s and 2090s. It was positive for most northern regions,mixed for the Northern Plains,and negative for Appalachia, the Southeast,the Delta states,and the Southern Plains. Adaptation measures helped somewhat for the southern regions,but the aggregate production was lower in these regions under both the 2030 and 2090 climates considered. Aggregate production is represented in Figures 5a,b as a price-weighted index across livestock and crop production. Many of the impacts,because they occur at the regional level,are dealt with in more detail in the regional chapters.

3. Resource and Environmental Effects

In terms of improving the coverage of potential impacts of climate change on agriculture,this study has made advances over previous assessments. Some of the advances were in the area of resource and environmental effects (Figure 6). Details of the studies underlying this summary are given in the Agriculture Sector Report (Reilly, et al.2000; http://www/nacc.usgcrp.gov).

Demand for land. Agriculture's pressure on land resources generally decreased under both climate scenarios across the 21st century. Area in cropland decreased 5 to 10 % while area in pasture decreased 10 to 15 %.

Grazing pressure. Animal unit months (AUMs) of grazing on western lands decreased on the order of 10% under the Canadian climate scenario and increased 5 to 10% under the Hadley climate scenario.

Demand for water, a national perspective. At the national level,the models used in this Assessment found that irrigated agriculture's need for water declined approximately 5-10% for 2030 and 30-40% for 2090 climate conditions as represented in the two scenarios. At least two factors were responsible for this reduction in water demand for irrigation. One was increased precipitation in some agricultural areas. The other was that faster development of crops due to higher temperatures resulted in a reduced growing period and thereby reduced water demand. In the crop modeling analyses done for the Assessment,shortening of the growing period reduced plant water-use enough to more than compensate the increased water losses from plants and soils due to higher temperatures.

Demand for water, a regional perspective. The competition for water between agriculture and other uses was explored through a case study of the Edwards Aquifer that serves the San Antonio region of Texas. Agriculture uses of water compete with urban and industrial uses and tight economic management is necessary to avoid unsustainable use of the resource. Aquifer discharge is through pumping and artesian spring discharge.

The study found that the Canadian and Hadley scenarios of climatic change caused a slightly negative welfare result in the San Antonio region as a whole,but had a strong impact on the agricultural sector.

The regional welfare loss,most of which was incurred by agricultural producers, was estimated to be between $2.2 and 6.8 million per year if current pumping limits are maintained.

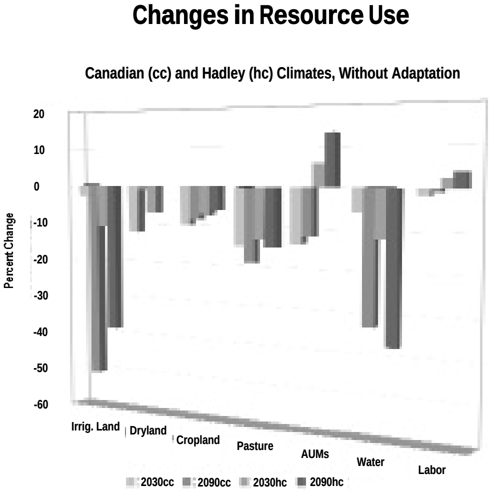
A major reason for the current pumping limits is to preserve the artesian spring flows that are critical to the habitat of local endangered species. To maintain spring flows at the currently specified level to protect endangered species,pumping would need to be reduced in the future with climate change. The study calculated that under the two climate scenarios,pumping would need to be reduced by 10 to 20% below the limit currently set and this would cost an additional $0.5 to 2 million per year. Welfare in the non-agricultural sector was only marginally reduced by the climatic change simulated by the two climate scenarios. The value of water permits rose dramatically.

The agricultural use of water is discussed in several of the regional chapters including the Great Plains.

Surface water quality. As part of the Assessment, a study was undertaken of the linkages between climate change and nitrogen loading of Chesapeake Bay. The Chesapeake Bay is one of nation's most valuable natural resources,but has been severely degraded in recent decades. Soil erosion and nutrient runoff from crop and livestock production have played a major role in the decline of the Bay. Based on simulations done for this Assessment, under the Canadian and Hadley scenarios for the 2030 period,nitrogen loading from corn production increased by 17 to 31% compared with conditions under current climate. Potential effects of climate change on water quality in the Chesapeake Bay must be considered very uncertain because current climate models may not fully represent the effects of extreme weather events such as floods or heavy downpours,which can wash large amounts of fertilizers,pesticides,and animal manure into surface waters.

Surface water quality is also discussed in the Southeast and West chapters.

Pesticide expenditures. The Assessment investigated the relationship between pesticide use and climate for crops that require relatively large amounts of pesticide. Pesticide expenditures increased under the climate scenarios considered for most crops studied and in most regions. Increases for corn were generally in the range of 10 to 20%, for potatoes of 5 to 15% and for soybeans and cotton of 2 to 5%. The results for wheat varied widely by state and climate scenario showing changes ranging from approximately –15 to +15%. These projections were based on cross-section statistical evidence on the relationship between pesticide expenditures and temperature and precipitation.



Changes in Resource Use

Canadian (cc) and Hadley (hc) Climates, Without Adaptation

Figure 6. In the simulations resource use generally declined as less crop and grazing land was needed. Use of water and irrigated crop land declined the most because the two climate scenarios used favored dryland over irrigated crops (cc-Canadian, hc=Hadley). Source: Changing Climate and Changing Agriculture: Report of the Agricultural Sector Assessment Team, 2000. See Color Plate Appendix

The increase in pesticide expenditures could increase environmental problems associated with pesticide use,but much depends on how pest control evolves over the next several decades. Pests develop resistance to control methods, requiring a continual evolution in the chemicals and control methods used.

The increase in pesticide expenditures resulted in slightly poorer overall economic performance but this effect was quite small because pesticide expenditures are a relatively small share of production costs. The approach used in the Assessment did not consider increased crop losses due to pests,implicitly assuming that all additional losses were eliminated through increased pest control measures. This may underestimate pest losses.

4. Potential Effects of Climate Variability on Agriculture

Ultimately, the consequences of climate change for US agriculture hinge on changes in climate variability and extreme events. Agricultural systems are vulnerable to climate extremes,with effects varying from place to place because of differences in soils, production systems,and other factors. Changes in precipitation type (rain,snow, and hail),timing,frequency, and intensity, along with changes in wind (windstorms,hurricanes,and tornadoes),could have significant consequences. Heavy precipitation events cause erosion, waterlogging,and leaching of animal wastes,pesticides, fertilizers,and other chemicals into surface water and groundwater. While all of the risks associated with these impacts are not known,the system is known to be sensitive to changes in extremes. The costs of adjusting to such changes will likely increase if the rate of climate change is high,although early signals from a rapidly changing climate would reduce uncertainty and encourage early adaptation.

One major source of weather variability is the El Niño/Southern Oscillation (ENSO) phenomenon. ENSO phases are triggered by the movement of warm surface water eastward across the Pacific Ocean toward the coast of South America and its retreat back across the Pacific,in an oscillating fashion with a varying periodicity. Better prediction of these events would allow farmers to plan ahead, planting different crops and at different times. The value of improved forecasts of ENSO events has been estimated at approximately $500 million per year.

ENSO's effects can vary from one event to the next. Predictions of the details of ENSO-driven weather are not perfect. There are also widely varying effects of ENSO across the country. The temperature and precipitation effects are not the same in all regions;in some regions the ENSO signal is relatively strong while in others it is weak,and the changes in weather have different implications for agriculture in different regions because climate-related productivity constraints differ among regions under neutral climate conditions.

As climate warms,ENSO is likely to be affected. Some models project that El Niño and La Niña events and their impacts on US weather will become more intense with climate change. The potential impacts of projected changes in frequency and strength of ENSO conditions on agriculture were modeled in this Assessment. An increase in these ENSO conditions was found to cost US farmers about $320 million on average per year if accurate forecasts of these events were available and farmers used them as they planned for the growing season. The increase in cost was estimated to be greater if accurate forecasts were not available or not used.

ADAPTATION STRATEGIES

Adaptations such as changing planting dates and choosing longer season varieties are likely to offset losses or further increase yields. Adaptive measures are likely to be particularly critical for the Southeast because of the large reductions in yields projected for some crops under the more severe climate scenarios examined. Breeding for response to CO_2 will likely be necessary to achieve the strong fertilization effect assumed in the crop studies. This is an unexploited opportunity and the prospects for selecting for CO_2 response are good. However, attempts to breed for a single characteristic are often not successful,unless other traits and interactions are considered. Breeding for tolerance to climatic stress has already been heavily exploited and varieties that do best under ideal conditions usually also outperform other varieties under stress conditions. Breeding specific varieties for specific conditions of climate stress is therefore less likely to encounter success.

Some adaptations to climate change and its impacts can have negative secondary effects. For example, an examination of use of water from the Edward's aquifer region around San Antonio,Texas found increased pressure on groundwater resources that would threaten endangered species dependent on spring flows supported by the aquifer. Another example relates to agricultural chemical use. An increase in the use of pesticides and herbicides is one adaptation to increased insects, weeds,and diseases that could be associated with warming. Runoff of these chemicals into prairie wetlands, groundwater, and rivers and lakes could threaten drinking water supplies,coastal waters, recreation areas,and waterfowl habitat.

The wide uncertainties in climate scenarios, regional variation in climate effects,and interactions of environment,economics,and farm policy suggest that there are no simple and widely applicable adaptation prescriptions. Farmers will need to adapt broadly to changing conditions in agriculture,of which changing climate is only one factor. Some of the possible adaptations more directly related to climate include:

Sowing dates and other seasonal changes
Plant two crops instead of one or a spring and fall crop with a short fallow period to avoid excessive heat and drought in mid-summer. For already warm growing areas,winter cropping could possibly become more productive than summer cropping.

New crop varieties
The genetic base is very broad for many crops,and biotechnology offers new potential for introducing salt tolerance,pest resistance,and general improvements in crop yield and quality.

Water supply, irrigation, and drainage systems
Technologies and management methods exist to increase irrigation efficiency and reduce problems of soil degradation,but in many areas,the economic incentives to reduce wasteful practices do not exist. Increased precipitation and more intense precipitation will likely mean that some areas will need to increase their use of drainage systems to avoid flooding and waterlogging of soils.

CRUCIAL UNKNOWNS AND RESEARCH NEEDS

Further research is needed in several areas. Broadly, these include:1) integrated modeling of the agricultural system;2) research to improve resiliency of the agricultural system to change;and 3) several areas of climate-agriculture interactions that have not been extensively investigated.

Integrated modeling of the agricultural system

- The main methodology for conducting agricultural impacts models has been to use detailed crop models run at a selected set of sites and to use the output of these as input to an economic model. This approach has provided great insights but future assessments will need to integrate these models to consider interactions and feedbacks, multiple environmental stresses (tropospheric ozone,acid deposition,and nitrogen deposition),transient climate scenarios,global analysis,and to allow study of uncertainty where many climate scenarios are used. The present approach of teams of crop modelers running models at specific sites severely limits the number of sites and scenarios that can be feasibly be considered.
- The boundaries of the agricultural system in an integrated model need to be expanded so that more of the complex interactions can be represented. Changes in soils, multiple demands for water, more detailed analysis and modeling of pests,and the environmental consequences of agriculture and changes in climate are areas that need to be incorporated into one integrated modeling framework. Agricultural systems are highly interactive with economic management choices that are affected by climate change. Separate models and separate analyses cannot capture these interactions.

Resiliency and adaptation

- Specific research on adaptation of agriculture to climate change at the time scale of decades to centuries should not be the centerpiece of an agricultural research strategy. Decision-making in agriculture mostly involves time horizons of one to five years,and long-term climate predictions are not very helpful for this purpose. Instead, effort should be directed toward understanding successful farming strategies and where adaptations to many changes are needed to manage risk.
- There is also great need for research to improve short-term and intermediate term (i.e.,seasonal) weather predictions and on how to make better use of these predictions.

New areas of research

- Experimentation and modeling of the interactions of multiple environmental changes on crops (changing temperature,CO_2 levels,ozone, soil conditions,moisture,etc.) are needed. Experimental evidence is needed under realistic field conditions such as Free Air Carbon Dioxide Enrichment (FACE) experiments for CO_2 enrichment.
- Much more work on agricultural pests and their response to climate change is needed.
- Economic analyses need to better study the dynamics of adjustment to changing conditions.
- Climate-agriculture-environment interactions are perhaps one of the more important vulnerabilities,but the existing research is extremely limited. Soil, water quality, and air quality should be included in a comprehensive study of interactions.
- Agricultural modeling must be more closely integrated with climate modeling and modelers to develop better techniques for assessing the impacts of climate variability. This requires significant advances in climate predictions to better represent changes in variability as well as assessment of and improvements in the performance of crop models under extreme conditions.

APPENDIX – REVIEW OF PREVIOUS ASSESSMENTS

Here we provide a short summary of the major assessments of the potential consequences of climate change for agriculture. The summary does not include a detailed scientific literature review that forms the foundation for past assessments as well as this one. A new set of reviews on climate change impacts on crops, livestock, pests, and soils, as well as discussion of global and regional impacts, has been published in a special edition of the journal, *Climatic Change*, Climate Change: Impacts On Agriculture (Reilly, 1999). The 5 articles included in the edition contain over 500 citations, providing a detailed guide to the scientific literature relating climate change and agriculture.

1976-1983: National Defense University

A National Defense University (Johnson, 1983) project produced a series of reports with the 1983 report providing the final report on agriculture, integrating yield and economic effects. It focused on the world grain economy in the year 2000, considering both warming and cooling of up to approximately 1ºC (1.8ºF) for large warming or cooling and 0.5ºC (0.9ºF) for moderate changes for the US, with associated precipitation changes on the order of +/- 0-2%. These estimates varied somewhat by region. The base year for comparison purposes was 1975. It relied on an expert opinion survey for yield effects, using the results to create a model of crop-yield response to temperature and precipitation for major world grain regions. There was no explicit account of potential interactions of pests, changes in soils, or of livestock or crops such as fruits and vegetables. No direct effects of CO_2 on plant growth were considered as the study remained agnostic about the source of the climate change (e.g., whether due to natural variability or human-induced). Economic effects were assessed using a model of world grain markets.

Crop yields in the US were estimated to fall by 1.6 to 2.3% due to moderate and large warming and to increase by very small amounts (less than 3%) with large cooling and even smaller amounts with moderate cooling. Warming was estimated to increase crop yields in the (then) USSR, China, Canada, and Eastern Europe, with cooling decreasing crop production in these areas. Most other regions were estimated to gain from cooling and suffer yield losses from warming. The net effect was a very small change in world production and on world prices. The study assigned subjective probabilities to the scenarios, attempted to project ranges of crop yield improvement in the absence of climate change, and compared climate-induced changes to normal variability in crop yields and uncertainty in future projections of yield. A summary point highlighted the difficulty in ultimately detecting any crop yield changes due to climate given the year-to-year variability and the difficulty in disentangling climate effects from the effects of new varieties and other changing technology that would inevitably be introduced over the 25-year period.

1988-1989: US EPA

US EPA (Smith and Tirpak, 1989) evaluated the impacts of climate change on US agriculture as part of an overall assessment of climate impacts on the US. The agricultural results were published in Adams, et al. 1990. The study evaluated warming and changes in precipitation based on doubled CO_2 equilibrium climate scenarios from 3 widely known General Circulation Models (GCMs), with increased average global surface warming of 4.0 to 5.2ºC (7.2 to 9.4ºF). In many ways the most comprehensive assessment to date, it included studies of possible changes in pests and interactions with irrigation water supply in a study of California. The main study on crop yields used site studies and a set of crop models to estimate crop yield impacts. These were simulated through an economic model. Economic results were based on imposition of climate change on the agricultural economy in 1985. Grain crops were studied in most detail, with a simpler approach for simulating impacts on other crops. Impacts on other parts of the world were not considered. The basic conclusions summarized in the Smith and Tirpak report were:

- Yields could be reduced, although the combined effects of climate and CO_2 would depend on the severity of climate change.
- Productivity may shift northward.
- The national supply of agricultural commodities may be sufficient to meet domestic needs, but exports may be reduced.
- Farmers would likely change many of their practices.
- Ranges of agricultural pests may extend northward.
- Shifts in agriculture may harm the environment in some areas.

1988-1990: Intergovernmental Panel on Climate Change (IPCC), first assessment report

In the first assessment report of the Intergovernmental Panel on Climate Change (IPCC), (Parry 1990a and in greater detail, Parry, 1990b)

North American agriculture was briefly addressed. The assessment was based mainly on a literature review and, for regional effects, on expert judgement. North American/US results mainly summarized the earlier EPA study. Some of the main contributions of the report were to identify the multiple pathways of effects on agriculture including effects of elevated CO_2, shifts of climatic extremes, reduced soil water availability, changes in precipitation patterns such as the monsoons, and sea-level rise. It also identified various consequences for farming including changes in trade, area farmed, irrigation, fertilizer use, control of pests and diseases, soil drainage and control of erosion, farming infrastructure, and interaction with farm policies. The overall conclusion of the report was that: "on balance, the evidence suggests that in the face of estimated changes of climate, food production at the global level could be maintained at essentially the same level as would have occurred without climate change; however, the cost of achieving this was unclear."

As an offshoot of this effort, the Economic Research Service of USDA (Kane et al., 1991 and subsequently, as Kane et al., 1992, and Tobey et al., 1992) published an assessment of impacts on world production and trade, including specifically the US. The study was based on sensitivity to broad generalizations about the global pattern of climate change as portrayed in doubled CO_2 equilibrium climate scenarios, illustrating the importance of trade effects. A "moderate impacts scenario" brought together a variety of crop model results based on doubled CO_2 equilibrium climate scenarios and the expert judgements for other regions that were the basis for the IPCC. In this scenario, the world impacts were very small (a gain of $1.5 billion 1986 US$). The US was a very small net gainer ($0.2 billion) with China, Russia, Australia, and Argentina also benefiting while other regions lost. On average, commodity prices were estimated to fall by 4%, although corn and soybean prices rose by 9-10%.

1990-1992: US DOE, Missouri, Iowa, Nebraska, Kansas (MINK) Study

In the Missouri, Iowa, Nebraska, Kansas (MINK) Study (Rosenberg, 1993; Easterling et al., 1993) the dust bowl of the 1930s was used as an analogue climate for global change for the four-state region. Unique aspects of the study included consideration of water, agriculture, forestry, and energy impacts, and projection of regional economy and crop variety development to the year 2030. Crop response was modeled using crop models, river flow using historical records, and economic impacts using an input-output model for the region. Despite the fact that the region was "highly dependent" on agriculture compared with many areas of the country, the simulated impacts had relatively small effects on the regional economy. Climate change losses in terms of yields were on the order of 10 to 15%. With CO_2 fertilization effects, most of the losses were eliminated. Climate impacts were simulated for current crops as well as "enhanced" varieties with improved harvest index, photosynthetic efficiency, pest management, leaf area, and harvest efficiency. These enhanced varieties were intended to represent possible productivity changes from 1990 to 2030 and increased yield on the order of 70%. The percentage losses due to climate change did not differ substantially between the "enhanced" and current varieties.

1992: Council on Agricultural Science and Technology (CAST) Report

The Council on Agricultural Science and Technology (CAST, 1992) report, commissioned by the US Department of Agriculture did not attempt any specific quantitative assessments of climate change impacts, focusing instead on approaches for preparing US agriculture for climate change. It focused on a portfolio approach, recognizing that prediction with certainty was not possible.

1992-1993: Office of Technology Assessment study

The Office of Technology Assessment (OTA, 1993) study, similar to the CAST study for agriculture, focused on steps that could prepare the US for climate change rather than estimates of the impacts. The study's overall conclusions for agriculture were that the long-term productivity and competitiveness of US agriculture were at risk and that market-driven responses may alter the regional distribution and intensity of farming. It found institutional impediments to adaptation, recognized that uncertainty made it hard for farmers to respond, and saw potential environmental restrictions and water shortages as limits to adaptation. It also noted that declining Federal interest in agricultural research and education could impede adaptation. The study recommended removal of institutional impediments to adaptation (in commodity programs, disaster assistance, and water-marketing restrictions), improvement of knowledge and responsiveness of farmers to speed adaptation, and support for both general agricultural research and research targeted toward specific constraints and risks.

1992-1994: US EPA Global Assessment

A global assessment (Rosenzweig and Parry, 1994; Rosenzweig et al., 1995) of climate impacts on world food prospects expanded the method used in the US EPA study for the United States to the entire world. It was based on the same suite of crop and climate models and applied these to many sites around the world. It used a global model of world agriculture and the world economy that simulates the evolving economy through to 2060,assumed to be the period when the doubled CO_2-equilibrium climates applied. The global temperature changes were +4.0 to +5.2ºC (7.2 to 9.4ºF). Scenarios with the CO_2 fertilization effect and modest adaptation showed global cereal production losses of 0 to 5.2%. In these scenarios,developed countries showed cereal production increases of 3.8 to 14.2%, while the developing countries showed losses of 9.2 to 12.5%. The study concluded that in the developing world there was a significant increase in the number of people at risk because of climate change. The study also considered different assumptions about yield increases due to technology improvement,trade policy, and economic growth. These different assumptions and scenarios had equal or more important consequences for the number of people at risk of hunger.

Other researchers simulated yield effects estimated in this study through economic models, focusing on implications for the US (Adams et al.,1995) and world trade (Reilly et al.1993;1994). Adams et al. (1995) estimated economic welfare gains for the US of approximately $4 and 11 billion (1990 US$) for two climate scenarios and a loss of $16 billion for the other scenario,under conditions reflecting increased export demands and a CO_2 fertilization effect (550 ppmv CO_2). The study found that increased exports from the US,in response to high commodity prices resulting from decreased global agricultural production,led to benefits to US producers of approximately the same magnitude as the welfare losses to US consumers from high prices. Reilly et al.(1993;1994) found welfare gains to the US of $0.3 billion (1990 US$) under one GCM scenario and up to $0.6 to $0.8 billion losses in the other scenarios when simulating production changes for all regions of the world through a trade model. They also found widely varying effects on producers and consumers,with producers'effects ranging from a $5 billion loss to a $16 billion gain, echoing the general findings of Adams et al.(1995). In particular, Reilly et al.1994 showed that in many cases,more severe yield effects produced economic gain to producers because world prices rose.

1994-1995:IPCC, Second Assessment Report

The Second Assessment Report of the IPCC included an assessment of the impacts of climate change on agriculture (Reilly et al.,1995). As an assessment based on existing literature,it summarized most of the studies listed above. The overall conclusions included a summary of the direct and indirect effects of climate and increased ambient CO_2, regional and global production effects,and vulnerability and adaptation. With regard to direct and indirect effects:

The results of a large number of experiments to resolve the effect of elevated CO_2 concentrations on crops have confirmed a beneficial effect. The mean value yield response of C_3 crops (most crops except maize,sugar cane,millet,and sorghum) to doubled CO_2 is +30% although measured responses range from -10 to +80%.

- Changes in soils,e.g.,loss of soil organic matter, leaching of soil nutrients,salinization,and erosion,are a likely consequence of climate change for some soils in some climatic zones. Cropping practices including crop rotation,conservation tillage,and improved nutrient management are, technically, quite effective in combating or reversing deleterious effects.
- Livestock production will be affected by changes in grain prices, changes in the prevalence and distribution of livestock pests,and changes in grazing and pasture productivity, as well as the direct effects of weather. Heat stress in particular may lead to significant detrimental effects on production and reproduction of some livestock species.
- The risk of losses due to weeds,insects,and diseases is likely to increase.

With regard to regional and global production effects:

- Crop yields and productivity changes will vary considerably across regions. Thus,the pattern of agricultural production is likely to change in a number of regions,with some areas experiencing significantly lower crop yields and other areas experiencing higher yields.
- Global agricultural production can be maintained relative to base production under climate change as expressed by GCMs under doubled CO_2 equilibrium climate scenarios.
- Based on global agricultural studies using doubled CO_2 equilibrium GCM scenarios,lower latitude and lower income countries are likely to be more negatively affected.

With regard to vulnerability and adaptation:

- Vulnerability to climate change depends on physical and biological response,but also on socioe-

conomic characteristics. Low-income populations depending on isolated agricultural systems, particularly dryland systems in semi-arid and arid regions, are especially vulnerable to hunger and severe hardship. Many of these at-risk populations are found in Sub-Saharan Africa, South and Southeast Asia, some Pacific island countries, and tropical Latin America.
- Historically, farming systems have responded to a growing population and have adapted to changing economic conditions, technology, and resource availability. It is uncertain whether the rate of change of climate and required adaptation would add significantly to the disruption likely due to future changes in economic conditions, population, technology, and resource availability.
- While adaptation to climate change is likely; the extent depends on the affordability of adaptive measures, access to technology, and biophysical constraints such as water resource availability, soil characteristics, genetic diversity for crop breeding, and topography. Many current agricultural and resource policies are likely to discourage effective adaptation and are a source of current land degradation and resource misuse.
- National studies have shown incremental additional costs of agricultural production under climate change that could create a serious burden for some developing countries.
- Material in the 1995 IPCC Working Group II report was reorganized by region with some updated material in a subsequent special report. Included among the chapters was a report on North America (Shriner and Street, 1998).

1995-1996. The Economic Research Service of the USDA

The Economic Research Service of the USDA (Schimmelpfennig et al., 1996) provided a review and comparison of studies that it had conducted and/or funded, contrasting them with previous studies. The assessment used the same doubled CO_2 equilibrium scenarios of many previous studies (global average surface temperature increases of 2.5 to 5.2ºC or 4.5 to 9.4ºF). Two of the main new analyses reviewed in the study used cross-section evidence to evaluate climate impacts on production. One approach was a direct statistical estimate of the impacts on land values for the US (Mendelsohn et al., 1994), while the other (Darwin et al., 1995) used evidence on crop production and growing season length in a model of world agriculture and the world economy. Both imposed climate change on the agricultural sector as it existed in the base year of the studies (e.g., 1990). A major result of the approaches based on cross-section evidence was that impacts of climate were far less negative for the US and world than had previously been estimated with crop modeling studies. While these studies showed similar economic effects as previous studies, they included no direct effects of CO_2 on crops, which in previous studies had been a major factor behind relatively small effects. Hence, if the direct effects of CO_2 on crop yields would have been included, the result would have been significant benefits. The more positive results were attributed to adaptations implicit in cross-section evidence that had been incompletely factored in to previous analyses. The report also contained a crop modeling study (Kaiser et al., 1993) with a complete farm-level economic model that more completely simulated adaptation responses. It also showed more adaptation than previous studies. A summary of this review was subsequently published as Lewandrowski and Schimmelpfennig (1999).

1998-1999: Pew Center Assessment

As part of a series on various aspects of climate change aimed at increasing public understanding, the Pew Center on Global Climate Change completed a report on agriculture (Adams et al., 1999). The report series is based on reviews and synthesis of the existing literature. The major conclusions were:

- Crops and livestock are sensitive to climate changes in both positive and negative ways.
- The emerging consensus from modeling studies is that the net effects on US agriculture associated with doubling of CO_2 may be small; however, regional changes may be significant (i.e., there will be some regions that gain and some that lose). Beyond a doubling of CO_2, the negative effects would be more pronounced, both in the US and globally.
- Consideration of adaptation and human response is critical to an accurate and credible assessment.
- Better climate change forecasts are a key to improved assessments.
- Agriculture is a sector that can adapt, but changes in the incidence and severity of pests, diseases, soil erosion, tropospheric ozone, variability, and extreme events have not been factored in to most of the existing assessments.

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