Agriculture: The Potential Consequences of Climate Variability and Change for the United States

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Foreword

Assessment efforts of this type offer an opportunity for researchers to apply their research tools and expertise to issues of national importance. We came into this effort hoping that the years spent analyzing, modeling, and studying will provide some measure of useful guidance to those who have commissioned the assessment. The efforts provide an opportunity to compare results among colleagues and to deepen one's understanding of the findings of other disciplines. I learned much from my colleagues, who graciously and enthusiastically accepted the invitation to serve on the team.The funding available for the assessment was adequate to support specific modeling tasks and essential travel. Team members generously contributed time well beyond the tasks that were specifically funded. For this I am grateful. It is my hope that members found the experience rewarding and thus found participation worthwhile.

This report represents the combined efforts of the Agriculture Sector Assessment Team but I would be remiss if I failed to point out the substantial contributions of the individual team members. Francesco Tubiello coordinated the crop model scenarios produced by the suite of crop models run by Goddard Institute for Space Studies (GISS), the University of Florida, and the Natural Resource Ecology Laboratory at Colorado State.The protocols and site data developed at GISS by Cynthia Rosenzweig for previous assessments were graciously made available to the teams of crop modelers. In addition to Francesco Tubiello at GISS, Shrikant Jagtap, Jim Jones, Keith Paustian, and Dennis Ojima composed the crop modeling teams that developed comprehensive and consistent scenarios for the two climate scenarios evaluated. The Pacific Northwest National Laboratory (PNNL) team of Cesar Izaurralde and Norman Rosenberg and assisted by Robert Brown applied a model with more geographically comprehensive coverage for several crops for one climate scenario. This provided an opportunity to assess the differences that arose from methodological differences of this approach compared to the detailed site approach used by the other teams. Keith Paustian and Dennis Ojima organised a crop modeling workshop to compare, in more depth, the performance of these models at selected sites to further understand the types of uncertainties that differing model structures could introduce. Linda Mearns contributed her crop modeling expertise as well as her expertise on variability and extreme events. A separate study she was leading that was funded by the National Science Foundation provided critical coverage for cotton.

Bruce McCarl developed national yield changes based on the site results from the crop studies and simulated economic effects. He, with several coauthors, also investigated several other aspects of the problem including the dependence of pesticide expenditures on climate, economic effects of changes in El Niño, and he interacted with the Water Sector Assessment to assure that our water supply assumptions were consistent with their estimates. Roy Darwin provided results on impacts on trade based on recent analyses that he has conducted with his global model. This large effort was possible within the short time-frame and restricted budget because of the tremendous expertise and experience of these team members.

In other aspects of the assessment, the analytical tools and approaches for conducting an integrated assessment have not yet been fully developed. Here we relied on modeling case studies, creative evaluation of historic data, and judgment of experts. Steve Hollinger studied data on crop variability over the past 100 years to provide an historical perspective on adaptation. Keith Fuglie, CIP-ESEAP-Indonesia, while not a part of the team provided additional analyses of historical variability of crop yields. David Abler applied a newly developed model of the economics of water quality in the Chesapeake Bay Region and summarized potential environmental/agro/climatic interactions. Eldor Paul and John Kimble evaluated potential effects of climate change on soils. Susan Riha provided a summary of our current understanding of carbon dioxide effects on plant growth and the potential to develop new crop varieties as a response to climate change and increased ambient CO_2 levels. These efforts pushed into some new, but critical territories, lending perspectives we otherwise would not have.

I am also grateful for the time our Steering Committee took from their busy schedules to guide the effort. I know we have not answered all of the questions they raised but hope that we have answered at least some of them. My thanks also to Jeff Graham of USDA. He left USDA before the report was completed, but left his mark on the effort. Margot Anderson, Director of the Global Change Program Office at USDA, was our initial contact, secured funding from the USDA agencies, and did her best to keep us on track and responsive to the goals of the assessment before leaving USDA in early 2000. Jim Hrubovcak and William Hohenstein picked up where Jeff and Margot left off and continued to provide support for the effort. The study benefited from the steady support of USDA from inception through the review process even as the people changed. USDA remained true to the concept of the National Assessment as a scientific and public participation activity—providing funding, personnel, technical support, and scientific review. A multi-institution activity of this type also required arrangement of travel, meetings, and contracting. Much of this support came from the University Corporation for Atmospheric Research (UCAR). My thanks to Tara Jay, Gene Martin, Jim Menghi, Amy Smith, and Kyle Terran.

Finally, our effort was possible because of the support of the National Assessment Coordination Office, led by Michael MacCracken. We were fortunate that NACO provided at our disposal two exceptional staff members who decided to start out their promising careers by becoming involved in the National Assessment. Justin Wettstein provided support through the planning and initiation stages of the agricultural assessment in 1998 and 1999. LaShaunda Malone took Justin's place in the late summer of 1999 and provided a seamless transition and continued support through the completion of our report. Both worked many extra hours and on a day-to-day basis kept the agricultural assessment process moving while providing support for many other aspects to the National Assessment. Many things that we discovered needed to be done late in the afternoon on a Friday appeared in e-mail early the following Monday. Their help was especially critical and greatly appreciated.

John Reilly
February, 2001

Preface

This report is part of the US National Assessment process, the Potential Consequences of Climate Variability and Climate Change, published by Cambridge University Press (National Assessment Synthesis Team, 2000, 2001). In addition to summarizing scientific understanding about the potential consequences for the Agriculture sector, the report provided input for the two-part national level report entitled, *Climate Change Impacts on the United States* which has been aimed at evaluating the impacts of climate change and climate variability on the United States, across its various regions and including sectors beyond agriculture.

The US National Assessment was undertaken as a joint activity of the federal government with academic institutions, local governments, and public and private groups to understand the implications of climate change and climate variability for the nation. Periodic assessments of global change research and the implications of global change for the US were mandated by Congress when the US Global Change Research Program (USGCRP) was authorized by the Global Change Research Act (GCRA) of 1990. The USGCRP initiated the National Assessment activity to fulfill, in part, the requirement for a periodic assessment in the GCRA. Details about the National Assessment beyond those provided here and links to other related sites can be found at *http://www.nacc.usgcrp.gov.*

The National Assessment includes regional assessment activities that are intended to make research results relevant and useful to conditions, issues, and concerns that vary across the country. Sector assessment activities also are incorporated, being designed to integrate the analysis across issues of national significance that bridge across regions and that may involve topics such as interregional and international trade and competitiveness. In addition to the agriculture sector assessment, the National Assessment has sponsored sectoral assessments for forests, water resources, human health, and coastal areas and marine resources. Although this list of sectors and activities affected by climate variability and climate change is not comprehensive, the sector assessment activities cover some of the sectors and systems that are presently perceived as most sensitive to climate. An important goal of the National Assessment has been that it be participatory and seek to engage stakeholders and the public. This philosophy flows from the belief that applied science must be applicable to the needs of those who are expected to use it. Research is far more likely to be applicable if the users and potential users are involved throughout the assessment process. In this spirit, the agriculture sector assessment sought a steering committee composed of stakeholders and potential users of the research to guide its activities. The individuals who accepted this responsibility and actively and graciously participated are listed below. The full report of the initial meeting of the steering committee and sector assessment team is available at *http://www.nacc.usgcrp.gov/sectors/agriculture/workshop-report.pdf.*

In carrying through these responsibilities, the agriculture sector assessment team has made an effort to coordinate closely with those regional assessment activities that have included a significant agriculture assessment (to the extent that the schedules of the efforts were compatible). Indeed, several members of the agriculture sector assessment team are responsible for agriculture assessment activities in various regional assessments. Similar efforts have been made to coordinate with the other sector assessments. Where possible, results from other sectors (for example, changes in water availability and their impact on irrigation water supplies) have been used as input into our evaluation of agriculture. Furthermore, as with regions, the agriculture sector assessment team overlaps with other sector assessment teams (i.e., water and forests), and so cooperative interactions have occurred quite naturally.

As part of the National Assessment, some aspects of the approach were under our direction and some were guided by the need for consistency across the various assessment activities. For example, with regard to future climate scenarios, our guidance was to focus on using the Canadian Climate Centre and Hadley Centre climate scenarios as one basis for projecting possible future climate change; in addition, we have used records of historic climate variability to evaluate resilience to recurrence of such conditions and considered whether possible thresholds might be important. The National Assessment also provided some guidance on future socioeconomic scenarios. We did not, however, develop numerical agroeconomy scenarios consistent with the economic scenarios; rather we imposed climate change on the agricultural economy as it exists today because projecting agricultural developments might well introduce additional uncertainties.

In keeping with the purpose and goals of the National Assessment, the agriculture sector assessment report has two broad objectives:

- To respond to the goals of the GCRA (Section 106: Scientific Assessment), which directs the National Science and Technology Council to conduct, on a periodic basis, an assessment that
  - "integrates, evaluates, and interprets the findings of the Program and discusses the scientific uncertainties associated with such findings;
  - analyzes the effects of global change on the natural environment, agriculture, energy production and use, land and water resources, transportation, human health and welfare, human social systems, and biological diversity; and
  - analyzes current trends in global change, both human-induced and natural, and projects major trends for the subsequent 25 to 100 years."
- To bring useful scientific results to decision makers in agriculture, with the aim of providing information for better decisions.

While we were not able to accomplish all that we wanted nor to resolve every question, we provide these results with confidence that they can help agricultural stakeholders more fully appreciate the potential consequences of climate variability and change.

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*Note: Individual affiliations are consistent with the time when the assessment was under review. Some individuals are no longer associated with the listed affiliation.

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 percent loss of income, while the savings of $3-6 billion to consumers represent less than a 1 percent reduction in the consumers food and fiber expenditures. Under the Hadley scenario, producers' profits are reduced by up to $3 billion (10 percent) while consumers save $9-14 billion (in the range of 1 percent). 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 percent for 2030 and 30-40 percent 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 percent 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 percent; for potatoes, 5-15 percent; and for soybeans and cotton, 2-5 percent. The results for wheat varied widely by state and climate scenario showing changes ranging from approximately –15 to +15 percent. 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.

Chapter 1

Changing Climate and Changing Agriculture

Introduction

Agriculture on the North American continent has changed rapidly and continuously at least since European colonization. All evidence suggests that agriculture will continue to change rapidly in the future. One of the forces to which future American agriculture will likely have to adapt is changing climate induced by the accumulation of greenhouse gases in the atmosphere. The impacts and adaptations that may occur in response to changing climate are the primary topics of this assessment. We also consider weather variability and its impact on agriculture, focusing on some of the implications for adapting to climate change.

In this chapter we begin by identifying key questions we address in this assessment. We then provide a broad overview of American agriculture: its past, current conditions, and trends that will take it into the future. We conclude this chapter with a report of the interests of agricultural stakeholders with whom we met as part of our assessment. These stakeholders include those who are in the business of producing food and fiber and related input and processing industries, those who are particularly concerned with the environmental attributes of agriculture, and those who are involved in public policy and program management in agriculture.

Within the agricultural community there is a great deal of interest in the effects of climate change mitigation policies on agriculture. There are potential costs (higher energy prices and costs of controlling non-CO_2 greenhouse gases such as methane and nitrous oxide) and potential opportunities (receiving payments for sequestering carbon in soils) for agriculture. Evaluating these costs and opportunities is not within the scope of this report. Interested readers are referred to the reports *Economic Analysis of U.S. Agriculture and the Kyoto Protocol* and *Economic Potential of Greenhous Gas Emissions Reductions: Comparative Pole for Soil Sequestration in Agriculture and Forestry.*[1]

We focused on answering four questions identified as important to stakeholders in our assessment:

- What are the key stresses and issues facing agriculture?
- How will climate change and climate variability exacerbate or ameliorate current stresses?
- What research priorities are most important to fill knowledge gaps?
- What coping options can build resiliency into the system?

These objectives and questions guided the agriculture sector assessment. We address the first question in succeeding sections of this chapter. We review results from previous assessments in chapter 2 to the extent they contributed to answering each of these questions. We address the second and fourth questions in chapters 3–5. We organize our conclusions in chapter 6 to review our answers to these four questions. To address these questions, we met with agricultural stakeholders, reviewed relevant research and recent assessments, and conducted a program of modeling and research.

Any research effort must operate within budgetary constraints. In general, we tried to build on past work rather than repeating previous exercises. Several assessments of climate change and agriculture within the past four years have involved literature review. We summarize the findings of these reviews and provide a more detailed discussion of our methods in chapter 2. Stakeholders identified questions that were much broader and more far-reaching than those covered in recent assessments, however (see "Stakeholder Interests," below). We

[1]*Economic Analysis of US Agriculture and the Kyoto Protocol* was prepared by the Office of the Chief Economist, Global Change Program Office of the US Department of Agriculture (USDA) with technical input from the Economic Research Service (*http://www.usda.gov/oce/gcpo/gcponews.htm*). *Economic Potential of Greenhouse Gas Emissions Reductions: Comparative Pole for Soil Sequestration in Agriculture and Forestry* was prepared by McCarl, Schneider, Murray, Williams, and Sands *(http://www.agecon.tamu.edu/faculty/mccarl/mitigate.html)*.

focused our new research on some of these topics for which the research tools to conduct quantitative assessment were adequate. In many cases, however, answers to these questions would require more accurate forecasts and projections than we can achieve—or the development of new assessment tools. The best we could do with regard to these topics was to identify them as open questions and offer some brief observations about the potential implications of climate change. Undoubtedly, this shortcoming will leave readers with these interests less than fully satisfied.

Our analysis is a fairly comprehensive treatment of the country, with details on individual crops and regions. Because of our limitations of funding and resources, however, the level of detail certainly is inadequate for state and local decision makers. The job of interpreting and deepening the analysis falls to the regional assessment efforts, which are composed of researchers with a firm understanding of the local context. This local assessment is particularly crucial for understanding coping strategies that are relevant to farmers whose conditions vary. In this regard, we follow a tradition in agricultural research and extension that relies on state and county experts to provide guidance that is directly relevant to local farmers.

Agriculture: Past, Present, Future

Our only guide to the future is what we know about the current state of agriculture and the trends and responses we have evaluated from the recent past. Part of this knowledge consists of trends in development and adoption of state-of-the-art technologies. By understanding the technological forefront, we hope to see a decade or two ahead; such assessment, however, is still based on current knowledge and historical experience with adopting new technology. In this section, we do not attempt to describe agriculture comprehensively, and we certainly do not offer precise predictions for US agriculture for the next 100 years. Throughout the report we use the term "projection" rather than "prediction" indicating that the climate scenarios we evaluate and the results we derive from them are based on the mathematical formulation of models that capture key interactions as we understand them. Precise prediction of future economic and social conditions is, of course, not possible. Given the limited exploration of the possible range of climate, technological, and socio-economic conditions we were able to explore, even probabilistic predictive statements (e.g. there is at least a 70 percent chance of an outcome exceeding a given level) were not possible. For those interested in greater detail on the US agriculture sector, the Economic Research Service (ERS) of the USDA regularly surveys and reports on the current status of American agriculture, its relationship to the rest of the world, its use of natural resources and the environment, and the health and nutritional status of the US population. Myriad data, reports, and assessments conducted by ERS are available at *www.ers.usda.gov*. Our goal here is to provide a broad-brush outline of the American agricultural system: what it has learned from the past, where it is now, and where it may be in the next century.

Our focus in this review is on identifying some of the important connections between agriculture and weather and climate. Any effort to cope with climate change and climate variability in the future will grow out of and react to the perception of the success or failure of past efforts to manage agriculture. As impossible as summarizing American agriculture may be, something of a description is needed to provide a context for studies of the impact of climate change and variability.

100 Years of Change

US agriculture has undergone vast changes over the past century. In 1900, 60 percent of the US population lived in rural areas; there were 6.4 million farms, and the average farm size was 132 acres. By 1990, only 25 percent of the population lived in rural areas; there were 2 million farms, and the average farm was 435 acres.[2] Even in 1900, however, US

[2]Data on the rural population are from the Census Bureau (*http://www.census.gov/population/censusdata/urpop0090.tx*t). Data on farmland are from the USDA National Agricultural Statistical Service, based on census data (1999 Agricultural Statistics available at *http://www.usda.gov/nass/*) and computed from Tables 9.7 and 9.8 at this WEB address. Definitions of farms—and thus land in farms and number of farms—have varied. Other tables give slightly different estimates.

agriculture was an export industry. Cotton, tobacco, and wheat crops were exported to Europe. As vast as the country seemed at the time, some observers predicted that the bounty would be exhausted soon by an ever-growing population. Sir William Crookes, of Great Britain, writing in 1900, concluded that "it is almost certain that within a generation the ever-increasing population of the United States will consume all the wheat grown within its borders, and will be driven to import, and like ourselves, will scramble for the lion's share of the wheat crop of the world" (quoted in Dalrymple 1980). Relative scarcity of supply compared with demand, and strong overall economic conditions over the next couple of decades did, indeed, produce some of the most prosperous times for farming. The years 1912–1913 were later regarded as the last point when farmers received a "fair" price for farm products. This period of relative prosperity for the farm sector became a benchmark in the 1940s for post-war farm programs whose goal was to revive the farm economy after the Depression of the 1930s. Through a series of economic downturns and even economic booms, agricultural prices seemed primarily to go down. Whereas the US economy boomed after World War II, agriculture seemed to be mired in low prices. In the early part of the century, economic development in rural areas lagged behind that in urban areas. The trend of declining prices represented a success for productivity and production and reflected overall declining costs of production; in and of itself, this price trend cannot be considered a cause of the economic hardship in rural areas or the farm sector. In fact, the income of farm households relative to nonfarm households in the US improved over the latter half of the century even as prices continued to decline. Declining prices do, however, put continual pressure on individual farmers to constantly reduce costs to keep up with market trends. As in any sector in which there is rapidly changing technology (e.g., computer production), many producers fall by the way as others lead in the adoption of successful technology.

Oddly (for those who had looked ahead to see food so scarce that hunger and famine would spread), even as more farmers left the farm, more food was produced, and commodity prices continued to fall. Evidence of this worldwide trend since the 1950s includes falling real prices for food commodities (Figure 1.1) and steadily increasing agricultural output. Indices of real prices for all food products and for cereals fell more than 60 percent from the early 1950s to the early 1990s.[3] Worldwide food production growth over the past three decades also has been relatively consistent—increasing by 2.7 percent per year during the 1960s, 2.8 percent during the 1970s, and 2.1 percent during the 1980s.

How did this happen? In the United States, the great dams and water projects of the West made the deserts bloom. New and more powerful machinery enabled those remaining on farms to till hundreds of acres instead of tens of acres. Starting mid-century, crop breeding began to produce a constant supply of new varieties of plants that have increased yields for more than 50 years. Although the rates of growth have varied since 1939, annual rates of growth in yield for corn, potatoes, and sorghum have been on the order of

Index of World Food Prices

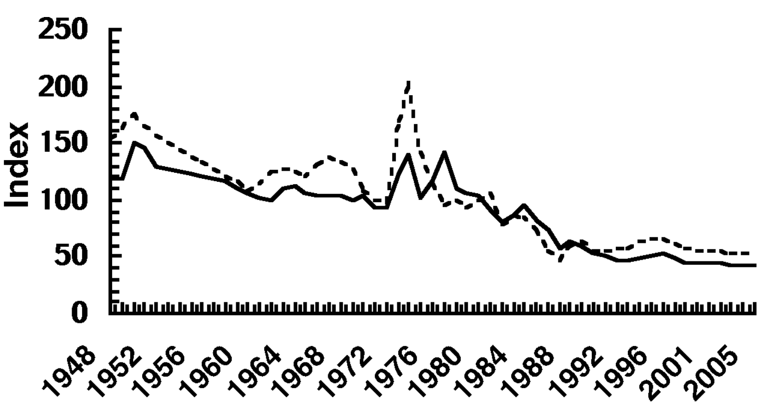


Figure 1.1: From the 1950s to the early 1990s, indices for real food prices for all food products and for cereals fell more than 60 percent. Dashed line: cereals; solid line: all food commodities (1970 = 100). Source: Reilly and Schimmelpfennig 1999.

[3]The real price declines were 63 percent for total food and 62 percent for cereals, using as a base the 5-year average for 1948 through 1952 as compared with the 1992–1996 period. Five-year averages were used to minimize the impact of choice of base year—which can be substantial, given the volatility of commodity prices.

2.5–3.0 percent; for rice, wheat, barley, and cotton, the increase has been on the order 1.8–2.2 percent; for soybean, oats, sunflower, and flaxseed, the increase has been on the order of 1.0–1.25 percent (Reilly and Fuglie 1998). Improved varieties that were the basis for these increases required (or were able to take advantage of) high levels of nutrients, which were supplied by cheap, inorganic fertilizers. Inorganic fertilizers were part of the chemical revolution that also brought new ways to control weeds, insects, and diseases in crops. Livestock also underwent improved productivity through breeding, better veterinary products, improved farm management practices, and increasing mechanization. Agricultural economists, observing these forces in the 1950s, termed technical change in agriculture the "technology treadmill." The technology treadmill is not unique to agriculture; in this interpretation, however, farmers must adopt the new cost-saving and yield-enhancing technologies just to stay even. Whoever failed to keep up with technology would be run off the treadmill into an abyss of economic losses as neighbors, the farmers in the next state, or competitors around the world kept running. Improved shipping and transportation reduced ever further any edge a farmer might have in supplying local markets.

Concern about farm income and prices coming out of the Great Depression of the 1930s led to enduring farm programs. Weather-induced variability was one justification for these massive programs. The idea was that the government would buy up commodities when harvests were large—keeping prices up—and sell these stocks when there were crop failures, thereby preventing prices from skyrocketing. In this hopeful view, farmers and consumers would benefit from stable prices. After nearly a half-century of these programs, however, analysts still argue about whether government intervention may have, instead, increased variability. In addition to the desire to even out prices, there was a desire to assure a reasonable income for farmers. Thus, the prosperous days of 1912–1913 became the benchmark for parity prices—prices (or some proportion of prices) that farm programs would seek to assure farmers. High prices brought more output, however, and increasing surpluses that depressed prices. In trying to fight these market forces, farm programs incorporated a complex combination of foreign (and domestic) food aid, acreage reduction programs, commodity stockpiles, and an array of payment mechanisms that were meant to provide income support without bringing on gluts of production. Farm legislation in 1996—the Federal Agriculture Improvement and Reform (FAIR) Act—was intended to transition US agriculture over a period of seven years toward full reliance on markets, ending once and for all this system of incentives and counter-incentives.

Dating to the Morrill Act of 1862, which granted states and US territories scrip to land that they could sell to develop colleges that would offer practical instruction in agriculture and the mechanical arts, a nationwide system of agricultural experiment stations has turned out increasingly high-yielding varieties, farm management assistance, and improved livestock. Publicly funded research, freely provided to farmers, was a major force behind yield improvements. The role of public funding has changed as the private sector has increased research and development—taking over much of the applied and product development research and using intellectual property rights protection to recoup the investment. Fuglie et al. (1996) provide a comprehensive analysis of public and private research in agriculture. Productivity growth—measured as the growth in output less the growth in inputs—has been high since at least the 1950s, averaging more than 1.9 percent per year (Ahearn et al. 1999). Output has doubled over that period, while input use remained essentially unchanged.

Changing regional competitiveness also has been a feature of changing agriculture. The changing competitiveness and fortunes of different regions cannot be traced to a single factor. The opening of canals; building of railroads; construction of large water projects; shifting population; changing technology; introduction of new pests; resource degradation or opening of new, more productive areas; and environmental considerations have all come into play. Woven into this dynamic was the nature of the people who took up farming in different regions or chose to move on or out rather than adapt. Milk production shifted from New York and Pennsylvania to Wisconsin and then to California and Florida; it has left behind fading red barns and reforested hills. Cotton shifted from the South to the Southwest and West as pests, depleted soils, and irrigation water changed the fortunes of different regions. Most fruit and vegetable crops, which once were locally produced and were available only seasonally, are now available in supermarkets year-round, with worldwide suppliers. Processed vegetable production also has shifted. Cheap and widely available transport gradually has increased the regional specialization of cropping and livestock production to areas that are especially favorable for a particular crop or unfavorable for everything else. As competitiveness demands greater management, farmers fare best if they focus on one or a few complementary crops that do well under the climatic and resource conditions they face. Farmers and the input suppliers and product processors can reap economies of scale from large and regionally concentrated production.

We asked two questions about the past 100 years that have a bearing on climate and agriculture interactions:

- Has yield variability changed over the past century?
- Has the production of major crops relocated geographically and climatically?

We found that long-run yield variability did not increase for corn and fell significantly for wheat and potatoes (Table 1.1). There were, however, substantial geographic shifts in production of these three major crops over the past 100 years (see Figures 1.2 through 1.4).

Is climate change responsible for these changes? There is some evidence of climate change over the past century that might have affected crop variability and the location of production. More rain has fallen in heavy precipitation events; on average, rainfall has increased across the United States, with more cloudy days (Karl and Knight 1998). Temperature variability increased during the period 1973–1993 compared with 1954–1973 (Parker et al. 1994) but decreased on times scales of one day to one year (Karl et al. 1995). Based on a fitted linear trend, the average frost-free season has increased by 1.1 days per decade (Easterling, in press); the average temperature increased by 0.6°C through the early 1990s (Karl et al. 1996).

Table 1.1: Long-term Trends in Variability in US Crop Yields

Commodity	Area harvested in 1997 (000 ha)	Area irrigated in 1997 (%)	Variation in crop yield from trend (%, with standard error in parentheses)					
			1870–1994		1900–1994		1950–1994	
			Mean variation	Trend in variation	Mean variation	Trend in variation	Mean variation	Trend in variation
Corn	28,258	15.2	7.77 (0.58)	-1.271E-2 (1.62E-2)	7.24 (0.68)	1.553E-2 (2.48E-2)	6.97 (0.89)	2.357E-1 ** (5.938E-3)
Wheat	23,820	6.8	6.28 (0.45)	-2.834E-2 ** (1.230E-2)	5.86 (0.51)	-3.122E-2 * (1.81E-2)	4.92 (0.63)	-5.662E-4 (4.719E-2)
Potato	549	79.0	5.75 (0.52)	-8.159E-2 ** (1.237E-2)	4.40 (0.46)	-7.608E-2 ** (1.457E-2)	2.42 (0.30)	-4.076E-3 (2.211E-2)

Yield variation is measured by V = absolute value of $(X_t - X_{trend})/X_{trend}$, where X_t is crop yield in year *t* and X_{trend} is the 9-year moving average of yield centered on year *t*, using annual crop yield data from 1866 to 1998. The trend in yield variation is the estimate of coefficient β from the linear regression model $V = \alpha + \beta t$.
* Significant at 10% level
** Significant at 5% level
Source: Data are from the US Department of Agriculture. Statistical estimation was conducted by Keith Fuglie of CIP-ESEAP, Indonesia.

Movement of Center of US Corn Production, 1871–1992

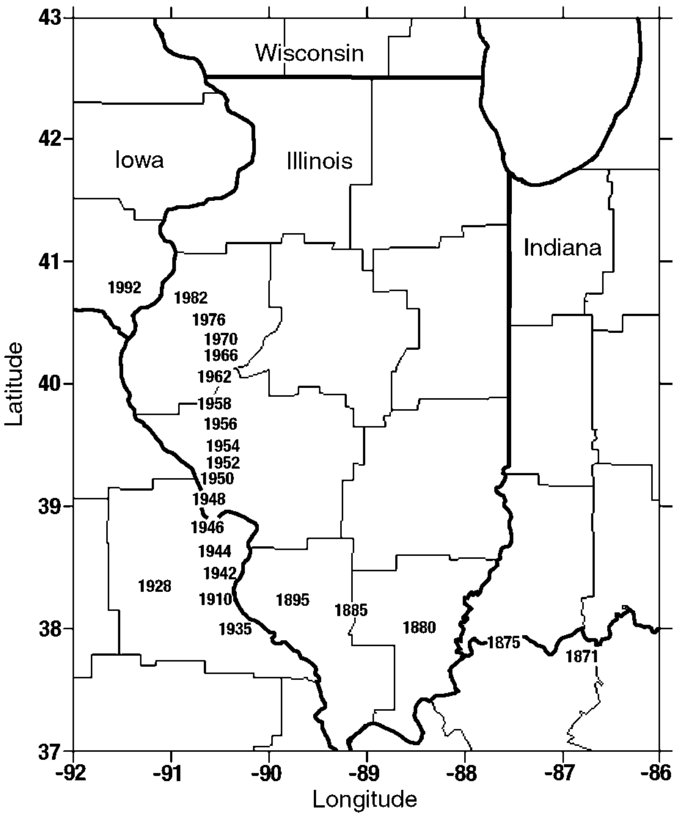


Figure 1.2: The US corn production geographical center (production weighted) moved westward from Indiana in 1871 into Missouri by the early 1900s. Since then production has shifted northward through Illinois.

Our findings tell us as much about the complexity of climate-agriculture-social interactions as they do about how the agricultural system might respond to climate change in the future. The result of no change or an actual decrease in yield variability despite climate change leaves three competing hypotheses:

- The various climatic forces have had coincidentally offsetting effects on yield variability.
- The time period coincidentally shows no change in variability. Indeed, one can pick sets of decades that show differences in variability, as in the 1950–1994 period (see Table 1.1).
- Yield variability is a function of economic and social acceptance of risk, which may be relatively constant over time. This hypothesis recognizes that farmers have variability-reducing technologies such as irrigation, shorter-maturing varieties, changes in type of crop grown, and abandonment of the area to cropping, and that they can make an economic and personal calculation about what to do. Lewandrowski and Brazee (1993) have shown, for example, that the structure of federal farm programs has affected farmers' decisions about risk.

Sorting out these competing theories requires far more sophisticated empirical evaluation than we were able to undertake.

Movement of Center of Wheat Production, 1871–1990

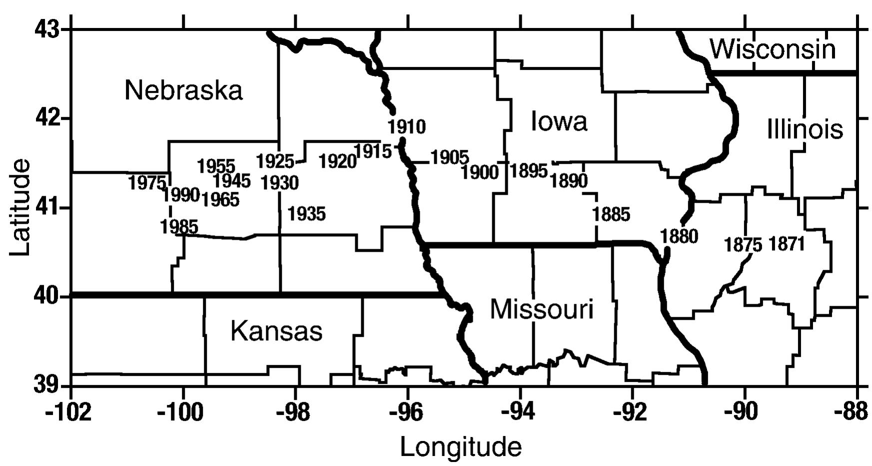


Figure 1.3: The US geographical center of wheat production (production weighted) shifted mainly westward from Illinois in the late 1800s as a result of expansion of production in the far west.

The northward movement of corn production could be a signal of warming and increased frost-free days. Notably, however, the mean temperature at which corn was grown fell by 4°C between 1935 and 1965—the period when the geographic centroid shifted north.[4] If corn production were shifting in response to warming, one would expect the mean temperature to remain unchanged. If there had been no response, the mean temperature would have risen rather than fallen. As a whole, these results indicate that some other process—such as the development of shorter maturing varieties or relocation of production as a result of economic factors—was causing a northward movement of production that is greater than can be explained by changes in temperature.

The westward migration of crops is more likely caused by expansion of irrigation in the semi-arid western United States over this period. Again, these results indicate the difficulty of separating climate signals from easily observable aggregate indices that are partially the result of climatic trends but also are heavily determined by socioeconomic factors. The movement of the centroid of production, however, does indicate that the geography of crop production has not been static and that relocation because of climate change over the next century, if it occurred, would not in itself be an unprecedented social change.

Movement of Center of Soybean Production, 1930–1990

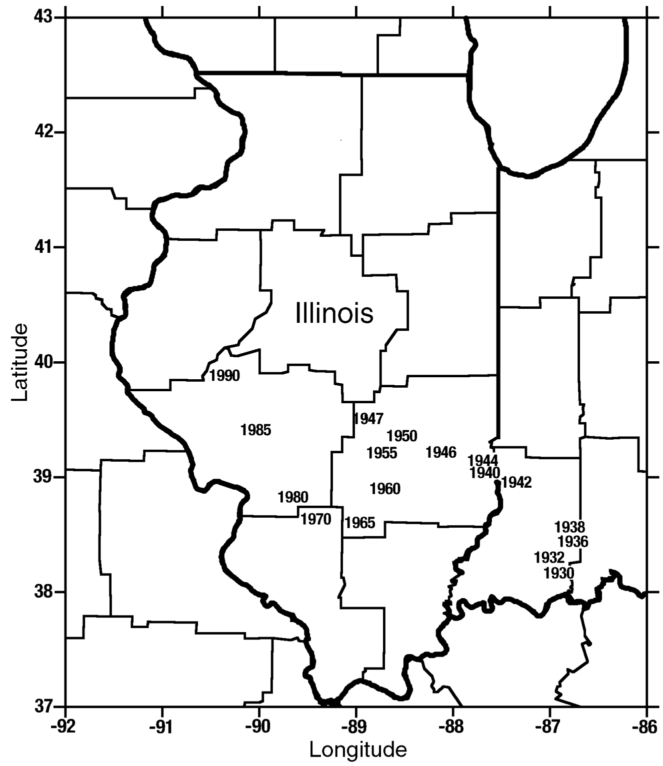


Figure 1.4: The US geographical center of soybean production (production weighted) shifted from southern Indiana northwest into Illinois.

Throughout the century, agriculture also has been subject to inclement weather. Droughts, cold, late and early frosts, extreme heat, and storms affect some areas of US agriculture in almost any given year. At times they are widespread or catastrophic enough or affect a large enough constituency that the weather and its effect on agriculture briefly gains media attention and are broadcast to the 99 percent of Americans who are not farmers. For the most part, however, whatever disaster befalls the farmer, the American consumer is little affected. For many Americans, the decision about whether to leave a 10, 15, or 20 percent tip at the restaurant probably has more economic consequences than any impact they will see from adverse weather effects on farm production. A widespread drought or weather catastrophe might increase retail food prices by three to four percent; yet Americans spend more than one-half their food dollars eating out. Moreover, the farm gate cost of food is a small fraction of the final cost to consumers. The nature of agricultural demand (highly inelastic in economic terms) means that a widespread drought can improve the bottom line of the farm economy—raising prices more than supply is cut back and thus increasing farm revenue. On the other hand, a localized drought (such as the one in the mid-Atlantic in 1999) combined with near-ideal growing conditions throughout large growing regions in the Midwest can lead to financial losses for most farmers. Lower prices resulting from good

[4]Authors' calculations based on spring and summer state average temperature and precipitation data from 1900 to 1997 (MWRCC 1999) and state yield data from 1865 to 1997 for corn and wheat, and from 1924 to 1997 for soybean from USDA (1999d).The mean temperature and precipitation for the growing region of each crop were computed by weighting the mean temperature and total precipitation for each state by the ratio of the state harvested acreage to the total acreage harvested in the U.S. Crop production centroids were computed from weighting the geographic centroid of each state by the ratio of the production in each state to the total national production.

production overall can mean that even farmers who experience excellent growing conditions and high yields do not cover costs. Those who suffer yield loss because of drought face low prices combined with reduced production.

Weather is so central to farming that most of the techniques used in farming, agribusiness, and the food industry somehow reflect a desire to overcome weather. It is not stretching the facts to observe that there is no such thing as a "normal" year. A year characterized by 30-year means for all months of the growing season and showing an "average" pattern of extremes would be truly abnormal. Conquering variability is manifest in nearly every dimension of farm management. Included are technologies such as crop drying, irrigation, drainage and tiling, and storage; shading and cooling for livestock; selection and breeding of livestock and crops that are hardy or hardier under a wider range of climatic conditions; financial and farm management such as financial savings, borrowing, crop insurance, diversified production strategies, and off-farm income; market instruments such as forward markets and contract production that shifts and pools risk; prediction and outlook on weather and economic conditions; and government policy such as disaster assistance, farm programs, and government involvement in the insurance markets.

As We Enter a New Century

Agricultural production is very diverse. This diversity bespeaks an industry undergoing rapid change. We excerpt below a verbatim summary of highlights from the 1999 Family Farm Report, a document produced each year by the ERS under Congressional mandate. The summary and details on ordering the report are available at *http://www.ers.usda.gov/epubs/htmlsum/aib735.htm*. The report finds that

- More than 2 million US farms produced agricultural commodities that generated an average of $74,000 in gross value of sales per farm in 1994. Still, 73 percent of farms had gross value of sales under $50,000 (noncommercial farms), although they accounted for just 11 percent of total US farm sales.
- Gross cash farm income (adjusted to exclude the share of production accruing to landlords and contractors) averaged nearly $69,000. However, gross cash farm income for the nation's largest farms (sales of $1 million or more) averaged almost $2 million, so fewer than 1 percent of farms accounted for 23 percent of gross cash farm income. Commodity sales accounted for 84 percent of total gross cash farm income; government payments added 5 percent and other farm income added 11 percent.
- Acreage per farm, which has tripled over the past six decades, averaged 448 acres operated in 1994, but half of all farms were smaller than 180 acres. Livestock farms producing some combination of beef cattle, hogs, and sheep accounted for the largest share of farms grouped by farm type. Although these farms had larger acreage than the US average, they had lower average gross cash farm income and gross value of sales.
- Half of all farms cash-rented or share-rented some or all of the land they operated in 1994. Farm operators who owned all the land they operated but had a rental arrangement for machinery, buildings, or livestock (5 percent of full owners) had income and sales five times as high as full owners who rented nothing.
- More than 90 percent of farm businesses were legally organized as individual operations; 6 percent of farms were partnerships, and 4 percent were corporations (most of which were family-owned).
- Farms organized as individual operations averaged more than $50,000 in gross value of sales and had farm assets that averaged more than $350,000.
- Although 13 percent of all farm operators reported having some contractual arrangement for production and/or marketing of farm commodities, farms with marketing contracts outnumbered farms with production contracts by more than 4 to 1.

- Use of contracting arrangements varied by farm characteristics such as sales class and type of production. For example, more than 60 percent of poultry farms had production contracts.
- Net cash farm income averaged $11,696 for farms nationwide but ranged from negative for farms with sales under $50,000 to more than $380,000 for farms with sales of $1 million or more.
- Farm assets generally increased with sales class, but even farms with sales under $50,000 had farm assets averaging more than $250,000. Farms with gross value of sales of $1 million or more used assets valued at more than $3 million to generate $2 million in gross cash income. These large farms also had the highest debt-to-asset ratio (0.25).
- In 1994, 61 percent of farms were in a favorable financial position, with a low debt-to-asset ratio (0.40 or less) and positive net farm income. Another 34 percent of farms had a low debt-to-asset ratio but were unable to generate enough income to offset expenses, so net farm income was negative—putting them in the marginal income category. Most of these operations were noncommercial farms.
- Only 4 percent of farms were in a vulnerable financial position, with a high debt-to-asset ratio (0.40 or more) and negative net farm income that threatened the long-term survival of the business.
- More than a third of farms received income from government payments, averaging $9,306 per receiving farm. Almost two-thirds of commercial farms (gross value of sales $50,000 or more), compared with one-fourth of noncommercial farms, received government payments. Government payments accounted for less than 3 percent of gross cash farm income for commercial farms, however, compared with 41 percent for noncommercial farms.
- More than 40 percent of the nation's farm operators reported farming or ranching as their principal occupation. Their farms accounted for more than 80 percent of gross cash farm income and gross value of sales. Households of operators with a principal occupation of farming had average total household income that was about 85 percent of the US average. About a third of total income for these households came from earnings from farming activities, and two-thirds from off-farm sources.
- Operators younger than 35 years old accounted for 9 percent of all operators, whereas operators 65 years old and older accounted for 24 percent. The youngest operators, however, generated their proportionate share of total US gross cash farm income and gross value of sales (based on number of farms), whereas the oldest group generated about half their proportionate share.
- About 13 percent of all farm operators used electronic information services to get farm business information. Use of this new technology increased with farm size and operator educational attainment level (20 percent of operators who completed college, compared with 10 percent of those who completed only high school).
- More than 60 percent of farm operators ranked getting out of debt and improving crop yield or livestock production as very important business goals. Commercial farm operators ranked these goals higher than noncommercial farm operators.
- Mean household income from all sources for farm operator households was near the US average. On average, 90 percent of total operator household income came from off-farm sources. For almost half of all farm households, earnings from farming activities (farm self-employment income plus other farm-related earnings) were negative, but total household income was positive because off-farm income exceeded the loss.

- As farm sales increased, household dependence on earnings from farming activities increased and household income relative to the US average increased.
- Operator households associated with farms that had a gross value of sales of $500,000 or more had average household income 3.5 times the US average, and earnings from farming activities accounted for 75 percent of total operator household income.
- Noncommercial farm operators worked half of their annual working hours on the farm; their spouses worked about one-fourth of their working hours on the farm.
- Commercial farm operators worked 88 percent of their total work hours on the farm; spouses averaged almost half of their total work hours on the farm.
- Rankings of eight selected measures of farm business success showed that having farm income sufficient to support the household was most important to operators reporting their principal occupation as farming.
- More than half of farm operators reported that passing the operation on to the next generation as very important.

The remarkable aspect of this summary is the diversity among farm operations. Indeed, the enterprise of farming appears to have divided into at least several broad categories. The bulk of commodities are produced on large commercial farms with large revenues, whose operators rely principally on the farm as a source of income and who earn a family income above the average of the US household. A second group of farm operators run small farms; net income from the farm is very small or negative, and the income of the household is determined by the off-farm earnings of the household members. Another group of farmers is near retirement or in semi-retirement. The farmers in this group typically own outright all the land they operate; in fact, they may rent most of their land or have it enrolled in a long-term easement program such as the Conservation Reserve Program that pays farmers of highly erodible land to maintain permanent cover on the land.

A fourth group comprises farmers who own mid-sized farms. This group of farmers is most vulnerable to the century-long trend toward larger farms. Farmers in this group are most likely struggling to earn an income from the farm operation and supplementing household income with off-farm employment, working for the day when the family can survive on farm income alone. They face difficulty in affording expensive new technologies, such as precision farming, that involve onboard computer monitoring guided by global positioning systems (GPS). As profit margins tighten, the scale of operation must grow if the main occupation is to remain the primary source of family income. One alternative for this group, already widespread in the poultry and hog industries, is to produce under contract with processors. The processor bears more of the risk and provides specific guidelines for production. This approach represents a major cultural change for many farmers who value the independent life that farming traditionally has represented.

The trend that has emerged in the past decade is that the smallest farm categories have exhibited increasing numbers. The reasons for this trend are highly diverse as well. People returning to farm—supplementing farm income with off-farm employment and perhaps no intention of fully supporting themselves through farming—are one group. Others have found niche and local markets where the profit margins are higher than for bulk commodities. Operators have found success with everything from organic foods and herbs sold to more expensive, high-end restaurants to Christmas trees, selling to local farmers markets, or inviting consumers to "pick their own"—perhaps combined with some form of entertainment for the urban dweller seeking a farm experience.

Climate change is unlikely to alter this dynamic in any fundamental way. The regional effects of climate change may vary considerably (as we detail in subsequent chapters). An increasing percentage of bulk commodities probably will be produced on the largest farms. Middle-sized farms will continue to be squeezed if they must compete in bulk commodity production. Niche producers for local markets can be successful if the products are cleverly chosen, the enterprises are well-run, and the products deftly marketed. Success, however, inevitably will invite competition If climate change is somehow beneficial to a region, it may slightly ease the pressure exerted on mid-sized farms. If climate change has adverse consequences for the region, it may tighten the grip on the most vulnerable producers. Agriculture is a highly variable enterprise, however, with relatively low barriers to entry relative to industries such as automobile and pharmaceutical manufacturing. Hence, any evidence of increased profitability will tend to draw more producers, bid up land prices, and keep the profit margin tight. Thus, even if climate change is somehow beneficial with respect to production, it is unlikely to manifest itself as widely perceived windfall profits. Likewise, if climate change is adverse, the gradual change is unlikely to be perceived as windfall losses. In both cases, downturns in commodity prices will continue to take out the vulnerable farmers, and upturns will encourage production expansion.

Forces Shaping the Future

A few broad forces will shape the future for American agriculture over the next few decades:

- Changing technology. Biotechnology and precision agriculture are likely to revolutionize agriculture over the next few decades, just as mechanization, chemicals, and plant breeding revolutionized agriculture over the past century—although public concerns and environmental risks of genetically modified organisms could slow development and adoption of crops and livestock containing them. Biotechnology has the potential to improve adaptability, develop resistance to heat and drought, and change the maturation schedule of crops. Biotechnology also will give rise to entirely new streams of products and allow the interchange of characteristics among crops. Precision farming—the incorporation of information technology (e. g., computers and satellite technology) in agriculture—will improve farmers' ability to manage resources and to adapt more rapidly to changing conditions.

- Global food production and the global marketplace. Increasing linkages are the rule among suppliers around the world. These links are developing in response to the need to assure a regular and diverse product supply to consumers. Meat consumption is likely to increase in poorer nations as their wealth increases, which will place greater pressure on resources. Climate change could exacerbate these resource problems. Trade policy, trade disputes (e.g., over genetically modified organisms), and the development of intellectual property rights (or not) across the world could have strong effects on how international agriculture and the pattern of trade develops.

- Industrialization of agriculture. The ever-faster flow of information and the development of cropping systems that can be applied across the world will transcend national boundaries. Market forces are encouraging various forms of vertical integration among producers, processors, and suppliers, in part driven by the need to produce uniform product and assure supply despite local variations induced by weather or other events.

- Environmental performance. Agriculture's environmental performance is likely to be a growing public concern in the future, which will require changes in production practices. Significant environmental and resource concerns related to agriculture include water quality degradation caused by soil erosion, nutrient loading, pesticide contamination, and irrigation-related environmental problems; land subsidence resulting from aquifer drawdown; degraded freshwater ecosystem habitats resulting from irrigation demand for water; coastal water degradation caused by run-off and erosion; water quality and odor problems related to livestock waste and confined livestock operations; pesticides and food safety; biodiversity impacts from landscape change (in terms of habitat and germplasm); air quality, particularly related to particulate emissions; and landscape protection. Tropospheric ozone is increasingly recognized as an industrial/urban pollutant that negatively affects crops. Agricultural use of land also can provide open space, habitat for many species, and—with proper management—a sink for carbon. These positive environmental aspects are likely to be increasingly valued.

In the past, it has been possible to summarize the forces shaping agriculture as a competition between increased demand for food driven by a larger and higher-income population and increased supply driven by new technology. Over a period of a few decades, a tenth of a percent difference in exponential growth rates of population and technological progress can make the difference between ever-falling or ever-rising prices. The ability to predict these rates of change with the degree of accuracy necessary to resolve the difference does not exist. Most likely, the rate of technical progress responds to demand pressure as well as opportunities created by improvements in basic research. As historical periods of rapid commodity price rises indicate, agricultural supply has tremendous ability to respond over the course of a few years. The best bet is that commodity prices will continue their long-run decline, as several major global forecasting efforts have suggested (see Reilly and Schimmelpfennig 1999).

The specific nature of technical change and what it means for different regions and farming systems remains elusive. Over the next few decades, there are no obvious biological limits on yields that would prevent continued increase (Reilly and Fuglie 1998). In the longer term, far greater changes are possible. Industrialization of agriculture could mean that raw biomass is processed into livestock feed and processed food products, using biotechnology-generated microbial organisms—greatly reducing the need for conventional crop production as we now recognize it. As we try to look forward 50 and 100 years, it is not clear whether the crops that will be grown then will resemble the crops grown today. Although such changes are possible with new technology, we must also look back to the fact that civilizations have relied on the major grain crops for centuries, and breaking from this trend would represent an epochal change in human history. Nevertheless, stretching our thinking is worthwhile if we are to imagine what the American agriculture could look like in the year 2100.

Farm policy will work around the edge of these broad forces, but in most respects it is unlikely to alter much the inevitable push of technology and fundamental market forces. This conclusion, if anything, is the lesson of farm policy over the second half of the 20th century. Well-meaning policies designed to improve the income of farmers created incentives to produce that overwhelmed the market and drove prices down, filling public granaries. Attempts to hold prices up in the face of technology that reduced costs and increased production also generated surpluses. Thus, ultimately, the federal programs were forced to liquidate stocks and lower the target price they hoped to maintain.

We cannot easily predict how policy will try to blunt the adjustments and dislocations that these forces will bring. On the near-term agenda, agricultural policy is evaluating the effects of the FAIR Act of 1996. The basic background is that the FAIR Act—passed with much fanfare and intended to bring an end to an era of farm programs—is being reconsidered. Reconsideration of FAIR is likely because low prices caused new financial stresses for agriculture, and most observers see little prospect that prices will improve in the next few years. Given this background, the major issues likely to come up in Congress over the next few years are the following:

- Congress may revisit the 1996 Farm Bill to strengthen the safety net for farmers. General observations by many observers in the agricultural policy community include the following:

  1. Assistance for economic disasters must be thought through.

  2. There is a sense that planting flexibility in FAIR worked and will be retained.

3. There is an interest in improving crop insurance, but there are widely different ideas about what "improved" means.
4. There is a sense that the shift away from counter-cyclical program payments was not well thought out by Congress in the 1996 bill.
5. Federal support for agriculture will continue. Decoupling payments—the underlying approach in FAIR—was better in theory than in practice.

- Some unresolved issues include linking of environmental performance to farm payments; causes of the hog price collapse that caused so much stress in 1998/99; and fundamental concerns with the structure of contracting and pricing in agriculture. In terms of international trade, the United States probably will continue to seek further reductions in barriers to trade within the World Trade Organization. Specific issues will be state trading and trade in genetically modified organisms. A problem facing further trade barrier reduction is that convincing farmers that freer trade is good for them is increasingly difficult.
- Environmental pressures, as they relate to agriculture, are likely to become more important in the future.

These policy considerations take us only a few years into the future (at most) and are subject to rapid change. They do, however, provide insight into the underlying concerns of the policy community that are likely to endure. These concerns are not much different from those that have driven farm policy for several decades.

Stakeholder Interests

The agriculture sector assessment developed a steering committee to provide input on the interests of the many and varied stakeholders in agriculture. Included among this group were small farmers, representatives from agribusiness, members of the agricultural research community, representatives from environmental groups, staff members of Congress, and those involved in implementing policy in the federal and state governments.

The comments received from stakeholders could be summarized into nine broad issues:

- Agriculture is diverse. We must speak to the diverse elements that exist. Different concerns require that the assessment activity take different cuts on agriculture.
- Agriculture is changing rapidly; biotechnology, computers, GPS, information technology, and the changing structure of production have collectively altered the sector. Farming is becoming an increasingly specialized, technology-driven enterprise, which means that farmers need a high level of training to operate successfully.
- The assessment should be more integrated than previous efforts. Interrelated issues such as water, pests, land use, and ozone levels must be dealt with effectively.
- Variability is a major concern; it wreaks havoc on farmers.
- Environmental links are unexplored but could be very important. Opportunities for win-win solutions exist and should be further investigated.
- The policy environment will be affected by climate change and will affect the ability of agriculture to adapt.
- Deep thought should be given to the structure of the assessment: Learn from past efforts.
- Further research is needed to assess the accuracy of scenarios and analyses, as well as where the errors are.
- The assessment will be useful if we identify the range and breadth of issues (potential surprises), even if we cannot quantify all of them.

Stakeholders also had specific questions they hoped the assessment could tackle. The following 16 questions reflect the observations of Robert White (from the legislative staff of Senator Richard Lugar) toward the end of the stakeholder meeting held in January 1999:

1. How will crops and livestock be affected? The assessment should consider not only the ability to genetically alter crops and livestock in response but also the effects of diseases and pests.
2. How will growing degree days change? Will the distribution of the current patterns change?
3. Will climate change result in changes in competition for land? How? What will the future baseline competition look like if climate changes?
4. Consider changes in the structure of agriculture: How will climate change affect operations? Will it make it harder or easier to enter into agriculture?
5. How will international competitiveness be affected?
6. Consider changes in variability and the predictability of weather and climate: Can we predict better? Cash is on the line for farmers if they act on predictions.
7. Consider direct and indirect effects—the interplay of water and nutrients—especially as they affect water availability and water quality.
8. How will climate change affect the environment via agriculture, and will it affect the structure of natural resource management?
9. Where will the regions that gain competitive advantage be?
10. What will be the effects on transportation, ports, lock and dam structures? They are currently in bad shape. Where should we build or abandon?
11. Where will processing plants exist? Do they need to co-locate with production? What if production shifts?
12. What about risk management strategies in terms of agricultural credit services? What will agricultural creditors demand as proof of ability to repay loans of farmers if production is much more variable?
13. How will federal, state, and local policymaking be affected? For example, the local tax base is dependent on property values—how will this tax base change? How will this change affect school systems through tax base erosion and/or a declining population? Will there be a return to price supports at a federal level? How important or necessary are current federal policies with respect to risk? Will there be more regulations at the state, federal, or international levels, and what might their impact be?
14. What will be the effect on the labor supply for agriculture? Labor is already tight in this sector.
15. Will there be adequate funding for research? What research should be funded?
16. Where will the new customers be so that better marketing strategies can be designed?

With this guidance, we undertook the research described in the following chapters. We could not address all of these questions with quantitative analysis, but we have tried to provide information and discussion on the main topics.

Chapter 2 Assessment Approach: Building on Existing Knowledge

Introduction

In this chapter we provide a review of previous assessments of the impacts of climate change on US agriculture. We also describe the methods and approaches used in the agricultural sector assessment.

We begin with a brief review of climate change impact studies, focusing on efforts that have sought a comprehensive assessment or relatively comprehensive review of the literature. Our goal is to summarize the main findings, identify as extensively as possible where some of the climate-agriculture links exist, and as a result indicate which links have not been explored. We then describe the method and approaches we have used to fill some of these gaps. Our purpose is to help the reader who may be unacquainted with past assessments to understand the context for our findings, what is new, and what reinforces previous work.

Past Assessments: General Findings

Several assessments of agriculture that include the United States or cover major parts of the United Stated have been conducted over the past 20 years. As the bibliographies of these reviews and assessments attest, there are many detailed studies on various aspects of climate change; numerous papers report experimental results of the impact of elevated ambient levels of CO_2 on crops, for example. This fundamental research is absolutely critical for developing and improving assessment models, assessment research, and ultimately assessments of this type. There are two aspects of this type of research that are critical to understand:

- Assessment inevitably involves scaling up results of bench-, site-, or field-level experiments to a farm, a region, the entire country, or world markets. There are two very broad concerns in scaling up. First, will a mix of independently conducted site studies be representative of the scaled-up area, and are they based on consistent assumptions and approaches? Second, are there "fallacies of composition" that occur in simply adding together effects? The most obvious example is that a farm-level model of the impact of climate change on farm profits is irrelevant by itself; production changes across the country and the world will result in changes in market prices. These changes can be far more important for farm profitability than the direct effect of climate on farm yields.
- Assessment usually involves translating results obtained under controlled, experimental conditions to conditions observed on the farm. The concerns here involve at least three issues. First, are the environmental controls in these experiments a reasonable approximation of open-field conditions? If not, are the estimated responses relevant to real-world conditions? Second, do these experiments consider complex interactions with the environment (e.g., changes in pests, soils, and other environmental factors)? If not, is there some validity in considering just one element at a time? Can one, for example, consider response to CO_2 independent of temperature, moisture, nutrients, salinity, tropospheric ozone and other factors? Third, how does farm management affect these results? For example, how do farmers change applications of water, nutrients, and other management practices in response to physiological changes in plants?

Broader assessments—those that attempt to simulate impacts of climate change on the agricultural economy—address the foregoing issues in a variety of ways. Sometimes they do so by making simplified assumptions (e.g., that an average CO_2 response, independent of other factors, can be used). In other cases, the effects are simply ignored (e.g., changes in the distribution of pests, in soils, or in variability) because there are no quantitative methods for assessing the problem or on the assumption that effects are small. In other cases, the method used may implicitly capture the effect under some conditions. For example, statistical evidence drawn from cross-section data can embody all of the effects associated with climatic conditions that vary across regions. Also implicit, however, is the assumption that climate change will involve the wholesale shift of climatic regimes with these associations intact. For example, this assumption would imply that pests, soil conditions, and farming practices would all change at the same rate as climate. Another approach is to use expert judgment. Experts also likely weigh a variety of evidence—perhaps including the potential effects of pests and diseases, for example, to come up with a judgment about crop yields under a changing climate.

Conclusions from Previous Assessments

We do not attempt to review here much of the detailed scientific literature that is the background for agricultural assessments. Excellent reviews on crops and livestock effects, pests, and soils—as well as discussion of global and regional impacts—are included in a special edition of the journal Climatic Change, "Climate Change: Impacts On Agriculture" (Reilly (ed.), 1999). The five articles included in the edition contain more than 500 citations, providing a detailed guide to the literature for readers so inclined. Instead, we provide a short summary of the major assessments, by approximate date over which the assessment occurred.

1976–1983: National Defense University

A National Defense University project (Johnson 1983) produced a series of reports focusing on agriculture. The final report integrated yield and economic effects. It focused on the world grain economy in the year 2000, considering warming and cooling of up to approximately 1ºC for large warming or cooling and 0.5ºC for moderate changes, with associated precipitation changes on the order of ± 2 percent. These estimates varied somewhat by region. The base year for comparison purposes was 1975. The study relied on an expert opinion survey for yield effects; it used these effects 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 livestock or crops such as fruits and vegetables. No direct effects of CO_2 on plant growth were considered because the study remained agnostic about the source of the climate change (natural variability or human-induced). Economic effects were assessed with a model of world grain markets. Crop yields in the United States were estimated to fall by 1.6–2.3 percent as a result of moderate and large warming and to increase by very small amounts (less than 0.3 percent) with large cooling and even smaller amounts with moderate cooling. Warming was estimated to increase crop yields in the (then) Soviet Union, 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 likely difficulty in ultimately detecting any 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 Environmental Protection Agency (EPA)

The 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 United States. 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 three widely known general circulation models (GCMs), with increased average global surface warming of 4.0–5.2° C. In many ways the most comprehensive assessment to date, this effort included studies of possible changes in pests, and, in a case study of California, interactions with irrigation water. The main study on crop yields used site studies and a set of crop models to estimate crop yield effects. These effects 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 greatest detail; a simpler approach was used to simulate impacts on other crops. Impacts on other parts of the world were not considered. The basic conclusions summarized in Smith and Tirpak (1989) were as follows:

- 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 probably change many of their practices.
- Ranges of agricultural pests may extend northward.
- Shifts in agriculture may harm the environment in some areas.

1988–1990: IPCC First Assessment Report

The first assessment report of the Intergovernmental Panel on Climate Change (IPCC) (Parry 1990a, 1990b) briefly addressed North American agriculture. The assessment was based mainly on literature review and, for regional effects, expert judgement. North American/US results mainly summarized the earlier EPA study. Among the main contributions of the report were that it identified 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, farmed area, 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 ERS (Kane, Reilly, and Tobey 1991; Kane 1992; Tobey, Reilly, and Kane, 1992) published an assessment of impacts on world production and trade, including specifically the United States. 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 study results, based on doubled-CO_2 equilibrium climate scenarios and expert judgments for other regions that were the basis for the IPCC study. In this scenario, the world impacts were very small (a gain of $1.5 billion in 1986 dollars). The United States was a very small net gainer ($0.2 billion); China, Russia, Australia, and Argentina also benefited, whereas other regions lost. On average, commodity prices were predicted to fall by 4 percent, although corn and soybean prices rose by 9–10 percent.

1990–1992: DOE Missouri, Iowa, Nebraska, Kansas Study

In the Missouri, Iowa, Nebraska, Kansas (MINK) study (Rosenberg 1993; Easterling et al. 1993), the dust bowl of the 1930s was used as a surrogate for climate change for the four-state region. Climate change in the rest of the world was not considered. 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 by using crop models, river flow with historical records, and economic impacts by using an input-output model of 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 10–15 percent. 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; they increased yield on the order of 70 percent. The percentage losses resulting from climate change did not differ substantially between the "enhanced" and current varieties. Despite relatively mild effects on the agriculture sector of the region as a whole, locally severe displacements could occur. For example, irrigation in western Kansas and Nebraska would be untenable and would move to the eastern ends of these states.

1992: Council on Agricultural Science and Technology

The Council on Agricultural Science and Technology (CAST) report (CAST 1992) commissioned by the USDA did not attempt any specific quantitative assessments of climate change impacts. It focused instead on approaches for preparing US agriculture for climate change. It used a portfolio approach to responding to climate change, recognizing that prediction with certainty was not possible. Attention was directed to reform of agricultural policy, improving energy and irrigation efficiency, maintaining input supply and export delivery infrastructure, preserving genetic diversity, maintaining research capability, developing alternative cropping systems, enhancing information systems, attending to development of human resources, harmonizing agricultural institutions, and promoting freer trade. Although the study did not provide quantitative assessments, it did conclude with a relatively optimistic view of US agriculture's ability to cope. The study also addressed opportunities to mitigate agricultural greenhouse gas emissions.

1992: National Research Council

The National Research Council (NRC) of the National Academy of Sciences undertook a broad assessment of the policy implications of greenhouse warming with regard to mitigation and adaptation. The report included a discussion of climate change impacts on agriculture and the effect of elevated CO_2 on crops (NRC 1992).

1992–1993: Office of Technology Assessment

The Office of Technology Assessment (OTA) study (OTA 1993), like the CAST study for agriculture, focused on steps that could prepare the United States for climate change rather than estimates of the impact. The study's overall conclusions for agriculture were that the long-term productivity and competitiveness of the US agriculture were at risk and that market-driven responses might alter the regional distribution and intensity of farming. The study found institutional impediments to adaptation, recognized that uncertainty made it hard for farmers to respond, and saw potential environmental restrictions and water shortages, technical limits to adaptation, and declining federal interest in agricultural research and education. 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 general agricultural research and research targeted toward specific constraints and risks that might be related to climate change (e.g., drought or heat stress).

1992–1994: 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 EPA study for the United States to the entire world. The global assessment was based on the same suite of crop and climate models and applied these models to many sites around the world. It used a global model of world agriculture and the world economy to simulate the evolving economy to 2060, assumed to be the period when the doubled-CO_2 equilibrium climates would apply. The global temperature changes were 4.0–5.2° C. Scenarios with the CO_2 fertilization effect and modest adaptation showed global cereal production losses of 0–5.2 percent. In these scenarios, developed countries showed cereal production increases of 3.8–14.2 percent; developing countries showed losses of 9.2–12.5 percent. The study concluded that there was a significant increase in the number of people at risk of hunger in developing countries because of climate change. The study also considered different assumptions about yield increases resulting from technology improvement, trade policy, and economic growth. These assumptions and scenarios had equally important or more important consequences for the number of people at risk of hunger.

Other researchers simulated the yield effects estimated in this study through economic models, focusing on implications for the United States (Adams et al. 1995) and world trade (Reilly et al. 1993, 1994). Adams et al. (1995) estimated economic welfare gains for the United States of approximately $4 and $11 billion for two of the three climate scenarios and a loss of $16 billion for the other scenario (1990 dollars). The study found that increased exports from the United States, 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 United States of $0.3 billion under one GCM scenario and $0.6–$0.8 billion in losses in the other scenarios, 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. Reilly et al. (1994) showed that in many cases, more severe yield effects produced economic gain to producers when world prices rose.

1994–1995: IPCC Second Assessment Report

The IPCC's Second Assessment Report included an assessment of the impacts of climate change on agriculture (Reilly et al. 1996). As an assessment based on existing literature, it summarized most of the foregoing studies. 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 conclusions were as follows:

- 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 C3 crops (most crops except maize, sugar cane, millet, and sorghum) to doubled CO_2 is +30 percent, although measured response ranges from –10 percent to +80 percent.
- 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 such as crop rotation, conservation tillage, and improved nutrient management are very effective in combating or reversing deleterious effects.
- 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, will affect livestock production.
- The risk of losses from weeds, insects, and diseases is likely to increase.

With regard to regional and global production effects, the conclusions were as follows:

- Crop yields and productivity changes will vary considerably across regions. Thus, the pattern of agricultural production is likely to change in many regions.

- 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 more negatively affected.

With regard to vulnerability and adaptation, the conclusions were as follows:

- Vulnerability to climate change depends not only on physical and biological response but also on socioeconomic characteristics. Low-income populations that rely on isolated agricultural systems, particularly dryland systems in semi-arid and arid regions, are particularly vulnerable to hunger and severe hardship. Many of these at-risk populations are in sub-Saharan Africa, South Asia, and Southeast Asia; they also include some groups in Pacific Island countries and tropical Latin America.
- Historically, farming systems have responded to a growing population and adapted to changing economic conditions, technology, and resource availabilities. There is uncertainty about whether the rate of change of climate and required adaptation would add significantly to the likely disruption from future changes in economic conditions, population, technology, and resource availabilities.
- 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: Economic Research Service (ERS)

The ERS (Schimmelpfennig et al. 1996; Lewandrowski and Schimmelpfennig 1999) provided a review and comparison of studies that it had conducted or funded, contrasting them with previous estimates. The assessment used the same three doubled-CO_2 equilibrium scenarios that Rosenzweig and Parry (1994) used but also added a fourth, cooler model that produced a global average surface temperature increase of 2.5°C.

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 United States (Mendelsohn et al. 1994); 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 (1982 and 1990, respectively). A major result of the approaches that were based on cross-section evidence was that impacts of climate were far less negative for the United States and the world than had previously been estimated with crop modeling studies. Although the studies showed economic effects that were similar to those of previous studies, they included no direct effect of CO_2 on crops, which in previous studies had been a major factor behind relatively small economic effects. Hence, if the direct effect of CO_2 on crop yields had been included, the expected result would have been significant benefits. The more positive results were attributed to the adaptation implicit in cross-section evidence that had not been completely factored into previous analyses.

The assessment also reported a crop modeling study (Kaiser et al. 1993a,b) with a complete farm-level economic model that more completely simulated adaptation response. It, too, showed more adaptation than previous studies. A summary of this review was subsequently published as Lewandrowski and Schimmelpfennig, 1999. The assessment also reported a study on the agricultural effects of climate change in developing countries (Winters et al. 1999) that found gross domestic product (GDP) losses for low income, cereal-importing countries in Africa, Latin America, and Asia. This finding was supported by a subsequent ERS-supported study (Darwin 1999), which found that climate change would have negative impacts on agricultural land and thereby reduce overall economic welfare in Southeast Asia, western and southern Asia, Latin America, and Africa. The latter study also showed that Southeast Asia, which is primarily in the tropics, is much more adversely sensitive to warming than the United States. Neither study included the direct effects of CO_2 on crops.

1996–1999: Electric Power Research Institute

The Electric Power Research Institute (EPRI) funded a study on the impacts of climate change on all market sectors in the continental United States. Three different approaches were used to analyze agriculture. All three explored a range of hypothetical climate scenarios combining 1.5°, 2.5°, and 5.0° C warming with 0 percent, 7 percent, and 15 percent precipitation increases. The studies explored a 1990 economy and a 2060 economy. Carbon dioxide levels were assumed to be 530 ppmv. Overall, the studies found substantial benefits for the United States resulting from climate impacts on US agriculture. Adams et al. (1999b) used a crop production approach in conjunction with a linear programming model to predict effects across major crops in the United States. The study adapted the agricultural model constructed for the EPA (Adams et al. 1990) to include a more complete accounting of farmer adaptation, livestock, and warm-loving crops. The Adams et al. (1999b) study found substantial benefits, with 1.5° and 2.5° C warming leading to between $32 billion and $54 billion in 2060. These benefits were reduced with a 5° C warming to between $9 billion and $32 billion. The study was unique in finding significant net economic benefits across the range of scenarios examined. When climate change was imposed on a 1990 economy, the magnitude of benefits was similar to the magnitude of benefits found in earlier studies for at least some scenarios. The relatively large benefits for 2060 reflects the fact that the underlying agricultural economy was considerably larger as a result of assumptions about growth in productivity.

Segerson and Dixon (1999) used cross-sectional data from the Midwest Plains to analyze grain crops. They relied on a production function model to estimate crop climate sensitivity. They found that crop sensitivity was slightly less than what Adams et al. (1999b) had assumed. These lower sensitivities were then introduced into the Adams et al. (1999b) model, which then generated slightly higher benefits from warming.

Mendelsohn, et al. (1999) explored cross-sectional analysis across all counties in the continental United States that had agriculture. The model accounted for farm value per acre and the fraction of land used for farming. The model also accounted for climate norms and climate variation. The study found that including variation changed the measured sensitivity of crops to warming. With variation in the model, warming is more beneficial. Climate variation itself, however, was highly damaging. The cross-section (Ricardian) analysis suggested net benefits from warming that were similar to the Adams et al. (1999b) study for the United States.

EPRI also has funded Ricardian studies in Brazil (Sanghi and Mendelsohn 1999) and India (Dinar et al. 1998; Sanghi et al. 1998); the World Bank also supported the latter. The Brazilian and Indian studies reveal that the Ricardian model works well in developing countries. Warmer winters and summers are harmful in both of these countries—as they are in the United States. Brazil and India, however, appear to be more sensitive to warming than the United States. Even adjusting for their different initial temperatures, the developing countries appear to be more temperature sensitive (Sanghi and Mendelsohn 1999).

1998–1999: Pew Center

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, Hurd, and Reilly 1999a). The report series is based on reviews and synthesis of the existing literature. The major conclusions were as follows:

- Crops and livestock are sensitive to climate changes in 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; regional changes may be significant, however (i.e., there will be some regions that gain and some that lose.) Beyond a doubling, the negative effects are more pronounced in the United States 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 into most existing assessments.

General Results and Conclusions from Past Assessments

Several general results and conclusions arise among past assessments; for those who have been involved in the research, they have become common wisdom or consensus conclusions. There are, however, important caveats and limitations to existing assessments. These limitations exist not because researchers have not recognized them but because, for one reason or another, overcoming these limitations in ways that have been convincing to most other researchers has proved difficult or impossible. Until more convincing evidence is marshaled on one side or the other, these limitations introduce uncertainty in the conclusions. We list first the major conclusions and then the major limitations of assessments to date.

Major Agreement and Consensus

- *Over the next 100 years and probably beyond, human-induced climate change as currently modeled will not seriously imperil aggregate food and fiber production in the United States,* nor will it greatly increase the aggregate cost of agricultural production. Most assessments have looked at multiple climate scenarios. About half of the scenarios in any given assessment have shown small losses for the United States (increased cost of production); about half have shown gains (decreased cost of production).[1]
- *There are likely to be strong regional production effects* within the United States, with some areas suffering significant loss of comparative (if not absolute) advantage to other regions of the country. With very competitive economic markets, whether a particular region gains or loses absolutely in terms of yield matters little; what matters is how it fares relative to other regions. The south and southeastern United States are persistently found to lose relative to other regions and absolutely. The effects on other regions within the United States are less certain. Although warming can lengthen growing seasons in the northern half of the country, the full effect depends on precipitation, which climate models predict notoriously poorly.

[1]Assessments have used several different "yardsticks" for measuring effects.These yardsticks include measures such as total grain production in tons or value of production, commodity prices, and economic welfare.The latter concept is generally favored among economists as showing the true economic cost.Although there are many differences among these measures, the basic conclusion here is not particularly sensitive to which measure is used.

- *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 is important, the relevant concern is the overall effect on global production and prices and how US producers fare *relative to their global competitors* or potential competitors. The worst outcome for the United States would be severe climate effects on production in most areas of the world and particularly severe effects on US producers. Consumers would suffer from high food prices, producers would have little to sell, and agricultural exports would dwindle. Although this outcome is unlikely (based on newer climate scenarios), some early scenarios that featured particularly severe drying in the mid-continental United States with milder conditions in Russia, Canada, and the northern half of Europe produced a moderate version of this scenario. The United States and the world could gain most if climate change was generally beneficial to production worldwide but particularly beneficial to US producing areas. Consumers in the United States and around the world would benefit from falling prices, and US producers would gain because the improving climate would lower their production costs even more than prices fell, thus increasing their export competitiveness. In fact, most scenarios fall 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 United States as a whole straddles a set of climate zones that include gainers (the northern areas) and losers (south and southeast).

- *Empirical studies of climate sensitivity will have to be completed in more developing countries to get an accurate picture concerning climate effects around the world.* Specifically, there is very little information about Africa, even though it is likely to be one of the most sensitive areas to warming in the world.

- *Effects on producers and consumers often are in opposite directions*, which often is responsible for the small net effect on the economy. This result is a near certainty without trade; it reflects the fact that demand is not very responsive to price, so anything that restricts supply (e.g., acreage reduction programs, environmental constraints, or 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.

- *US agriculture is a competitive, adaptive, and responsive industry and will adapt to climate change; all of the foregoing assessments have factored adaptation into the assessment to some degree.* The final effect on producers and the economy after adaptation is considered may be 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.

- *The relatively small net effect on the US agricultural economy across assessments is the combination of a variety of negative and positive effects.* In many of the earlier assessments, the direct effect of carbon dioxide on plant growth offset fairly large yield declines related to changes in temperature and precipitation. Some later assessments have not included the carbon dioxide effect at all but have estimated a much larger adaptation response and have found small negative and even positive effects despite the omission.

- *The agriculture and resource policy environment can affect adaptation.* Lack of water markets, agricultural commodity programs, crop insurance, and disaster assistance can encourage the continuation of practices that are no longer economic on a regular basis. The FAIR Act of 1996 eliminated farm program payments tied to base acreage (failure to maintain base acreage in a crop could mean loss of payments, which encouraged continued production of the same crop). More-effective water markets could transfer water to the highest-value uses and encourage greater irrigation efficiency, but establishment of markets is hampered by water laws dating to the 1800s that granted water rights in the far west and open access to subsurface resources in the plains states. The pressure of increasing competition for these resources is leading to some progress in this regard. Crop insurance and disaster assistance can have the perverse effect of encouraging continued cropping in areas that are prone to crop disasters, essentially subsidizing production in areas that are no longer competitive. There is growing awareness of the perverse effect these programs can have and some interest in managing them in ways that minimize or eliminate the effect. It appears difficult, however, for Congress and the administration to resist pressure to come to the aid of farmers in a time of need regardless of whether those in need have themselves prepared well for the inevitable vagaries of weather and the variability of crop prices.

There have been several assessments of the agricultural impacts of climate change; the consensus and agreement among the studies is strengthened by the fact that the assessments were conducted by different teams of researchers, using different methods, and were sponsored by different organizations. All of these research teams have labored under the same set of constraints, some quite severe; thus, many of the results are conditioned on these limits. These limitations include the following:

- *The climate scenarios on which these results rely have been very unrealistic representations of what climate might really be like over the next several decades to 100 years.* Most climate scenarios are based on doubled-CO_2 equilibrium scenarios. There is no particular future year to which these scenarios apply, and other factors that affect climate such as sulfate aerosols have not been included. One assessment assumed that climates were realized in 2060; most others apply the conditions to today's agriculture and are silent about when the effects might be realized. As a result, there are no estimates of climate impacts for the next several decades that are based on actual results of climate models and no estimates of potential consequences in the far distant future—beyond a doubled-CO_2 environment.
- *Detailed predictions of climate models are particularly uncertain; most climate modelers place little or no confidence in the details because the processes that control these details are not well represented.* Clouds and precipitation are key concerns. The big climate models do a poor job of representing current variability and do not simulate events such as the El Niño-Southern Oscillation (ENSO), hurricanes, and typhoons—nor do they have any ability to represent changes in small-scale convective storms.
- *The climate scenarios used represent atmospheric physics as currently understood, almost exclusively constructed for research rather than assessment purposes.* The scenarios had limited or no interaction with oceans and terrestrial systems and excluded other climate forcings. For assessment purposes, trying to roughly take into account as many things as we think are important would be far preferable to being very precise about the things we know well while leaving out completely things we suspect but have not proved. Having a range of scenarios that bound our uncertainty about these many features rather than everyone's version of a central estimate (central, conditioned on recognizing that some things were left out completely) also would be preferable. Scenarios that could happen with great consequence but with low probability need to be assessed, appropriately discounted for the fact that there might only be a 1 in 100 or 1 in 1000 chance of occurrence.
- *The CO_2 fertilization effect will probably increase yields, but the magnitude of the effect remains uncertain.* Experimental evidence suggests an average yield increase of 30 percent for many crops but closer to 7 percent for corn,

[2]The distinction here is between C3 and C4 crops (referring to the pathways through which carbon is utilized).The C4 crops—corn, sorghum, and sugar cane—experience much less gain.Virtually all other crops of commercial importance are C3 crops.

sorghum, and sugar cane[2] under doubled-CO_2 levels (from~ 300 ppm to ~600 ppm) and improvements in water-use efficiency. The range of experimental results of doubled CO_2 is from –10 percent to +80 percent; some investigators would fasten on the low end of this range. A wide variety of factors could reduce the anticipated gain considerably. Only about two-thirds of the increase in greenhouse gas forcing may be caused by CO_2; other gases would cause warming but not have beneficial effects. Most of this experimental evidence is from single plants grown under glass (highly artificial conditions); the effects could be quite different under open-field conditions, with pessimists imagining necessarily less effect. The CO_2 effect depends on and interacts with many other factors—probably explaining, in part, the wide range of experimental results. Grain quality and forage quality may be reduced (less protein) for crops grown under elevated CO_2. Not all of these interactions necessarily would lead to a lower fertilization effect. For example, the evidence indicates a stronger effect when crops are under stresses such as water, heat, and salinity—conditions that are more likely to be observed under commercial conditions than experimental conditions. Most of the crop models used in assessments apply a very simple multiplier to represent elevated CO_2 rather than model the complex interactions explicitly.

- *Many broader agroecological (system-wide) effects have not been included in assessments.* The dominant "crop model methodology" simulates only the short-term and local effects of essentially different weather on crop growth. Persistent changes in weather (i.e., climate) may lead to changes in soils, pest prevalence, irrigation water availability, concentrations of other pollutants such as tropospheric ozone, and changes in the ability of farmers to conduct field operations. For the most part, these factors have not been explicitly incorporated into assessments.

- *The extent, ease, and cost of the adaptation response are controversial and unresolved.* Although some amount of adaptation is inevitable, some analysts question whether the analogous situations that are used as evidence of adaptability are good analogies for climate change. Gradual climate change may be difficult to detect. Hence, the producer may not know that climate has changed; he or she may interpret a string of odd weather as normal variability and thus experience losses for some time before he or she recognizes that climate has changed. There also is debate about adjustment costs—whether climate will change so gradually that any adaptation can be handled as a part of normal replacement of capital or whether adaptation will require disruptive and costly replacement of equipment made obsolete by changing climate. For adjustment to be costly, local climates likely would have to experience some type of punctuated change; the global average change in temperature is quite slow relative to the normal rate of capital turnover in agriculture. There is little confidence, however, that climate models would capture such types of change, if indeed they were a possibility.

- *Regional and local predictions remain vaguely probabilistic at best.* For example, the finding that the South and Southeast usually have been negatively affected may not apply to every corner of the region, every crop grown there, or every climate scenario. The predictability of detail at the small geographic levels for many key dimensions of climate is nearly zero. The climate models themselves are only coarsely resolved. Better downscaling methods are being applied but have not been broadly used in the foregoing assessments.

Approach of the Current Assessment

As the review of past efforts suggests, there are two broad methods of assessment: Review and synthesize existing literature, or conduct a broad-scale modeling/analysis effort centered on a consistent set of scenarios. The IPCC and Pew Center efforts are examples of the former approach; the EPA and EPRI efforts are examples of the latter. There also are two broad objectives of assessments: Assess the impact (measured in a variety of ways) of climate change on agriculture, and assess strategies for limiting or avoiding negative consequences or take advantage of opportunities presented by climate change. The CAST and OTA assessments were examples of the latter; the USDA and EPRI studies are examples of the former. The second IPCC assessment, which used literature review, included an evaluation of impacts and potential responses that could limit impacts. Assessments also vary in their attempts to provide quantitative information and qualitative conclusions.

This assessment tackles several of the caveats and limitations—but not all. We use transient climate scenarios and therefore are able to consider impacts representative for the years 2030 and 2090. This approach is a substantial improvement compared with previous analyses; whether and what types of actions might be taken over the next 5 to 10 years depend on when the climate impacts are expected. We evaluated and include in our assessment the potential implications of changes in pesticide expenditures resulting from climate change. The issue of pests and climate remain uncertain, but this inclusion adds another dimension to the complex climate agroecosystem interactions we might ultimately expect. We have evaluated a broad group of crops, including the major grains (wheat, corn, sorghum) and soybeans, forage crops (alfalfa and range), and some of the more important fruits and vegetables (tomatoes, citrus, and potatoes). By including vegetables and fruits, as well as other crops that are heat loving, we help remove a potential bias in some previous work that considered only the major grains; the concern with some of these studies was that omitting heat-loving crops that may have benefited from warming could have overestimated damages. We also have considered more completely the effects of climate change on irrigation water supply. We were able to use results of the water sector assessment to evaluate more realistic changes in water supply to agriculture.

We provide a brief discussion of the scenarios used for the various analyses. Then we provide a summary and overview of models used in the analysis. Finally, we provide a brief discussion of surprise, uncertainty, and the scope of climate–agroecosystem–economic interactions. The ability to assess the complete system in all its complexity does not yet exist; conveying a sense of these complexities is useful nonetheless.

Scenarios

Socioeconomic Scenarios and Assumptions

Following the pattern of many past assessments of climate change impacts, we applied climate change to the cropping and economic system as it exists today (i.e., the year 2000). To many observers, this approach appears to go against common sense. Crop yields are likely to be higher in the future, agricultural prices will be different, land-use patterns will change, the global trade picture will change, and the entire set of technological options available to farming will change. Indeed, our steering committee suggested that we must consider climate change operating in a future world. Paraphrasing one committee member, the historical response and even the response of today's agricultural system is irrelevant because agriculture is changing so fast.

The assessment team chose to take an alternative approach, for several reasons. The simple answer was that developing interesting scenarios of the future that differed in ways that are important in terms of climate response would have required resources beyond those we had. There is no widely developed set of long-term forecasts for agriculture. The ERS produces a 10-year ahead baseline for the United States. We require scenarios for 30 and 90 years in the future. Several forecasts of world agriculture try to look out 30 years (for a review, see Reilly and Fuglie 1998); these types of scenarios do not necessarily change the sensitivity of agriculture to climate change, however.

The EPA global study and the MINK study developed future scenarios of world agriculture and agriculture for the MINK region, respectively. The lessons from these studies and from other future forecasts are as follows:

- Future prices and other measures of agricultural shortfall or excess depend almost completely on the rate of yield growth relative to population growth.
- Any extrapolation of yield growth at rates like those experienced over the past few decades will result in yields at least 70 percent above today's yields by 2030; it is hard to imagine or conceive of crops that would maintain such yield growth through 2090.
- Factors other than climate change are more important for the agricultural economy in the future, and these factors are uncertain; changing underlying assumptions within a range most experts would accept as bracketing what might happen in the future can lead to vastly different and larger effects than those from climate change.
- When different assumptions about these other factors have been incorporated in climate assessment, they have not changed the climate response very much.

For example, after adjusting crop response to generate higher yields, the MINK study still found about the same percentage effect of climate change on crops. The EPA global study found that for measures of people at risk of hunger, the absolute number increased with population increase; because hunger risk depended directly on income and food prices, scenarios with higher income or more rapid yield growth produced smaller numbers of at risk people. One analysis used crop yield results from the EPA global study imposed on the current (1990) agricultural economy. This analysis came to broad conclusions that were similar to those of the original study in terms of areas that win and lose as a result of climate change and in terms of the net effect on the world food system. As a first approximation, measuring economic response in terms of producer and consumer surplus is likely to be relatively insensitive, in percentage terms, to the scale of activity (more or less production) and even to whether prices have fallen or risen, unless demand and supply responses are highly nonlinear.

The "noneffect" of other variables on climate response to forecast futures is hardly an absolute finding or certainty, however. It probably reflects instead our inability to foresee or create scenarios that would substantially change the climate response. If there were much more irrigation, or much less, the response to precipitation would change. If future US agriculture concentrated in particular areas that were much more beneficially or negatively affected by climate change than other areas, the response would change. By 2090, crops and production practices may be unrecognizable to us today; perhaps any fast-growing, highly productive crop will be a feedstock for manufactured food and feed products—eliminating (or nearly so) the need to produce grain and other specialized crops. Suitable biomass crops might be grown under many conditions, including freshwater and marine environments.

One problem with trying to assess what these different scenarios might mean for climate change is that such dramatic changes may represent, in part, a response to a gradually changing climate. If technological change itself is highly responsive to relative scarcity of land (and the climatic conditions that go with it), the variety of dramatically different scenarios would develop only under some climate scenarios but not others. Considerable evidence has been collected by some researchers (Hyami and Ruttan 1985) showing strong endogenous response of technology to relative input prices. In this framework, broadly worsening climate conditions would increase the price of land in the few remaining good areas, and these price increases would spur technical change to reduce the need for good climate. For example, the response might be to generate the production system outlined above as a possibility for 2090, whereby almost any type of biomass crop could be used as a feedstock for food production.

On the other hand, improving climate conditions could turn many areas into potentially prime producing areas. This scenario could greatly reduce the need for yield-enhancing research; improving climate and higher levels of ambient CO_2 would produce yield increases without any research effort. Research dollars would be invested more profitably elsewhere rather than to spur even greater yield increases that caused commodity prices to plummet. The ability to quantify and forecast this endogenous response over long periods of time is almost nonexistent at present and presents a formidable challenge for research.

For the foregoing reasons, we chose to impose climate on agricultural markets as they exist today, supplementing this modeling work with a discussion of possible future changes and how they could alter climate sensitivity of agriculture.

With regard to the future, our stakeholder meeting identified several important changes for agriculture. Given their importance, speculating on how these changes might interact with climate sensitivity is worthwhile. The first of these changes is the technological change. Precision agriculture and biotechnology are the two main technological forces behind agricultural research at the moment.

Precision agriculture allows farmers to precisely and differentially manage (in terms of application of water, nutrients, pesticides, etc.) small areas of a field by using computer monitoring and global position systems. The idea is that much more efficient use of inputs and higher yields are possible by directing the right amount of input to each area rather than using an average amount of input that is too much in some areas and too little elsewhere. Although precision agriculture may have such effects, it is not clear that it would reduce climate sensitivity. A crop growing with ideal levels of nutrients, water, and pest control would still be subject to losses from climate. Indeed, the current practice tends to entail relatively high levels of applications of inputs to get high yield over most of the field. More-careful monitoring and faster response to changing conditions could reduce adjustment costs, however, if farmers are able to detect and respond to changing weather conditions more rapidly. Clear detection of climate change, based on pure data analysis of historic weather, is fundamentally limited by the ability to separate trends from a very noisy record.

Biotechnology offers the possibility to modify crops and livestock well beyond the limits imposed by the genetic diversity within varieties that can be interbred. Biotechnology appears to be capable of dramatically changing the technological response. Some broad biological limits remain and concerns about environmental and health risks may be impediments to development of genetically modified crops. Without water, for instance, high levels of biomass production per hectare probably are not possible. Genetic diversity across species, however, could allow improved response to many different environmental conditions. If anything, biotechnology increases the potential for endogenous technological change to minimize climate effects.

Globalization of markets and industrialization of agriculture are two additional forces. A major force behind globalization is to ensure supply to markets under current weather variability. Along these lines, globalization almost certainly will reduce any negative impacts of climate change on commodity and food markets—minimizing the impact of climate on people who obtain their food from these markets. Globalization is likely, however, to amplify regional effects on producers and could further marginalize poor people in developing countries. Already, the global market places considerable pressure on producing areas that have difficulty competing with more-productive, lower-cost producing areas. With a strong network of interwoven international markets, crop failures in a region need not increase market prices if the losses are balanced by gains elsewhere. In contrast, in a world with regionally differentiated markets, producers in the failing area would benefit from higher regional prices. Food consumers in the region obviously would pay more.

An interesting example of the attempt to shield regional producers from competitors in other regions is the milk marketing system that is gradually being dismantled in the United States. Regional consumers paid higher prices, but these prices supported a dairy industry in the Northeast against competition from Wisconsin. Also at risk are subsistence farmers and consumers around the world. Governments and markets have not been particularly kind to traditional and tribal populations when they have had the unfortunate luck of being located on a resource that became valuable. If climate change caused world commodity prices to rise, wealthy consumers in developed countries would import food they need, leaving less available for poorer consumers in developing countries who could not afford higher prices.

Industrialization of agriculture is a broad idea, incorporating many different changes in the structure of the agriculture sector. In part, it includes the increasing technological sophistication and precision management of production that allows production of commodities to meet processing specifications. It also includes the increasing horizontal (across producing entities and regions) and vertical (with input and processing industries) integration of production. One feature of this structural change is contract production, whereby many smaller farms produce under contract with a processor with some form of price guarantee and with greater specification for inputs and production practices to assure uniformity and timely delivery of the product. One feature of this form of production is that the large processor pools risks across many farmers and areas, creating greater assurance of return for farmers under contract. This broad-scale integration is likely to reduce further the chance that a local or regional crop failure will disrupt supply in the region. Integration also will pool income risks for producers. Contract production could have similar effects, but the relative risk to the producer and contractor depends on the specific terms of the contract.

The other major trend in US agriculture is increasing demand for improved environmental performance. We examine many of these issues in more detail in Chapter 5. There are three broad issues. One is competition between agriculture and the environment for resources—mainly land and water. In the western United States, the desire to improve fish habitat (e.g., salmon spawning areas on rivers) is leading to a rethinking of the allocation of water and pressure to remove dams that supply water. There is continuing debate and discussion about grazing on federal land and its implications for wildlife habitat. Other concerns about endangered species habitat, wetland preservation, and further demands for parkland and open space will increasingly bid for land now in agriculture. We investigate competition for groundwater in the Edwards Aquifer in the area including San Antonio, Texas. We also examine overall agricultural resource use implications in Chapter 3.

A second issue involves interactions of agriculture and urban/suburban land in the landscape. There are positive and negative aspects of this interaction. Farmland can provide green space in the midst of urban development. Such farmland can provide unique services and products for the local urban area, from fresh produce for farmers markets to farm experiences for urban dwellers. On the negative side, intensive production, particularly large livestock operations, has created large concerns about odor and pollution. The positive aspects of this interaction have led many states to develop programs to preserve farmland. The negative aspects have led to regulations and prohibitions on farming practices.

A third aspect is production practices that lead to pollution—mainly water pollution, but with recent concerns about air pollution effects. Soil erosion runoff into lakes and rivers carries with it nutrients and agricultural chemicals. Irrigation drainage water also concentrates chemicals and salts in water bodies. Leaching of chemicals applied to crops can lead to groundwater contamination. Climate change has the potential to greatly affect these interactions by changing land use, irrigation water use, and the intensity of rain and wind that is responsible for erosion. We consider the impact on land and water use in Chapter 3 and the impact on soils, nutrient runoff into the Chesapeake Bay, and implications for pesticide expenditures in Chapter 4. As our case studies in Chapter 4 illustrate, the drive to improve agriculture's environmental performance could, by itself, significantly change farming practices—which could greatly affect how climate change will affect agriculture and the environment.

Climate Scenarios

We used the Hadley and Canadian model simulations to develop climate scenarios for the crop modeling work. In this regard, we followed previous agricultural assessments and applied monthly mean changes in climate between the greenhouse gas-forced scenarios and control runs to a 30-year actual record of weather for sites at which we ran crop models. This approach has been used in the past because, although climate model output broadly agrees with observed seasonal and spatial patterns of climate, the agreement with actual weather at a specific site is very poor. Applying the differences (additive for temperature and as a ratio for precipitation) means, for example, that all days are warmer but the pattern of warm and cool days (i.e., the variance) remains the same. Thus, any change in variance projected by the GCMs is averaged out. We discuss later in more detail what the climate models indicate about variance of weather and climate and some results using changes in variability.

Broadly, the Hadley and Canadian scenarios fall in the middle and at the high end, respectively, of IPCC (1996) projections of warming by the year 2100; the newer IPCC projections, however, are somewhat higher. Both scenarios have increased precipitation at the global level, consistent with the enhanced hydrological cycle accompanying warming. For the continental United States, the Canadian model scenario projects a 2.1º C average temperature change with a 4 percent decline in precipitation by 2030 and a 5.8º C warming with a 17 percent increase in precipitation by 2095. The Hadley scenario projects a 1.4º C (2030) and 3.3º C (2095) increase in temperature with precipitation increases of 6 and 23 percent, respectively. Both scenarios indicate more warming in the winter and relatively less in the summer. The mountain states and Great Plains are also projected to experience more warming than other regions in both models. The Hadley scenario also shows greater warming in the Northwest. More detail on the climate scenarios is available at *http://www.cgd.ucar.edu/naco/vemap/vemtab.html.*

Agricultural Models

Climate and other factors strongly interact to affect crop yields. Models have provided an important means for integrating many different factors that affect crop yield over the season. Scaling-up results from detailed understanding of leaf and plant response to climate and other environmental stresses to estimate yield changes for whole farms and regions can, however, present many difficulties (e.g., Woodward 1993).

Higher-level, integrated models typically accommodate only first-order effects and reflect more complicated processes with technical coefficients. Mechanistic crop growth models take into account (mostly) local limitations in resource availability (e.g., water and nutrients) but not other considerations that depend on social and economic response such as soil preparation and field operations, management of pests, and irrigation.

Models require interpretation and calibration when they are applied to estimate commercial crop production under current or changed climate conditions (see Easterling et al. 1992; Rosenzweig and Iglesias 1994); in cases of severe stress, reliability and accuracy to predict low yields or crop failure may be poor. With regard to the CO_2 response, recent comparisons of wheat models have shown that even though basic responses were correctly represented, the quantitative outcome between models varied greatly. Validation of models has been an important goal (Rosenberg et al.1992; Olesen and Grevsen 1993; Semenov et al. 1993a,b; Wolf 1993a,b; Delécolle et al. 1994; Iglesias and Minguez 1994; Minguez and Iglesias 1994).

To generate results at the national and global level, results from crop models are used in an economic model (e.g., Adams et al. 1995; Reilly et al. 1994). There are two basic types of economic models:

- Those that include costs of many different activities (crops, cropping practices, rotations, etc.) (e.g., Adams, et al. 1995). With changed conditions, such as changed productivity resulting from climate changes, such models find the least costly way to satisfy demand.
- Those based on statistical estimates of supply and demand for individual crops (e.g., Reilly et al. 1994). Changes in climate can then be represented as shifts in supply.

The activity type of model tends to have much more spatial and cropping practice detail. We apply the activity model in this assessment because of the spatial and crop detail.

There have been efforts to further integrate crop yield, phenology, and water use with geographic-scale agroclimatic models of crop distribution (Brown and Rosenberg 1999; Kenny et al. 1993; Rötter and van Diepen 1994), thereby providing greater representation of diverse conditions across a large geographic scale. There also have been efforts to integrate crop models and farm-level economic response (e.g., Kaiser et al. 1993). Simplified representations of crop response have been used with climate and soil data that are available on a global basis (Leemans and Solomon 1993). More aggregated statistical models (Ricardian models) have been used to estimate the combined physical and socioeconomic response of the farm sector (Mendelsohn et al. 1994). There also have been efforts to integrate high resolution (e.g., 0.5 degrees latitude by longitude) agroclimatic models with applied general equilibrium economic models to simultaneously capture farm-level adaptations and the response of the US farm sector to climate-induced changes in other domestic and international markets (Darwin et al. 1995).

Incorporation of the multiple effects of CO_2 in models generally has been incomplete. Some models do not include any CO_2 effects and thus may overestimate negative consequences of CO_2-induced changes in climate. Other models consider only a crude yield effect. More detailed models consider CO_2 effects on water use efficiency (e.g., Wang et al. 1992). With few exceptions, most models fail to consider CO_2 interactions with temperature and effects on reproductive growth. The erosion productivity impact calculator (EPIC) model incorporates the CO_2 effect in a relatively simplified fashion (Stockle et al. 1992a,b).

We use site-level models for our basic analysis, following the approach used in many previous assessments. To examine the sensitivity of our results to this modeling approach, we also have applied the Brown and Rosenberg (1999) model. It has fewer crops and is expensive to use, so we simulated it only with the Hadley scenario. The results are reported in detail in Izaurralde et al. (1999). The model projects corn, winter wheat, soybeans, and alfalfa under dryland and irrigated conditions. This strategy allowed us to investigate the extent to which the projections of this crop modeling approach differ from the site approach. In both of these approaches, the crop models include a CO_2 fertilization effect; we also include in our estimates higher ambient levels of atmospheric CO_2 consistent with the climate scenarios (specific assumptions are provided in Chapter 3). The reduced-form statistical approach (Ricardian analysis) of Mendelsohn et al. (1994) is relatively simple to apply, once the response is estimated. However, it does not include a CO_2 fertilization effect, and it captures all response as change in land value. Thus, there is no detail on specific crops. The case for this approach is that it takes better account of farm-level response, at least under long-run equilibrium conditions, and includes (implicitly, though not explicitly) all crops that contribute to agricultural land value.

Broadly, our approach has been to try to use several different approaches and to test results with sensitivity analysis. This strategy has allowed us to consider the extent to which the results depend on the particular method used.

Vulnerability, Surprise, Uncertainty

Quantitative analysis of climate change impacts faces many difficult challenges. The great value of quantitative analysis is that it enforces considerable rigor on our thinking about effects. The limitations are that potential interactions are only partly or poorly quantified and often are not incorporated in assessment models; climate scenarios are uncertain; we have only a vague idea of what agriculture may look like in the future, when climate change is expected to occur; and, with something as far-reaching as global climate change, there are likely to be things that happen that we never foresaw or imagined. These set of concerns have caused analysts to approach assessment in ways other than the linear approach that typically has been used (e.g., from climate scenario to crop impact to economic impact).

Vulnerability and sensitivity analysis has been one alternative approach. The idea is that climate scenarios are so uncertain that one should investigate instead a wide range of climatic conditions. Such analysis identifies climatic conditions that are particularly damaging. Applied to agriculture, the analysis might then identify actions that could be taken to reduce or eliminate these damages. Such an approach is one way to avoid the narrow range of climate conditions simulated by GCMs. The difficulty, however, is that imagining disastrous weather is not difficult, and spending large amounts of money to protect oneself against an outcome that is extremely unlikely to occur would not make sense. The usefulness of this approach rests in finding things that are simple, cheap, and easy to do that could insulate one against things that one had not anticipated.

If a probabilistic scenario analysis can be completed, one can include the probability and damage associated with each scenario in an uncertainty/vulnerability analysis. In principle, one can estimate the expected cost associated with climate and undertake only actions whose costs were less than the expected reduction in damages (for a more formal discussion, see Reilly and Schimmelpfennig 1999). For example, avoiding a $10,000 damage that had only a 1 in 100 chance of occurring would be worth only $100. Unfortunately, current climate modeling is unable to generate such probabilistic scenarios.

The other concern is the potential for surprises: climate interactions with agriculture that we never anticipated. By their very nature, once we have thought of such interactions, they are no longer a complete surprise. It is easy, however, to make the mistake of applying existing assessment approaches and models, implicitly assuming that they contain all of the important interactions. The antidote to this trap is to rethink fundamental relationships and interactions, consider broader connections, and conduct targeted research to investigate some of the links where little is known.

What are possible surprises? The most significant surprise for agriculture would be significantly different climate scenarios than are now projected by the major climate modeling centers. Significant increases in variability could greatly disrupt agriculture. (We consider this issue in detail in Chapter 4.) Climate scenarios used to date are mainly central tendency estimates and do not exhibit major nonlinearities or state changes. Describing the likelihood or the character of such scenarios is well beyond the scope of the agriculture assessment, but the impacts on agriculture of such climatic consequences of warming would be far different than any scenarios evaluated to date, including those in this assessment. Under such scenarios, rapid change—at least at a regional level—could occur and bring with it significant adjustment costs.

Within the agricultural system, the development of new pests or expanded pest range and greater resistance to control methods are possible but difficult to foresee. We know that weather and climatic factors are one critical element of pest range, but we are poorly equipped to evaluate the full set of habitat interactions. We will observe climate change as a change in extreme events (more hot days and fewer cold days; more heavy rain or longer droughts) rather than changes in the means. One-in-100-year or one-in-1,000-year events will always be a surprise. Our ability to identify whether the occurrence of such an event signals a change or is simply a matter of chance will at least partly determine whether we go back to doing the same things or adapt. In this regard, institutional preparedness and response are nearly impossible to predict. An unwillingness to adapt and change, rigidities in policy, or counterproductive policy responses could increase costs. Faced with loss of comparative advantage and threats to its local farming community, a region might seek federal money to subsidize farming, create protectionist trade policy, or build huge water projects only to maintain regional production. Such programs could have huge economic and environmental costs and ultimately might fail as climatic conditions continue to change.

Finally, we know very little about how a regional and local economy responds to multiple changes. The local tax base, recreation, agriculture, water, and forests would be affected simultaneously. History has many cases of regions and communities declining and depopulating when a critical resource is exhausted, an industry on which a community is based fails or fails to keep pace with competitors, or other areas are deemed more livable or more fashionable. On the other hand, many areas have diversified, shifted, and reoriented themselves to take advantage of new conditions.

Chapter 3

Impacts of Climate Change on Production Agriculture and the US Economy

Introduction

Climate change affects farmers and the US economy through several different pathways. Analysis of effects such as impacts on crop yields, water demand, water supply, and livestock, using biophysical models, can tell us a great deal about why a particular climate scenario causes yields to rise or fall. This analysis also can suggest directions for adaptation at the farm level. All of these changes occurring together and across the United States and the entire world mean that national and global markets can be affected. Thus, assessment of the economic viability of farming and impacts on consumers and the US economy requires consideration of the full effect of changes in crop yield, water demand, water supply, pests, and livestock as they vary across the country and the world. Many studies have demonstrated that farmers can suffer economic losses even if crop yields improve because commodity prices fall (see Chapter 2). The net effect on the US economy can be positive in this situation because consumers gain from lower food prices. Such results are sensitive to how climate change affects agricultural production in the rest of the world.

The techniques and approaches we use in this assessment build on previous efforts, the most recent of which is reported in Adams et al. (1999). The other notable direct ancestor of this work is Adams et al. (1990).

In this analysis, we considered five principal direct effects of climate change:

- Crop yields and irrigated crop water use
- Irrigation water supply
- Livestock performance and grazing/ pasture supply
- Pesticide use
- International trade

We combine these effects of climate change in an economic model that determines the new set of price, consumption, regional production, and resource use levels.

The focus of the analysis was to estimate the consequences for the agriculture sector of climate-induced changes via each of the foregoing mechanisms in terms of the overall level of producer income and the welfare of agricultural consumption by consumers. We also estimated changes in the location of production and utilization of resources as influenced by climate change. We estimated these changes by using a US national agricultural sector model (ASM) that is linked to a global trade model. In particular, the basic analytical approach entailed introduction of estimates of climate change-induced alterations in the five data items and examination of how the model solution differs from the base solution, without climate change. The most important aspect of this analysis was the generation of changes in necessary inputs into the economic model such as crop yields and water demands for irrigation. Several teams of crop modelers simulated changes in yields and water demand to provide these changes.

The results were simulated for transient scenarios drawn from the Canadian model and the Hadley model. Although the impact analysis was based on these transient scenarios, it used average climate conditions for the 2020–2039 and 2080–2099 periods. Simulated climates vary from year-to-year. The intent of using 20-year averages was to produce climate change scenarios that were more representative of the years 2030 and 2090 than would be any single year of simulated climate. We thus refer to the results generated in this way as results for the year 2030 and 2090.

The underlying yield and water demand changes were simulated for crops like those that exist today. Similarly, changes in pesticide use, water supply, livestock changes, and trade scenarios are based on patterns that exist today. The economic results were produced by simulating the impact of climate change on the agricultural economy as it existed in the year 2000. We also considered the impacts of climate change on a scenario of the agricultural economy projected forward to the years 2030 and 2090. These scenarios took advantage of scenarios generated under the forest sector assessment (Joyce et al. 2001; Irland et al. 2001). The ASM model we used in this analysis is part of the combined forest-agriculture sector model that was used in the US National Assessment Forest Sector Assessment. Thus, we were able to simulate the combined effects of forest and agricultural changes on the US economy and consider the implications for land use.

We considered climate change via the five principal direct effects so that these changes could be introduced into the economic model. The economic model we used in the analysis does not use climate data directly. It uses changes in crop yields, water demand, water supply, and other factors as they are affected by climate. The changes are then introduced into the ASM model alone or in combination to evaluate their effect on the agricultural economy and resource use. In the following section we review the basis for these changes and discuss the additional assumptions needed to introduce them into the economic model. In the remainder of this chapter, we describe basic methods and findings from the crop studies; describe the approaches and additional assumptions needed to use these site-level results in a national level economic model; provide details on the estimation of livestock effects; briefly describe the process by which pesticide use was included in the economic estimates (we provide greater detail in Chapter 6); describe the basis for considering the effect of changes in production elsewhere in the world that affect US agriculture through international trade; and report the economic and resource use results that we estimated with the economic model.

Yield and Water-Use Changes

The crop yield and irrigation water-use impacts developed here were based on crop studies conducted as part of the agriculture sector assessment. Coordinated site studies were conducted by teams at the Goddard Institute of Space Studies (GISS), the University of Florida, and the National Resource Ecology Laboratory (NREL) at Colorado State University; these studies provide the core set of yield and irrigation water-use estimates in the economic analysis. The Pacific Northwest National Laboratory (PNNL) also produced a set of crop yield results; these results, however, were developed only for the Hadley climate scenarios, and they did not include as many crops as the coordinated site-level studies or consider adaptation. An advantage of the PNNL work, however, is that it estimated impacts for each of more than 200 representative regions, whereas the detailed site studies were based on 45 sites, and not all crops were simulated at all sites. The PNNL analysis also used a different crop model—the Erosion Productivity Index Calculator (EPIC)—to estimate yield and irrigation water demand effects, different assumptions about ambient carbon dioxide levels, and a somewhat different method to develop weather scenarios. We also adapted results from a Southeastern US project being conducted at the National Center for Atmospheric Research (NCAR) in Colorado (led by Linda Mearns) to provide estimates of impacts on cotton—an important crop for which we were unable to conduct new yield estimates. We describe very briefly here the basic approach and summarize the principal findings from the core site-level crop studies. We also review very briefly other related crop studies. Details on each of the studies conducted under the auspices of the agriculture assessment are included in reports available at the National Assessment web site (*http://www.nacc.usgcrp.gov*).

Using these results in an economic model that covers the entire United States and many crops raises two methodological issues: how to treat crops for which crop simulations were not conducted and how to extrapolate from sites to regional scale impacts. We discuss how we did this extrapolation and summarize the national average yield changes below. We then provide more detail on the crop model simulations and site-level results.

National Average Yield and Water-Use Changes

With regard to omitted crops, the basic issue is that production and resource effects in the economic model depend on *relative* changes in yield and water use among crops. As a result, the production of crops omitted from the simulation studies is affected in the economic model even if no direct climate effects are assumed for them. This problem could create regional and resource use shifts that reflect the relative importance of omitted crops rather than the estimated climate effects. Left unaffected by climate change, the omission of impacts on some crops could lead to a bias in the estimate of the overall economic impact of climate change. Generally improving conditions would be underestimated if no yield increase were included. The converse also is true: If conditions were generally worsening, the impact would be underestimated. These considerations lead to the conclusion that, for assessment purposes, it is useful to make a best guess for these omitted crops.

We assumed that, for each omitted crop, one of the crops for which yields were simulated in the crop studies could serve as a proxy (a common assumption). Crops that were grown in similar areas and simulated for sites in those areas were used as proxy crops. The use of proxy crops has many limitations; without actually simulating the omitted crops, one cannot easily establish the error involved in using one crop or another as a proxy. In simulating economic effects, we follow previous work in assuming that a crude assumption is better than leaving omitted crops unaffected. The latter approach would lead to production shifts to (or away) from the crop. For cotton, we adapted the results of NCAR's Southeastern US study. We discuss the specific approach for each omitted crop in the following pages.

Proxy Crops

We used a direct proxy crop approach for the crops listed in Table 3.1. For example, silage sensitivity was assumed to be the same as corn sensitivity.

Cotton

We were unable to secure and run a new set of results for cotton. Thus, we relied on existing NCAR work undertaken by Linda Mearns that included cotton but used a different set of climate scenarios. The NCAR study simulated yield effects by using many of the same crop models we used in our assessment and for several climate scenarios, including the Hadley scenario. NCAR used a climate representative of 2060, however, and did not conduct simulations based on the Canadian climate model. A comparison of yield effects among the NCAR crops shows that none of the other crops responds similarly to cotton, suggesting that no single crop would serve as a proxy for cotton. An attempt to use

Table 3.1. Proxy Crops

Crop with missing data	Crop used as proxy
Hard Red Spring Wheat	Spring wheat
Hard Red Winter Wheat	Winter wheat
Soft Wheat	Wheat[a]
Durham Wheat	Wheat[a]
Barley	Wheat[a]
Oats	Wheat[a]
Silage	Corn
Oranges, fresh	Oranges
Oranges, processed	Oranges
Grapefruit, fresh	Oranges
Grapefruit, processed	Oranges
Tomatoes, processed	Tomatoes
Tomatoes, fresh	Tomatoes
Sugar Cane	Rice
Sugarbeet	Hay

[a]For each ASM region, the dominant variety of wheat (spring or winter) grown in that region was used for the proxy for these crops.

multiple regression analysis to statistically relate cotton yields to the yields of all other crops verified the conclusion that no single crop—nor any combination of crops—explained the site-level variation in yield impacts of cotton. The approach we adopted instead was to adapt the NCAR cotton yield sensitivity data directly, as explained in McCarl (2000). Operationally, this analysis involved extrapolating the 2060 spatial distribution of cotton yield and water-use sensitivity from the NCAR study to 2030 and 2090, based directly on the climate in these years relative to the Hadley climate for 2060.

The intent of these assumptions was to avoid underestimating overall economic impacts of climate on the US agriculture economy by assuming no effect at all on these crops. Crop coverage has been an issue in all assessments of this type. Early agricultural assessments often were limited to corn, wheat, rice, and soybeans. More recent assessments, including this one, have worked to provide broader crop coverage. Caution obviously is warranted in using detailed crop results from the economic model where crop yield effects were not simulated directly. These uncertainties also introduce uncertainties in

Table 3.2a National Average Change in Dryland Yields Without Adaptation (percentage change from base conditions)

	CC	CC	HC	HC	HC-PNNL*	HC-PNNL*
Crop	**2030**	**2090**	**2030**	**2090**	**2030**	**2090**
Cotton	18	96	32	82	32	82
Corn	19	23	17	34	11	16
Soybeans	20	30	34	76	7	9
Hard Red Spring Wheat	15	-4	20	30	17	24
Hard Red Winter Wheat	-16	-1	21	55	24	41
Soft Wheat	-5	3	8	20	58	68
Durum Wheat	15	-5	21	30	10	18
Sorghum	17	21	15	70	15	70
Rice	-2	-8	3	10	3	10
Barley	56	25	83	132	70	124
Oats	23	-2	54	101	158	182
Silage	17	18	15	32	11	24
Hay	-10	-1	2	15	43	57
Sugar Cane	-5	-5	0	8	0	8
Sugar Beet	7	11	9	24	30	45
Potatoes	7	-25	6	-3	6	-3
Orange, Fresh	32	91	40	69	40	69
Orange, Processed	13	120	28	49	28	49
Grapefruit, Fresh	21	101	33	60	33	60
Grapefruit, Processed	15	112	29	53	29	53
Pasture	3	20	22	38	22	38

* Shaded cells in the final two columns are yields that were not based on PNNL crop yield simulations either directly or indirectly using the proxy crop method; PNNL climate assumptions differed somewhat from the site study climate assumptions as described in the text.

the overall economic results. In a very limited way, we explored this uncertainty by simulating the economic model, using the different approaches we developed for cotton.

With regard to extrapolation from site-level data, the ASM model includes 63 regions (see Figure 3.1, with overlay of the USDA production regions). Not all crops were simulated at each of the 45 sites. In some cases, multiple sites were located in a single ASM region. When multiple simulation sites appeared in a region, we used an unweighted average across those sites.[1] We used proxy regions for regions in which no sites were located; in these cases, we used adjacent regions as proxies. McCarl (2000) discusses the ASM, the use of adjacent regions as proxies, and other details of the methods we used in greater detail. Briefly, the ASM is a spatial equilibrium model that includes domestic and foreign demand for agricultural products and foreign supplies for agricultural products. Multiple activities (crops, irrigated and nonirrigated, types of livestock, etc.) are represented in the model. Each US production region has bilateral trade with other domestic and foreign regions. Model solutions involve solving for a set of prices for all goods in all markets where the quantity demanded for each product is equal to the quantity supplied. Activity choice is solved simultaneously in the determination of equilibrium prices, based on their profitability.

Table 3.2b National Average Change in Dryland Yields With Adaptation (percentage change from base conditions)

	CC	CC	HC	HC	HC-PNNL*	HC-PNNL*
Crop	**2030**	**2090**	**2030**	**2090**	**2030**	**2090**
Cotton	18	96	32	82	32	82
Corn	20	24	17	34	11	16
Soybeans	39	64	49	97	7	9
Hard Red Spring Wheat	20	14	23	36	17	24
Hard Red Winter Wheat	-9	13	23	59	24	41
Soft Wheat	-3	4	9	21	58	68
Durum Wheat	18	12	22	33	10	18
Sorghum	43	87	32	96	32	96
Rice	7	4	9	18	9	18
Barley	96	133	105	197	70	124
Oats	33	24	57	106	158	182
Silage	18	20	16	32	11	24
Hay	-10	-1	2	15	43	57
Sugar Cane	6	7	7	16	7	16
Sugar Beet	7	11	9	24	30	45
Potatoes	8	-20	7	1	7	1
Orange, Fresh	32	91	40	69	40	69
Orange, Processed	13	120	28	49	28	49
Grapefruit, Fresh	21	101	33	60	33	60
Grapefruit, Processed	15	112	29	53	29	53
Pasture	3	20	22	38	22	38

* Shaded cells in the final two columns are yields that were not based on PNNL crop yield simulations either directly or indirectly using the proxy crop method; PNNL climate assumptions differed somewhat from the site study climate assumptions as described in the text.

[1]There is no obvious basis for selecting weights within an ASM region; thus, we treat these data as multiple representative draws from the same population.

ASM Regions with USDA Regions Overlaid

As with crop proxies, the lack of direct estimates for a site within a region introduces considerable uncertainty in estimates for that region. Even for regions with site estimates, a sample of one or two sites may not be representative of the region. The PNNL crop yield model results were based on a denser selection of sites, although the model simulates all crops at one site in every hydrological basin; thus, the results for many of the sites (where production does not now occur, nor would it occur in the future) are weighted as zero in the national

Figure 3.1: This figure presents Agriculture Sector Model (ASM) regions as they appear when overlaid with USDA regions. The ASM regions follow state boundaries and each state is typically a region except where further disaggregated. For example, the California region is an ASM region. The USDA regions are delineated with the heavier black line. For example, one USDA region is the Pacific which includes Washington, Oregon, and California.

Table 3.3a National Average Change in Irrigated Yields Without Adaptation (percentage change from base conditions)

	CC	CC	HC	HC	HC-PNNL*	HC-PNNL*
Crop	**2030**	**2090**	**2030**	**2090**	**2030**	**2090**
Cotton	36	122	56	102	56	102
Corn	-1	-2	0	7	21	22
Soybeans	16	28	17	34	17	34
Hard Red Spring Wheat	-10	-18	4	6	4	6
Hard Red Winter Wheat	-4	-6	5	13	5	13
Soft Wheat	-6	-5	3	9	3	9
Durum Wheat	-10	-21	5	6	5	6
Sorghum	-1	-16	1	-2	1	-2
Rice	-2	-8	3	10	3	10
Barley	-40	-71	8	15	8	15
Oats	-17	-31	12	28	12	28
Silage	1	0	1	9	26	30
Hay	3	2	23	24	37	40
Sugar Cane	-5	-5	0	8	0	8
Sugar Beet	22	23	39	42	41	44
Potatoes	-6	-28	-3	-13	-3	-13
Tomato, Fresh	-9	-21	1	-4	1	-4
Tomato, Processed	-16	-6	-6	-14	-6	-14
Orange, Fresh	32	91	40	69	40	69
Orange, Processed	13	120	28	49	28	49
Grapefruit, Fresh	21	101	33	60	33	60
Grapefruit, Processed	15	112	29	53	29	53

* Shaded cells in the final two columns are yields that were not based on PNNL crop yield simulations either directly or indirectly using the proxy crop method; PNNL climate assumptions differed somewhat from the site study climate assumptions as described in the text.

average change. Nevertheless, these results indicate, in part, the uncertainty in estimated impacts that derive from different approaches for estimating yield impacts. As a sensitivity analysis, we therefore used the available PNNL results in the economic model as a substitute for the coordinated site-level results.

These assumptions provide the basis for estimating yield impacts for all crops in each region of the ASM. The national average change in yields for dryland and irrigated crops with and without adaptation are listed in Tables 3.2a,b and 3.3a,b. Table 3.4a,b lists the national results for changes in water use on irrigated crops. We constructed the national averages by weighting ASM regional estimates generated from the crop model results as described above by harvested acreage in each ASM region; the weights were based on data from the 1992 National Resource Inventory (NRI). McCarl (2000) provides additional details.

The estimates in Tables 3.2 through 3.4 are a summary of input into the ASM model. Actual national production depends on changes in the agricultural economy induced by these changes. The estimates are, however, a useful intermediate result that summarizes the crop modeling simulations. The site simulation results by themselves can provide a misleading impression of overall impacts because crops were simulated at many sites where little of the crop is grown or sites under dryland conditions where the crop is mainly grown only with irrigation. Weighting results for the site by area provides a better guide to how climate would affect

Table 3.3b National Average Change in Irrigated Yields With Adaptation (percentage change from base conditions)

	CC	CC	HC	HC
Crop	**2030**	**2090**	**2030**	**2090**
Cotton	36	122	56	102
Corn	1	0	1	9
Soybeans	23	33	23	40
Hard Red Spring Wheat	-1	-6	7	10
Hard Red Winter Wheat	-1	0	8	16
Soft Wheat	-5	-3	5	11
Durum Wheat	2	-4	9	10
Sorghum	22	8	22	21
Rice	7	4	9	18
Barley	3	-16	28	40
Oats	-6	-15	17	33
Silage	3	3	2	10
Hay	3	2	23	24
Sugar Cane	6	7	7	16
Sugar Beet	22	23	39	42
Potatoes	-4	-21	-1	-8
Tomato, Fresh	1	6	10	13
Tomato, Processed	10	44	10	17
Orange, Fresh	32	91	40	69
Orange, Processed	13	120	28	49
Grapefruit, Fresh	21	101	33	60
Grapefruit, Processed	15	112	29	53

Table 3.4a National Average Change in Water Use on Irrigated Crops, Without Adaptation (percentage change from base conditions)

	CC	CC	HC	HC
Crop	**2030**	**2090**	**2030**	**2090**
Cotton	-11	107	36	60
Corn	-34	-54	-30	-60
Soybeans	0	3	-12	-26
Hard Red Spring Wheat	-28	-22	-17	-21
Hard Red Winter Wheat	5	-9	-8	-29
Soft Wheat	5	-29	-12	-44
Durum Wheat	-28	-15	-18	-21
Sorghum	-7	-23	-9	-35
Rice	-10	37	-2	-4
Barley	-98	-90	-61	-85
Oats	-57	-73	-47	-80
Silage	-35	-50	-33	-63
Hay	2	26	-29	-36
Sugar Cane	-23	3	-8	-1
Sugar Beet	-12	40	-28	-28
Potatoes	-5	7	-1	4
Tomato, Fresh	-9	14	-5	5
Tomato, Processed	-3	-6	-4	-4
Orange, Fresh	-21	94	-6	-6
Orange, Processed	0	438	11	24
Grapefruit, Fresh	-1	324	8	21
Grapefruit, Processed	1	401	11	24

production. These tables also provide input data for the ASM, based on PNNL crop results. The PNNL modeled only corn, alfalfa, wheat, hay, and soybeans. Crops other than these four (and those for which one of these crops were proxies) have identical changes as the core results for the Hadley climate scenario. These entries are shaded in the table. As shown Table 3.2, the PNNL results differ substantially in magnitude for some dryland crops for some periods and thus indicate substantial uncertainty in the estimates of crop yields resulting from these different methodological approaches. The results of the two approaches agree in that both find generally substantial positive yield effects for the dryland crops considered by both. The PNNL results, in contrast to the coordinated site studies, generally show increased yields for irrigated crops (Table 3.3). We discuss these differences further below; in general, however, the source of these differences cannot be isolated without highly controlled comparisons of these models. As part of the agriculture assessment, we funded a model comparison workshop aimed at establishing such a comparison (Paustian et al. 2000).

Table 3.4b National Average Change in Water Use on Irrigated Crops, With Adaptation (percentage change from base conditions)

	CC	CC	HC	HC
Crop	**2030**	**2090**	**2030**	**2090**
Cotton	-11	107	36	60
Corn	-33	-55	-32	-60
Soybeans	18	12	0	-20
Hard Red Spring Wheat	-12	-15	-12	-15
Hard Red Winter Wheat	9	-3	-6	-25
Soft Wheat	5	-24	-10	-45
Durum Wheat	-3	-5	-9	-12
Sorghum	3	-19	2	-27
Rice	2	48	5	8
Barley	-40	-57	-41	-61
Oats	-37	-60	-38	-68
Silage	-35	-52	-35	-62
Hay	2	26	-29	-36
Sugar Cane	-19	-11	-6	7
Sugar Beet	-12	40	-28	-28
Potatoes	-3	10	0	7
Tomato, Fresh	-8	6	2	13
Tomato, Processed	3	-14	-3	-6
Orange, Fresh	-21	94	-6	-6
Orange, Processed	0	438	11	24
Grapefruit, Fresh	-1	324	8	21
Grapefruit, Processed	1	401	11	24

The results vary across crops, time periods, and climate scenarios, but some broad patterns emerge.

- Even without adaptation, the weighted average yield impact for many crops grown under dryland conditions across the entire United States is positive under the Canadian and Hadley climate models. In many cases, yields under the 2030 climate conditions are improved compared with the control yields under current climate and improve further under the 2090 climate conditions. These generally positive yield results are observed for cotton, corn for grain and silage, soybeans, sorghum, barley, sugarbeet, and citrus fruit. The yield results are mixed for other crops (wheat, rice, oats, hay, sugar cane, and potatoes); yield increases under some conditions and declines under other conditions.
- Changes in irrigated yields, particularly for the grain crops, were more often negative or less positive than dryland yields. This result reflects the fact that precipitation increases were substantial under these climate scenarios. Precipitation increases do not provide a yield benefit to irrigated crops because no water stress occurs; all of the water that is needed is provided through irrigation. Higher temperatures speed development of crops and reduced the grain filling period, thereby reducing yields. For dryland crops, the negative effect of higher temperatures was counterbalanced by the positive effect of increased moisture.
- Water demand by irrigated crops dropped substantially for most crops. The faster development of crops resulting from higher

temperatures reduced the growing period and thereby reduced water demand more than offsetting increased evapotranspiration because of higher temperatures while the crops were growing. To a large extent, the reduced water use thus reflects the reduced yields on irrigated crops. Increased precipitation also reduced the need for irrigation water.

- Adaptation contributed small additional gains in yields of dryland crops, particularly those with large yield increases from climate change. Adaptation options were considered for sites with losses and those with gains; for the most part, however, these adaptations had little additional benefit where yields increased from climate change. This finding suggests that adaptation may be able to partly offset changes in comparative advantage across the United States that results under these scenarios. Other strategies for adaptation, such as whether to switch crops or to irrigate or not, are part of 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. We did not consider adaptation for several crops because the measures we considered (such as planting date) were not applicable to many perennial and tree fruit crops. We conducted adaptation studies only for a limited number of sites.
- Adaptation contributed greater yield gains for irrigated crops. Shifts in planting dates can reduce some heat-related yield losses. With higher yields than in the no-adaptation case, water demand declines were not as substantial. Again, this finding reflected the fact that the adaptations we considered extended the growing (and grain-filling period), and this extension meant a longer period over which irrigation water was required.

The PNNL results for dryland crop yields show similar positive effects to those estimated with the more detailed site-level crop models, although the magnitude of the impact varies. The differences between the PNNL and site-level models were not consistently higher or lower. These differences are likely partly related to the site selection (where the PNNL approach has advantage because of denser sampling), differences in the crop models (where the site-level models have an advantage because they have been developed to better represent each crop), and differences in experiment design (i.e., assumed ambient levels of ambient CO_2 were different). The PNNL did not consider adaptation. The PNNL also considered irrigation only for corn and alfalfa. The PNNL results for these irrigated yields for the crops they considered also differ substantially from the site-level models. Whereas the site-level models show yield losses and reductions in irrigation water use, the PNNL results show yield gains. In the site-level models, higher temperatures speed development of the crop and reduce yield and water demand. The EPIC model on which the PNNL results are based do not show this negative effect of temperature; instead, temperature increases yield. These differences should be interpreted, therefore, as indicative of the level of uncertainty in the estimates contributed by crop modeling and experimental design; we could not conclude that one approach or the other was clearly superior on all counts.

Crop Model Results and Methods

The national average results presented above were based on site-level studies for several major crops: wheat, maize, soybean, potato, citrus, tomato, sorghum, rice, and hay. The GISS-Florida-NREL results were obtained from 45 sites across the United States (Table 3.5). Greater details on the methods and results are given in Tubiello et al. (2000). We used a network of major crop growing sites, based on current USDA national and state-level statistics. A subset of these sites had been used in previous work (Adams et al. 1990; Rosenzweig and Iglesias 1994; Adams et al. 1999). The study sites we selected do not span the United States homogeneously; they focus on areas of major production and importance to national output. We simulated crops at current sites of production for winter and

Table 3.5 Crop Study Sites

	Site	Crops simulated
1.	Abilene, TX	Winter Wheat, Sorghum, Pasture
2.	Alamosa, CO	Potato, Pasture
3.	Bakersfield, CA	Citrus, Rice, Pasture
4.	Boise, ID	Winter Wheat, Spring Wheat, Potato, Pasture
5.	Buffalo, NY	Potato, Tomato, Pasture
6.	Caribou, ME	Potato, Pasture
7.	Columbus, OH	Tomato, Winter Wheat, Corn, Pasture
8.	Columbia, SC	Soybean, Sorghum, Tomato, Pasture
9.	Corpus Christi, TX	Citrus, Pasture
10.	Daytona Beach, FL	Citrus, Pasture
11.	Des Moines, IA	Corn, Soybean, Pasture
12.	Dodge City, KS	Winter Wheat, Pasture
13.	Duluth, MN	Corn, Soybean, Pasture
14.	El Paso, TX	Citrus, Rice, Sorghum, Tomato, Pasture
15.	Fargo, ND	Spring Wheat, Potato, Corn, Pasture
16.	Fresno, CA	Rice, Spring Wheat, Tomato, Pasture
17.	Glasgow, MT	Spring Wheat, Pasture
18.	Goodland, KS	Winter Wheat, Sorghum, Pasture
19.	Indianapolis, IN	Potato, Corn, Soybean, Tomato, Pasture
20.	Las Vegas, NV	Citrus, Pasture
21.	Louisville, KY	Soybean, Sorghum, Pasture
22.	Madison, WI	Potato, Corn, Soybean, Pasture
23.	Medford, OR	Potato, Pasture
24.	Memphis, TN	Corn, Soybean, Pasture
25.	Miami, FL	Rice, Citrus, Pasture
26.	Montgomery, AL	Citrus, Rice, Soybean, Sorghum, Tomato, Pasture
27.	Muskegon, MI	Potato, Soybean, Tomato, Pasture
28.	North Platte, NE	Winter Wheat, Corn, Soybean, Sorghum, Pasture
29.	Oklahoma City, OK	Winter Wheat, Sorghum, Pasture
30.	Pendleton, OR	Potato, Pasture
31.	Peoria, IL	Corn, Soybean, Sorghum, Pasture
32.	Pierre, SD	Spring Wheat, Sorghum, Pasture
33.	Port Arthur, TX	Rice, Citrus, Pasture
34.	Raleigh, NC	Soybean, Sorghum, Tomato, Pasture
35.	Red Bluff, CA	Rice, Citrus, Pasture
36.	Savannah, GA	Citrus, Soybean, Sorghum, Pasture
37.	Scott Bluff, NE	Potato, Pasture
38.	Sioux Falls, SD	Corn, Sorghum, Pasture
39.	Shreveport, LA	Rice, Citrus, Pasture
40.	Spokane, WA	Winter Wheat, Spring Wheat, Pasture
41.	St. Cloud, MN	Spring Wheat, Corn, Soybean, Pasture
42.	Tallahassee, FL	Citrus, Tomato, Pasture
43.	Topeka, KS	Winter Wheat, Corn, Soybean, Sorghum, Pasture
44.	Tucson, AZ	Spring Wheat, Citrus, Pasture
45.	Yakima, WA	Potato, Pasture

spring wheat, maize, soybean, potato, hay, and citrus. Some of the sites may not have been ideally located for the remaining crops in this analysis, such as tomato and rice. In addition, we simulated at more northerly sites the production of some crops currently limited to southern locations, to estimate the potential for northward shifts under climate warming. Ideally, we would have included a much denser network of sites, but our resources for more extensive data and time intensive calculations were limited. We contrast these results for the Hadley climate scenario with the PNNL modeling results conducted for each of the 204 eight-digit Hydrological Unit Areas defined by the US Geological Survey, using EPIC-based crop models for corn, soybean, winter wheat, and alfalfa.

At each of the 45 sites we examined, we collected observed time series of daily temperatures (minima and maxima), precipitation, and solar radiation for the period 1951–1990, representing the "baseline" climate for this study. We simulated the crop models over this 40-year period to compute an average yield and water use for the baseline climate. We produced scenarios of climate change according to transient simulations performed with two general circulation models (GCMs): the Canadian Climate Centre (CCC) model and the Hadley Centre (HAD) model. We considered two time periods in this analysis: 2030 and 2090—representing changes in climate projected by each GCM—and calculated by using 20-year averages centered around the years 2030 and 2090, respectively. We used absolute average temperature deviations and percentage changes in precipitation to adjust the 40-year historical record to produce an altered climate that was representative of these years. We then used the crop models to simulate yields for each of these 40-year altered climates and compared the average yield and water use with the simulated baseline yield and water use to compute the impact of climate change. Atmospheric CO_2 concentrations used for the crop model simulations—350 ppm for the baseline; 445 ppm for 2030, and 660 ppm for 2090—were based on the IPCC IS92a scenario of future emissions. The IS92a emissions scenario is approximately consistent with a 1 percent per year increase in total emissions of greenhouse gases (GHGs). Thus, the CO_2 concentrations we used in the crop models are less than if all of the 1 percent increase were CO_2—reflecting the fact that other GHGs will contribute to warming. If all of the increase were caused by CO_2 emissions, CO_2 concentrations would be higher and the crop models would show a larger CO_2 fertilization effect.

We downscaled GCM output to each of the study sites by linear interpolation, using the four gridpoints closest to each location. We then applied mean monthly changes in temperature and precipitation to the observed baseline meteorological series to produce representative weather for the future scenarios. We used a total of five scenarios in this study:

- the baseline, representing current conditions
- the Hadley climate model for 2030 (HAD 2030)
- the Canadian climate model for 2030 (CCC 2030)
- the Hadley model for 2090 (HAD 2090)
- the Canadian model for 2090 (CCC 2090).

HAD 2030 and CCC 2030 are representative of the climate and CO_2 concentration for the 2020–2039 period; HAD 2090 and CCC 2090 are representative of the climate and CO_2 concentrations for the 2080–2099 period.

We used a suite of crop models to simulate the growth and yield of study crops under the current and climate change scenarios. The Decision Support Systems for Agrotechnology Transfer (DSSAT) family of models was used extensively in this study, to simulate wheat, corn, potato, soybean, sorghum, rice, citrus, and tomato (Tsuji et al., 1994). The CENTURY model was used to simulate grassland and hay production (Parton et al., 1994).

All of the models we employed have been used extensively to assess crop yields across the United States under current conditions as well as under climate change (Rosenzweig et al. 1995; Parton et al. 1994; Tubiello et al. 1999). Apart from CENTURY, which was run in monthly time-steps, 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, so they were able to assess the effects of different management practices on crop growth.

The simulations performed for this study considered rainfed production and optimal irrigation—defined as refilling of the soil water profile whenever water levels fall below 50 percent of capacity at 30 cm depth. Fertilizer applications were assumed to be optimal at all sites.

The climate change scenarios we used in this study are more realistic than those previously available. Because they include the effects of sulfate aerosols on future climate change, they result in projected changes in temperature and precipitation that are smaller than those in previous "equilibrium" and transient climate change simulations, particularly in the first half of the 21st century. In fact, the temperature increases in 2090 become substantial at all sites we considered, as the "masking" effect of aerosols on climate warming becomes small compared to the magnitude of greenhouse forcing.

Additional analyses, independent from the foregoing site studies, have been developed by other groups in the United States as part of the assessment effort or in ongoing research with the same or similar climate models. There are some important differences in the assumptions in these analyses, however, that make them not directly comparable to the core studies reported above.

Researchers at PNNL developed national-level analyses for corn, winter wheat, alfalfa, and soybean, using climate projections from the Hadley GCM (Izaurralde et al. 1999). 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). EPIC was used to simulate the behavior of 204 "representative farms" (i.e., soil-climate-management combinations) under the baseline climate, the two future periods, and their combinations with two levels of atmospheric CO_2 concentrations (365 ppm and 560 ppm). This approach differed from the core studies that used 2030 and 2090 CO_2 levels. The CO_2 effect was independent of climate effects in the PNNL work, however, allowing interpolation. The results of the PNNL study with CO_2 effects interpolated were used in the economic model to compare the approach with that used in the coordinated site studies.

Another group, coordinated at Indiana University, focused only on corn; this group developed a regional analysis for the Corn Belt region, using Hadley model projections (Southerland et al. 1999). Baseline climate was defined by using the period 1961–1990. Several future scenarios were analyzed for the decade of 2050, with atmospheric CO_2 concentration set at 555 ppm. Corn yields were simulated with the DSSAT model at 10 representative farms. Adaptations studied included changes in planting dates, as well as the use of cultivars with different maturity groups. Although this work was not conducted with funding from the agriculture assessment, it offers some additional site-level information for corn.

Although specific differences in time horizons, CO_2 concentrations, and simulation methodologies complicate comparison of these additional analyses with the work discussed herein, model findings overall were in general agreement with ours. We discuss them briefly, crop-by-crop, in the "results" section of this work.

Simulations Under Current Climate

A test of the basic validity of the models involves simulating yields under current climate and compare them, coarsely scaled, to the state level by using statistical information on percent irrigation. These comparisons generally showed good agreement with reported yields variations across the United States.

In addition to current practices at each site, we also simulated different adaptation techniques for use under climate change. These simulations consisted largely in testing the effects of early planting—a realistic scenario at many northern sites under climate change—and testing the performance of cultivars that are 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 early temperatures. New, better-adapted cultivars were tested for winter crops (e.g., wheat) to increase the time to maturity (shortened under climate change scenarios) and to increase yield potential.

Winter Wheat

We simulated winter wheat at Abilene, Texas; Boise, Idaho; Columbus, Ohio; Dodge City, Kansas; Topeka, Kansas; Goodland, Kansas; North Platte, Nebraska; Oklahoma City, Oklahoma; and Spokane, Washington. The differences in yields between irrigated and rainfed production for the crop simulations were similar to differences between actual county-level averages of yield for irrigated and rainfed production. Record irrigated yields were simulated at Boise; all remaining sites produced 4.5–5.5 t/ha. Coefficients of variation (CVs) for irrigated production were 10–15 percent. The largest differences between irrigation and rainfed practice were at Boise (more 400 percent) and Spokane (150 percent). The smallest gains with irrigation were at the wet sites: Columbus and Topeka. Simulated yields at these sites had been compared previously with current conditions and were well correlated with production data at the state level.

Spring Wheat

Spring and durum wheat are grown extensively in North and South Dakota and Montana; there also are some important production centers in the Northwest, California, and Arizona. We chose a total of eight sites of importance to US spring wheat production: Boise, Idaho; Fargo, North Dakota; Fresno, California; Glasgow, Montana; Pierre, South Dakota; St. Cloud, Minnesota; Spokane, Washington; and Tucson, Arizona. Simulated irrigated yields were 50–60 percent higher than rainfed yields, with lower year-to-year variability (CV). The simulated marginal (i.e., additional) returns on irrigation were large at Boise, Spokane, and Tucson, where irrigated yields were 100 percent, 300 percent, and 1,000 percent higher, respectively, than under rainfed conditions. The highest irrigated yields, 7–8 t/ha, were simulated at Tucson and Fresno; all remaining sites produced 3–5 t/ha. Coefficients of variation were 10–15 percent for irrigated production and 40–50 percent for rainfed production. Simulated yields at these sites previously had been compared with current conditions and were well correlated with production data at the state level.

Maize

Simulated maize yields agreed well with reported state-level averages; the highest dryland yields—above 8 t/ha—were simulated at Columbus, Ohio; Madison, Wisconsin; and Indianapolis, Indiana. Production at the remaining sites was in the 5–7 t/ha range, with low yields and high CVs simulated at St. Cloud, Minnesota—currently at the northern margin of the main US corn production area.

Potato

We chose a total of 12 sites of importance to national potato production: Alamosa, Colorado; Boise, Idaho; Buffalo, New York; Caribou, Maine; Fargo, North Dakota; Indianapolis, Indiana; Madison, Wisconsin; Medford, Oregon; Muskegon, Michigan; Pendleton, Oregon; Scott Bluff, Nebraska; and Yakima, Washington. We simulated viable continuous rainfed potato production at Buffalo, Caribou, Fargo, Indianapolis, and Madison. Under current climate, crop simulations correlated well with reported production. The highest simulated irrigated yields—slightly above 80 t/ha—were at the Northwestern sites (Medford, Pendleton, and Yakima), where the marginal impact of irrigation was also the greatest (irrigated yields were about 10 times rainfed yields). At all remaining sites, production was between 40 and 50 t/ha. Coefficients of variation for irrigated production were 6–9 percent. CVs were between 30 and 40 percent under rainfed conditions.

Citrus

We conducted simulations for Valencia oranges at eight sites with substantial current production. Of these, four sites—Bakersfield, California; Corpus Christi, Texas; Daytona Beach, Florida; and Miami, Florida—corresponded to high-producing areas in the United States, yielding more than 11 t/ha of fruit. One site (Red Bluff, California) represented mid-level production—around 7 t/ha; three sites—Tucson, Arizona; Port Arthur, Texas; and Las Vegas, Nevada—produced 4–6 t/ha, representing marginal production levels. We chose an additional five sites to investigate the potential for citrus expansion northward of the current production area: El Paso, Texas; Montgomery, Alabama; Savannah, Georgia; Shreveport, Louisiana; and Tallahassee, Florida. Under current climate, simulations at these sites yielded 2–2.5 t/ha. Simulated yields at these sites previously had been compared with current conditions and were well correlated with production data at the state level.

Soybean

We simulated soybean production across the United States at 15 sites: Charleston, South Carolina; Louisville, Kentucky; Raleigh, North Carolina; Des Moines, Iowa; Duluth, Minnesota; Indianapolis, Indiana; Madison, Wisconsin; Memphis, Tennessee; Montgomery, Alabama; Muskegon, Michigan; North Platte, Nebraska; Peoria, Illinois; Savannah, Georgia; Saint Cloud, Minnesota; and Topeka, Kansas. Simulated yields at these sites previously had been compared with current conditions and were well correlated with production data at the state level.

Sorghum

We simulated sorghum production across the United States at 14 sites: Charleston, South Carolina; Louisville, Kentucky; Raleigh, North Carolina; Abilene, Texas; El Paso, Texas; Goodland, Kansas; Montgomery, Alabama; North Platte, Nebraska; Oklahoma City, Oklahoma; Peoria, Illinois; Pierre, South Dakota; Savannah, Georgia; Sioux Falls, South Dakota; and Topeka, Kansas. Simulated yields at these sites compared well to state-level variations across the US sorghum production area.

Rice

We selected eight sites, accounting for 48 percent of US rice production, to represent the US rice growing regions: Louisville, Kentucky; Bakersfield, California; Des Moines, Iowa; El Paso, Texas; Fresno, California; Miami, Florida; Montgomery, Alabama; Port Arthur, Texas; Peoria, Illinois; Red Bluff, California; Shreveport, Louisiana; and Topeka, Kansas. We chose these sites to include regions with current production and those where rice production could be viable under climate change. The highest simulated yield under current conditions was 9 t/ha (in California), and the lowest was 5 t/ha (in Louisiana)—in agreement with observed state-to-state yield differences.

Tomato

We simulated tomato production across the United States at 18 sites: Charleston, South Carolina; Louisville, Kentucky; Raleigh, North Carolina; Boise, Idaho; Buffalo, New York; Duluth, Minnesota; El Paso, Texas; Fresno, California; Indianapolis, Indiana; Montgomery, Alabama; Muskegon, Michigan; North Platte, Nebraska; Oklahoma City, Oklahoma; Peoria, Illinois; Tallahassee, Florida; Topeka, Kansas; Tucson, Arizona; and Yakima, Washington. Simulated yields at these sites, compared with current conditions, correlated well with state-level data.

Simulation Results Under Climate Change

In this subsection, we provide a brief summary of the main climate change results, including those incorporating adaptation. Many of the yield results were positive, particularly for dryland crops at northern and western sites and particularly under the Hadley climate scenario. Results for the Canadian climate scenario differed substantially from this general result, particularly for 2030 and for crops grown in the Great Plains and southern states. These differences are directly related to differences in the climate scenario. The Canadian scenario showed declines in precipitation for 2030 compared with present climate; it also showed greater temperature increases than the Hadley scenario. The temperature increases and precipitation reductions were particularly strong in the southern and Great Plains states. In contrast, the Hadley scenario exhibited smaller temperature increases and much greater precipitation increases. Furthermore, the Canadian scenario for 2090 (in contrast to the result for 2030) exhibited a large increase in precipitation compared with present climate. In the discussions of detailed results by crop that follow, we note some differences from these generalizations (e.g., for heat-loving crops such as citrus and tomatoes that did well in the south, for cool-loving crops such as potatoes that did not do particularly well even at northern sites, or for irrigated crops where additional precipitation had no yield benefit because water was already available as needed by the crop). The adaptations we considered in the crop yield simulations were changes in variety and changes in planting dates. Other changes that involve economic decisions—such as whether to irrigate or not, the amount of water to apply, whether to shift to different crops or reduce acreage planted, and the amount of labor and other inputs to use—are included in the economic model.

Winter Wheat

The two climate scenarios we considered in this study gave opposite responses for US wheat production. The Canadian climate scenario resulted in large negative to small positive impacts, whereas the Hadley scenario generated positive outcomes. The warmer temperatures projected under climate change were favorable to northern site production but deleterious to southern sites. Increased precipitation in the Northwest and decreased precipitation in the central plains were the major factors controlling the response of wheat yields to the future scenarios we considered in this study. We first analyze results for production based on current varieties and planting dates (current management) and then discuss the potential yield effects of changes in varieties and planting dates (changes in management or adaptation).

In agreement with the results presented here, the PNNL study found that "winter wheat exhibited consistent trends of yield increase under the [Hadley] scenarios of climate change across the US" (Izaurralde et al. 1999). The PNNL study did not consider the Canadian climate scenario.

Under rainfed conditions, Columbus, Ohio, was the only site where all climate scenarios resulted in yield increases: 3–8 percent in 2030 and 16–24 percent in 2090. At all other sites, including the major production centers in the Great Plains, the Canadian scenarios resulted in large negative impacts for continuous and fallow production. Grain yields decreased 10–50 percent in 2030 and 4–30 percent in 2090. Most important, at Dodge City, Kansas; Goodland, Kansas; and North Platte, Nebraska, coefficients of variation of yield consistently increased in both decades, indicating greater variability in yield from year to year and greater risks to producers. Under the Hadley climate scenario, yields increased at all sites. Rainfed production increased by 6–20 percent in 2030 and by 13–48 percent by 2090. Year-to-year variation decreased at most sites.

Irrigated wheat yields increased under both GCM scenarios, although increases were larger under the Hadley scenario than under the Canadian scenario. In 2030, yield increases were 2–10 percent. In 2090, yields were 6–25 percent greater than under current conditions. At the same time, irrigation water use decreased by 10–40 percent.

Crop simulations showed no benefit from changing from current crop and water management of practices for wheat production under the Hadley scenario. Under the Canadian scenario, simulations of rainfed cultivation were subject to a high frequency of years with very low yields, suggesting that rainfed production may no longer be viable in Kansas if these climate conditions are observed in the future.

All else being equal, maintenance of current production would require irrigation.

Adaptation strategies simulated for wheat in the central plains involved shifting to cultivars that are better adapted to a warmer climate. Specifically, cultivars that require less vernalization and have longer grain filling periods could be planted to counterbalance the hastening of maturity dates resulting from warmer spring and summer temperatures. For example, cultivars currently grown in the south could be planted at northern locations. Projected yield decreases at North Platte were eliminated by shifting to a southern-grown variety. The same strategy did not yield positive results for the Kansas and Oklahoma sites we considered in this study because of large decreases in precipitation projected by the Canadian model at these sites.

Spring Wheat

Warmer temperatures were the major factor affecting spring wheat yields across sites, time horizon, and management practice. Considered alone, they hastened crop development and affected crop yields negatively.

Despite warmer temperature in 2030, rainfed spring wheat production increased by 10–20 percent under both GCM scenarios because of increased precipitation that also reduced CVs and thus year-to year production risks. This positive trend continued in 2090 under the Hadley scenario, generating yield increases of 6–47 percent. The largest increases (47 percent) were simulated at Pierre, South Dakota.The 2090 Canadian scenario resulted in significant decreases in spring wheat yields at current production sites. Yields decreased at Fargo, North Dakota (16 percent), and Glasgow, Montana (24 percent). The Canadian scenario also generated yield decreases at Fresno, California (20 percent). By 2090, the Canadian scenario projected high temperatures at all sites we considered, affecting wheat development and grain filling negatively and depressing yields despite the gains from precipitation increases.

Irrigated spring wheat production decreased by 1–24 percent at the eight sites we considered under both scenarios. In 2030, yields decreased at Boise, Idaho (7–17 percent); Spokane, Washington (1–4 percent); Tucson, Arizona (3–6 percent); and Fresno (16–24 percent). The same negative trends continued at these sites in 2090, with the largest reduction simulated at Fresno (30–45 percent).

Under every scenario and at all sites, irrigation water use decreased significantly. Daily water consumption did not change substantially; instead, the growing period was shortened as higher temperatures accelerated growth and there were fewer days when irrigation was required. Thus, the overall changes in water use were mainly related to accelerated growth rather than stomatal closure during the growth period. By 2090, simulated yield reductions at all sites were in the range of 20–40 percent and consistently above 50–60 percent at Fresno.

Simulated rainfed production became increasingly competitive with irrigation under all scenarios, as a result of increased precipitation. For example, at Spokane and Boise—which now are irrigated sites—current production levels could be maintained under the scenarios we considered by shifting some irrigated land to rainfed production. By 2090, there would be no need for irrigated production at Boise under the Canadian scenario. At Fargo, North Dakota, and Glasgow, Montana, additional simulations indicated that yields could be maintained at current levels by planting two to three weeks earlier, compared to current practices.

Corn

Climate change affected dryland corn yields positively. Projected increases in precipitation more than counterbalanced the otherwise negative effects of warmer temperatures across the US sites we analyzed. We simulated increases at current major production sites: Des Moines, Iowa (15–25 percent); Peoria, Illinois (15–38 percent); and Sioux Falls, South Dakota (8–35 percent). We simulated larger increases at northern sites: Fargo, North Dakota

(25–50 percent); Duluth, Minnesota (30–50 percent), and St. Cloud, Minnesota, where warmer temperatures and increased precipitation contributed to increased corn yields compared to current levels. We simulated smaller changes—in the range –5 percent to +5 percent—at the remaining sites.

The PNNL results were in agreement with the findings of the site-level studies for rainfed corn production, for which "increases were predicted for future production of dryland corn in the Lakes, Corn Belt and Northeast regions of the US" (Izaurralde et al. 1999). On the other hand, the PNNL results found increases in irrigated corn yields in almost all regions of the country. In contrast, the site-level results found that climate change affected irrigated yields negatively—in the range of –4 percent to –20 percent—at the two major irrigated production sites we considered (in Kansas and Nebraska). As with the wheat results, higher temperatures resulted in a shorter growing and grain-filling period. At northern sites, simulated irrigated yields—which currently are limited by cold temperature—increased substantially. For instance, at St. Cloud, Minnesota, simulated yields under the 2090 Canadian scenario were almost three times as much as current levels.

Additional simulations suggested that early planting would help maintain or slightly increase current production levels at sites experiencing small negative yield decreases. In general, dryland corn production could become even more competitive than irrigated corn production, with higher yields and decreased year-to-year variability. We simulated great potential for increased production and improved water management at the northernmost sites, in North Dakota and Minnesota. A study for the Corn Belt region, conducted at Indiana University (Southerland et al. 1999), was in general agreement with our findings, projecting increases in corn yields across the northern Corn Belt region. For five southwestern locations in Indiana and Illinois, the Indiana University work projected corn yield decreases in the range of 10–20 percent. The coordinated site studies we conducted did not show yield losses in the southern Corn Belt sites, but we did not have as many sites in this southern portion of the Corn Belt. The PNNL analysis, which provides a much denser sampling, showed yield declines for corn consistent with the Indiana results for this area. There also were differences in the analysis protocol used by the Indiana group that probably led to differences in results. For reliability at sub-state levels, a far denser sampling is needed than the 45 sites we chose to cover the entire nation.

Potato

Irrigated potato yields generally fell; under rainfed conditions, yield changes generally were positive.

Under rainfed conditions, both climate scenarios considered in this study resulted in sizable gains in 2030. At four of the five sites we considered, crop production increased by an average of 20 percent; the exception was at Indianapolis, where the Canadian scenario projected a 33 percent reduction and the Hadley scenario resulted in a 7 percent increase. CVs for all sites generally decreased as a result of increased precipitation. In 2090, the Canadian scenario resulted in large decreases at most sites; under the Hadley scenario, potato yields increased by 10–20 percent, largely maintaining the gains reached by 2030. Under the Canadian scenario, rainfed production decreased by an average of more than 20 percent. Smaller effects were simulated at Madison, and the largest effect was at Fargo (63 percent). Under this scenario, large increases in temperature in 2090 counterbalanced the beneficial effects of increased precipitation.

Irrigated yields decreased in 2030, by 1–10 percent; a few sites registered no change or small percentage increases. The projected temperature increases affected crop production negatively. Under the Canadian scenario, most sites showed simulated yield reductions of 6–13 percent. Exceptions were Indianapolis (a 36 percent decrease) and Yakima (a 5 percent increase). Under the Hadley scenario, yields decreased by 6–8 percent, although small increases (2 percent) were simulated in Fargo and Yakima. Both GCM scenarios projected 5 percent increases in yield at Caribou, Maine.

The simulated decreases continued in 2090 under both climate scenarios. Potato yields decreased by 10 percent at two of the three major production sites in the Northwest; water use increased by an average of 10 percent. Both GCMs resulted in larger decreases at Boise, Idaho (30–40 percent), and Scott Bluff, Nebraska (27–50 percent), and smaller ones at Pendleton, Oregon; Medford, Oregon (10–15 percent); and Buffalo, New York (8–18 percent).

As with other crops, simulations suggested that rainfed production could become more competitive with irrigated production, compared to today. Cultivar adaptation would do little to counterbalance the negative temperature effects in our simulations. Current US potato production is limited to cultivars that need a period of cold weather for tuber initiation. The only viable strategy would be a change in planting dates to allow for increased storage of carbohydrates and sufficient time for leaf area development prior to tuber initiation. Additional simulations suggested, however, that current production levels could not be reestablished even with a shift in planting date. For example, moving planting ahead by as much as one month at Boise and Indianapolis helped reduce yield losses under climate change by 50 percent relative to simulations without adaptation. This offset is substantial, but it still leaves sizable losses compared to current yields.

Citrus

Fruit production benefited greatly from climate change. Simulated yields increased 20–50 percent, while irrigation water use decreased. Crop loss from freezing was 65 percent lower, on average, in 2030 and 80 percent lower in 2090 (at all sites). Miami experienced small increases—in the range of 6–15 percent. Of the three remaining major production sites, we simulated increases in the range of 20–30 percent in 2030 and 50–70 percent in 2090. Irrigation water use decreased significantly at Red Bluff, California; Corpus Christi, Texas; and Daytona Beach, Florida. All sites experienced a decrease in CV, as a result of the reduction of crop loss from freezing.

Fruit yields increased in Tucson and Las Vegas. Slight to no changes in simulated water use implies, however, that these sites—which currently are at the margin of orange production—will be even less competitive in 2030 and 2090 than they are today. In fact, all of the additional sites we chose to investigate the potential for northward expansion of US citrus production continued to have lower fruit yield and higher risk of crop loss from freezing than the southern sites of production.

Hay and Pasture

Simulated dryland pasture and hay production increased under all scenarios and at most sites—except under the 2030 Canadian scenario, which resulted in decreases of up to 40 percent in the Southeast, Delta, and Appalachian regions. The largest increases—in the range 40–80 percent—were simulated for the Pacific Northwest and Mountain regions. By 2090, both climate scenarios resulted in increases of greater than 20 percent at all sites. Results from the PNNL study were in general agreement with these findings.

Soybean

Under rainfed conditions and the two climate scenarios we considered, soybean yields increased at most of the sites we analyzed; increased temperatures favored growth and yield compared to current conditions. Notable exceptions were the southeastern sites. Under the Canadian scenario, yields in this area were reduced in 2030 by 1–36 percent. By 2090, losses of more than 70 percent were simulated at Montgomery, Alabama, and Memphis, Tennessee. Adaptation in this area—by shifting the crop maturity group—reduced losses by more than 50 percent.

At sites in the major producing areas of the Corn Belt, rainfed yields increased by 10–30 percent. At the three northernmost sites in this study (Duluth, Minnesota; St. Cloud, Minnesota; and Muskegon, Michigan—which currently are at the northern margin of US soybean production), yields increased by more than 30 percent in 2030 and more than 50 percent in 2090 as a result the positive effects of warmer temperatures.

The PNNL study, using the Hadley climate scenario, also found increases in soybean yields in the Lake states of Michigan, Minnesota, and Wisconsin, as well as the Northeast. It also found, however, that "soybean yields decreased in the Northern and Southern Plains, the Corn Belt, Delta, Appalachian, and Southeast regions" (Izaurralde et al. 1999). Thus, there is considerable disagreement between the two approaches for soybeans, particularly for the important Corn Belt region.

Irrigated soybean yields increased at all sites and under all scenarios—by 10–20 percent in 2030 and by 10–40 percent in 2090. Again, increasing temperature was the main factor that enhanced soybean yields in this simulation analysis. In the rainfed case, at the northern sites yields increased by more than 50 percent in 2030 and more than 100 percent in 2090.

Sorghum

Under rainfed conditions, the two climate scenarios we analyzed in this study produced opposite results at many sites, as a result of differences in projected changes in precipitation. Under the Hadley scenario, rainfed production increased at all sites (because of increased precipitation with respect to the current climate) by 1–10 percent in 2030 and by 10–60 percent in 2090. Under the Canadian scenario, reductions of 10–30 percent were simulated at southern and southeastern sites. The largest decreases were simulated in 2090 at Savannah, Georgia (15 percent); Charleston, South Carolina (20 percent); and Oklahoma City, Oklahoma (30 percent). Under both GCM scenarios, warmer temperatures and, where projected, increased precipitation enhanced production at the northernmost sites. Large increases in sorghum yields were simulated at North Platte, Nebraska (30 percent and 80 percent); Pierre, South Dakota (45 percent and 100 percent); and Sioux Falls, South Dakota (50 percent and 60 percent) in 2030 and 2090, respectively.

Under irrigated production, the generally negative effects of increased temperature on sorghum development and growth resulted in yield reductions of 10–20 percent at most sites, under both scenarios and time horizons. The largest decreases were simulated in 2090 at Oklahoma City (38 percent). Yields increased by 10–15 percent at two of the northernmost sites; they decreased at Pierre (3 percent).

Early planting by two to four weeks helped to counterbalance the negative effect of warmer temperatures at most sites we analyzed.

Rice

Under irrigated production, the two climate scenarios we analyzed produced much different projections of future rice yields, largely because of differences in the size of the projected changes in temperature. In 2030, the Hadley scenario resulted in small positive yield increases—in the range of 1–10 percent—with larger increases at two northern sites, that currently are well outside the US rice production region (Peoria, Illinois, and Des Moines, Iowa) but that we considered because of the potential that climate change will make rice production viable. The Canadian scenario resulted in small reductions—on the order of –1 percent to –5 percent—at major production sites in California and at sites in the Delta region. In 2090, the patterns of simulated changes among scenarios, as well as their geographic distribution, was similar to that projected for 2030. Yields increased under Hadley scenario, except in Bakersfield, California (–12 percent). The Canadian scenario resulted in larger yield decreases in 2090 than in 2030: up to –20 percent in California and the Delta region and by –50 percent in El Paso, Texas.

We simulated adaptation by planting cultivars that are better adapted to warmer temperatures, as well as by early planting. These techniques helped to reduce—but not to counterbalance completely—the yield reductions we simulated under climate change and no adaptation.

Tomato

Under irrigated production, the climate change scenarios generated yield decreases or small increases, depending on the scenario chosen, at most southern sites. At the northernmost locations analyzed in this study, increased temperatures were highly beneficial in terms of yield.

In 2030 under the Canadian scenario, tomato yields decreased at most southern sites, in the range of 10–20 percent. Larger decreases were simulated at Oklahoma City, Oklahoma (45 percent), and at Tucson, Arizona (37 percent). At northern sites, simulated yields increased: at Boise, Idaho (20 percent); Duluth, Minnesota (80 percent); Muskegon, Michigan (40 percent); and Yakima, Washington (30 percent). This trend continued in 2090 under the Canadian Centre scenario, with larger magnitudes of both projected gains and losses. In 2090, general decreases at most sites were in the range of 20–40 percent. Decreases of more than 70 percent were simulated in Oklahoma and Texas. Northern sites continued to benefit under warmer temperatures; yields increased by as much as 170 percent at Duluth.

We simulated the same patterns under the Hadley scenario except that—because of smaller projected increases in temperatures—the simulated losses at most sites and the gains at northern locations were smaller than those projected under the Canadian scenario. Specifically, under the Hadley scenario, sites in the Delta region and in the Southeast experienced moderate gains (in the range of 5–15 percent) with respect to current production levels.

PNNL Results

The PNNL results were based on slightly different assumptions and were produced only for the Hadley scenario, for climates representative of 2030 and 2095 (H1 and H2). In addition, the PNNL agricultural model includes a simulator that produces random weather scenarios exhibiting changes in mean conditions like those derived from the climate scenarios. The detailed site studies used actual historical weather adjusted by the changes derived from the climate scenarios. Thus, the specific weather conditions simulated in the PNNL study differed from that used in the site studies. The climate change scenarios are applied with two levels of atmospheric CO_2 concentration: 365 ppm (current ambient) and 560 ppm to represent a CO_2 fertilization effect. The results are shown in Figures 3.2 and 3.3 (see color plate section) and are summarized in Tables 3.5 and 3.6. The land areas indicated in the figures are the 4-digit (USGS nomenclature) hydrologic basins. Data in the table are aggregated from these regions into production regions as defined by USDA.

Temperatures rise modestly (1–2 ºC) by 2030, and precipitation increases by 25–125 mm y^{-1} over most of the corn-growing region. By 2095, temperature increases by 2.0–3.5 ºC, and precipitation increases by more than 175 mm y^{-1} over the entire region. Yield in the EPIC model used for this analysis is directly proportional to biomass production, which is favored by a reduction in cold stress and a lengthening of the growing season in the Lake region, the Corn Belt, and the Northeast (Figure 3.1). Table 3.6 shows that yields increase at current CO_2 concentrations and improve still more at higher concentrations. Yields are slightly depressed in the Delta, Appalachian, and Southeastern regions, where higher temperatures shorten the growing season (Figure 3.2). With no CO_2 fertilization, regional yields are reduced by 2030 and 2095 in the Delta and Southeast but only in 2030 in the Appalachian region. Climate-related losses are more than offset by CO_2 fertilization in all cases.

Figure 3.3 shows baseline winter wheat yields and deviations resulting from the climate and CO_2 scenarios are shown for the Northern and Southern Great Plains, Mountain (Great Plains portions of Montana, Wyoming, and Colorado), and the Western regions; Table 3.7 summarizes these data by USDA production region. Temperatures in these regions increase by 1–2 ºC in 2030 but are considerably higher by 2095. By 2030, precipitation increases by 25–50 mm y^{-1} over much of the Plains and Mountain growing regions, as well as in Washington and Idaho, but is lower in California. By 2095, precipitation increases still more in the Plains and Mountain regions; it increases in California and is variable in the northwestern states. CO_2 fertilization alone increases yields in all regions. The C-3 crops[2], including wheat, experience increased photosynthetic rates and decreased transpiration rates under elevated CO_2. The reduction in transpiration is particularly important for wheat, which generally is grown in semi-arid regions. Aggregate regional production increases under all scenarios in the Pacific region and under most scenarios in the Mountain and Plains regions. Decreases in aggregate production were projected for the Mountain and Plains regions when wheat growth was simulated without a CO_2-fertilization effect in 2030 and for the Southern Plains by 2095 (also without the CO_2-fertilization effect). Higher temperatures reduce the frequency of cold stress and increase the length of the growing season by shortening the winter dormancy period. In more northerly regions, the crop matures before the extreme heat of summer.

Irrigation Water Supply

Water supply for irrigation is also an important consideration. The ASM includes estimates of available agricultural water supply that is allocated to crops. Estimates of changes in water supply under the climate change scenarios for each ASM region were developed based on total water supply changes by river basin. The changes in water supply were from the Water Sector Assessment (Gleick 2000). The critical assumption made was that the change in water

Table 3.6. Simulated Yields of Dryland Corn Under Baseline Climate (B) and Hadley Centre Projections in 2030 (H1) and 2095 (H2), at Two CO_2 Concentration Levels (365 and 560 ppm) for Six Major Growing Regions of the United States

CO_2 / Scenario	Region: Lakes	Corn Belt	Delta	Northeast	Appalachian	Southeast
			Mg ha^{-1}			
B-365	4.57	6.05	6.26	4.16	6.13	5.76
B-560	4.95	6.53	6.55	4.54	6.73	6.35
H1-365	5.30	6.31	5.84	4.70	5.94	5.34
H1-560	5.94	6.98	6.74	5.24	6.70	6.13
H2-365	6.04	6.53	5.84	4.81	6.27	5.04
H2-560	6.69	7.09	6.32	5.35	6.95	5.76

Table 3.7. Simulated Winter Wheat Yields Under Baseline Climate (B) and Hadley Centre Projections in 2030 (H1) and 2095 (H2), at Two CO_2 Concentration Levels (365 and 560 ppm) for Four Major Growing Regions of the United States

CO_2 / Scenario	Region: Pacific	Mountain	Northern Plains	Southern Plains
		Mg ha^{-1}		
B-365	3.37	1.84	3.09	3.75
B-560	4.08	2.44	3.71	4.61
H1-365	3.68	1.74	2.90	3.65
H1-560	4.45	2.38	3.85	4.66
H2-365	3.81	2.42	3.20	3.21
H2-560	4.59	3.21	4.21	4.02

[2]C-3 refers to the photosynthetic pathway of carbon in the plant. Another significant group of plants are C-4 plants. The C-3 pathway produces a higher photosynthetic response to elevated ambient carbon dioxide than the C-4 pathway. Most crops are C-3. The principal exceptions of importance in the US are corn and sorghum which are C-4.

supply to agriculture was proportional to the change in total water supply; i.e. that agriculture and non-agricultural users faced the same proportional change in water supply. More detail on the specific changes and how they were derived from the estimates developed by the Water Sector Assessment are provided in McCarl (2000).

Crop Input Usage

Yield changes also can imply changes in some inputs, such as chemical inputs and those related to crop harvesting, drying, and storage. A larger (or smaller) yield will require more (or less) of these other inputs. This association between yield and input use is evident over time. Technological progress that has increased yield has been accompanied by increases in input usage. On the other hand, yield by definition is per unit of land; other inputs, such as labor, are more closely related to area than to yield. As part of the EPRI study that used the ASM model, Adams et al. (1999) estimated a yield-input relationship. Land, labor, and water inputs were excluded from the estimation. For most crops, the increase in use of these other inputs was 40 percent of the yield change. Thus, if yield decreased by 1 percent, crop input use decreased by 0.4 percent. Similarly, a 2 percent yield increase would be matched by a 0.8 percent input usage increase. This relationship was included in the simulations. It has the effect of making yield improvements less economically beneficial than they otherwise would be because achieving the increases requires purchasing these other inputs. Conversely, yield losses are not as economically costly because the purchase of material inputs is reduced. This type of adjustment is appropriate for consideration of ongoing climate change, for which technological change—the basis for the estimate—provides a good analogy.

Livestock Performance, Grazing and Pasture Usage

Much of the work on climate change impacts on agriculture focuses mainly on impacts on crops; it considers impacts on the livestock sector only indirectly, through changes in crop yields. Temperature change also can cause livestock to achieve altered rates of gain. Heat stress has a variety of detrimental effects on livestock, including significant effects on milk production, meat quality, and reproduction in dairy cows. Analyses suggest that the most detrimental effects would occur during warm periods in already warm regions (Rötter and van de Geijn 1999). The EPRI study (Adams et al. 1999) developed relationships between temperature change, livestock performance, and feedstuff consumption in consultation with experts on livestock production and management. These estimates were used as a basis for estimating temperature-related declines in livestock performance. McCarl (2000) provides the assumed changes in livestock production on a per head basis.

Altered livestock performance—in terms of altered ending weights of sale animals or sales of livestock products—means that animals need different amounts of feedstuffs to produce that ending weight or volume of products. In this study, we assumed that feedstuff usage was strictly proportional to the volume of products, although changes in climate could change this proportion. Thus, if 10 percent more milk were produced, 10 percent more feedstuffs had to be consumed. When the livestock unit produced multiple products, we used a weighted average of the percentage change in output to adjust the feedstuff usage. The feed usage quantities for which we applied these adjustments included not only traditional grains but also the number of animal unit months required of grazing and the acreage of pasture required.

Other Livestock Input Usage

As with crops (and with the same rationale), we assumed that changes in nonfeed input use was 40 percent of the production change.

Pasture Supply

Grazing and pasture use also are important assumptions in the ASM model and are influenced by climate change. The crop modeling component of the agriculture assessment included estimates of changes in grass and pasture growth resulting from climate change. Alterations in the growth rate of grass changes the available feed supply from a given area of pasture. Pasture use and grazing land availability are represented in the ASM model and were changed to reflect the change in grass and pasture growth. Pasture use was adjusted by the change in grass growth. Thus, if grass growth increased by 10 percent, livestock pasture use was multiplied by 0.9 (1/1.1). We made this adjustment after changing the pasture required as a result of any change in body weight directly related to temperature.

We addressed grazing on western rangelands like the adjustment for pasture; the availability of such lands, however, traditionally has been measured in terms of animal unit months (AUMs) of grazing. We developed an estimate of AUM supply sensitivity to climate change by assuming that the change in AUM supply was the same as the change in grass supply. Thus, if grass growth increased by 10 percent, the AUMs available increased by 10 percent. We did not make any further adjustments relating to possible changes in forage quality resulting from CO_2 enrichment.

This combination of climate effects on livestock includes most of the primary effects of climate on the livestock sector. The principal omissions are direct losses of livestock from extreme storms. Other potential changes to the livestock sector that we do not consider here include an increase or decrease in floods or extreme winter weather events.

Pesticide Costs

Change in the incidences and ranges of agricultural pests represents another likely effect of climate change. Most insects, weeds, and diseases are sensitive to climate; climatic factors are an important determinant of the range of many important agricultural pests. No previous assessment of agricultural impacts of climate change has explicitly considered the effects of climate change on agricultural pests with the resulting economic effects of these changes. Studies based on cross-section evidence such as Mendelsohn et al. (1994) and Darwin et al. (1995) and subsequent analyses with these approaches implicitly include changes in pests and many other factors, assuming that entire production and climate regimes shift, intact, as a result of climate change.

To consider how climate could affect agriculture through its affect on pests, we conducted a statistical analysis that related pesticide expenditures to climate. We conducted this analysis on cross-section data; we explain it in greater detail in Chapter 5. We estimated changes in pesticide expenditures for corn, cotton, soybeans, wheat, and potatoes with regard to a percentage change in precipitation and temperature. Based on these statistical relationships, we estimated a change in pesticide costs under each climate scenario. The limitations and advantages of such cross-section evidence applied to time-series phenomena such as climate change have been discussed in the context of other such efforts—the broadest such effort being the Ricardian rent method developed by Mendelsohn et al. (1994). A main additional limitation in this context is that, as applied, this approach implicitly assumes that any additional potential damage from pest range and incidence expansion is fully controlled by the use of additional pesticides. Thus, the only economic loss to farmers is additional pesticide expenditures. If crop losses were greater, even with additional pesticide expenditures, the lost revenue from the reduced sale of crops would be an additional loss. The full interaction of pests, climate change and climate variability, and habitat is complex. Many pests (weeds, insects, diseases) respond to changes in humidity and precipitation and are known to have tolerance limits to extreme temperatures. Pests also respond to habitat modification that might be induced by climate change or by management change (such as changing the crop mix or expanding irrigation). A comprehensive review is included in Patterson et al. (1999).

International Trade

Studies that have considered global impacts of climate change have demonstrated that the economic impact on a country can be heavily affected by how climate change affects agriculture production in major agricultural exporting and consuming countries (see Chapter 2). The ASM model includes an international sector; thus, in all scenarios, climate impacts on the United States affect US competitiveness in export markets. In the base scenarios, however, although US agricultural production is affected by climate there is no climate impact elsewhere in the world. Conducting a full assessment of the rest of the world was beyond the scope of this assessment, however. Our approach is roughly equivalent to assuming that, although there may be positive and negative impacts of climate change on agriculture elsewhere in the world, the net impact is a "balancing out" (i.e., no change). In fact, in the global studies that have been conducted, the net global effect often is relatively small because of a combination of gainers and losers around the world.

To consider the sensitivity of our results to the implicit assumption of no impact elsewhere in the world, we constructed three sensitivity scenarios for potential climate impacts on the rest of the world, based on previous global assessments. Two scenarios were developed from work that was based on an economic modeling analysis of international yield changes based on climate scenarios of the Goddard Institute for Space Studies (GISS) and United Kingdom Meteorological Office (UKMO) climate scenarios (Reilly et al. 1993). Production changes in other regions are given in Tables 3.8a,b. Another scenario was based on a previous global modeling exercise that used the Hadley climate scenario. The US estimates in this scenario were based on a different approach than the one used here and, therefore, are not directly consistent with our US crop study estimates. This scenario is based on a model developed at the Economic Research Service (Darwin et al. 1995). The GISS/UKMO climate scenarios are fairly old; the impact analysis dates to the early 1990s and involves doubled CO_2 equilibrium scenarios. The advantage of these scenarios is that the underlying approach used for the crop studies is similar to the approach we used in this assessment, and the study provides details on the major crops and world regions represented in the ASM model. For the Darwin scenario, we based adjustments on changes in net exports from the United States.

Although none of these scenarios is completely consistent with the analysis of the United States that we conducted, they provide a useful way to demonstrate the sensitivity of the economic estimates we obtained to different assumptions about how climate change could affect the rest of the world. We chose the GISS/UKMO scenarios in part because in the study from which they were taken they represented the mildest (GISS) and the most severe (UKMO) scenarios among those that considered both adaptation and the CO_2 fertilization effect.

Economic Results

In the following subsections, we discuss the main economic results. We first discuss the results from the core scenarios. We then consider sensitivity cases, including the trade sensitivity results, the alternative Hadley scenarios that are based on the PNNL crop modeling, and a set of miscellaneous sensitivities. We report here the major results. Altogether we ran 43 scenarios representing different impact combinations (e.g., with and without adaptation or pest effects) and alternatives (e.g., alternative trade and crop yield effects), producing results for aggregate economic effect, regional production, and resource use for each scenario. In most cases, the general pattern of change across regions and resource use closely reflects differences in the aggregate economic effect across scenarios.

We have tried to highlight here the broad pattern of results. Complete tables of results are provided in McCarl (2000).

Results from Core Scenarios

A value of an economic model such as the ASM is that it can summarize the net impact of a combination of many different changes. The model also provides the ability to consider distributional and resource use effects.

Aggregate Economic Impacts

We report aggregate results in terms of a change in welfare—measured as the sum of producer and consumer surplus. Welfare is preferred as a measure of economic impact over measures such as change in

Table 3.8a International Trade Scenarios: Percentage Production Changes, Based on GISS Climate Scenario

Region	Wheat	Coarse Grains	Rice	Other Crops	Secondary
Canada	20.0	17.2	2.2	20.3	1.4
Western Europe	-0.7	3.1	4.5	12.0	0.7
Former Soviet Union	23.0	12.0	13.2	17.6	0.1
Eastern Europe	6.8	1.3	1.3	13.7	0.1
Australia & New Zealand	-11.6	10.7	17.1	8.2	0.4
China, Taiwan, & South Korea	14.9	0.1	1.1	15.6	-0.1
Other East Asia	-21.0	-32.9	-5.7	-15.6	0.4
India	-4.4	-13.9	-2.2	-6.1	0.8
Argentina	-25.8	8.5	9.8	6.0	0.4
Brazil	-35.2	-10.3	-11.8	-0.5	0.2
Mexico	-34.9	-34.8	-18.0	-19.9	0.2
Japan	-1.9	22.2	11.4	11.2	0.4
Africa (all) & Middle East	-19.0	-24.0	3.2	-5.3	1.9
Other Latin America	-29.1	-10.6	-9.7	-18.6	0.1

Table 3.8b International Trade Scenarios: Percentage Production Changes, Based on UKMO Climate Scenario

Region	Wheat	Coarse Grains	Rice	Other Crops	Secondary
Canada	4.5	-6.6	6.0	-7.5	-2.0
Western Europe	11.0	9.8	13.5	11.6	-1.4
Former Soviet Union	-8.1	-6.0	-7.4	-1.4	-0.3
Eastern Europe	1.5	3.0	3.1	11.2	-0.3
Australia & New Zealand	46.2	19.8	28.0	27.0	-0.3
China, Taiwan, & S. Korea	0.9	0.7	2.6	12.9	0.5
Other East Asia	-15.0	-30.0	-15.7	-10.2	-0.8
India	-19.8	-36.0	-17.1	-25.6	-1.2
Argentina	-7.6	-0.6	18.7	17.5	0.0
Brazil	-28.4	-13.7	-18.6	-7.0	-0.6
Mexico	-27.2	-33.8	-24.1	-16.1	-0.2
Japan	1.6	17.3	8.5	10.4	-1.7
Africa (all) & Middle East	-12.8	-25.3	8.7	-8.0	-1.6
Other Latin America	-28.7	-17.6	-15.5	-25.2	0.1

agricultural production or consumption because it includes consideration of the fact that with less production, fewer inputs are used and the fact that consumers, may shift consumption among agricultural products, or might substitute consumption of other goods. Figure 3.4a displays the results based on the Canadian climate scenario, and Figure 3.4b displays results based on the Hadley scenario. Included in these figures are changes of consumer and producer surplus in the United States, as well as a change in total surplus. The difference between the two is the economic impact on producers and consumers outside the United States. The scenarios reported in Figures 3.4a,b do not include any direct climate impact on agriculture outside the United States, but impacts on foreign producers and consumers occur because of changes in prices of internationally traded commodities. The figures provide results for 2030 and 2090 under three different scenarios.The first scenario reflects the impact of climate change—including crops, livestock, and water demand—and supply effects without adaptation. The second adds adaptation, and the third adds, in addition, the effects of climate on pesticide expenditures.

Given the differences in the climate models and the intermediate crop modeling results, the economic results are generally as expected. Overall, the effects on total surplus generally are positive—much more so for the Hadley scenario. Net economic benefits range from about –$0.5 to +$3.5 billion (year 2000 dollars) in the Canadian scenario and between 6 and 12.5 billion dollars for the Hadley scenario. In both climate scenarios, the total and domestic surplus increases between 2030 and 2090. Several analysts have suggested that at more extreme levels of climate change, one should expect losses. We have not conducted a full transient crop model/economic analysis, so we cannot be sure whether benefits by 2090 are declining from some peak experienced between 2030 and 2090 or whether benefits are continuing on a general upward trend. As illustrated by the Canadian scenario, however, the time path of impact may not be easily described by a simple function. In 2030—at least for the no-adaptation case and for the US surplus—the net effect is an economic loss that turns to gains by 2090 for all but the no-adaptation case. Given the multitude of effects across many different regions, tracing these results

Figure 3.4a. Economic Impacts of Climate Change, Canadian Centre Climate

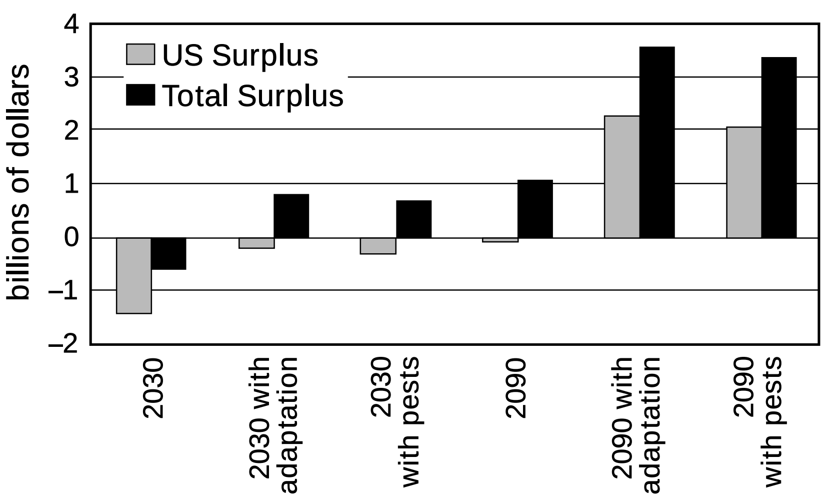
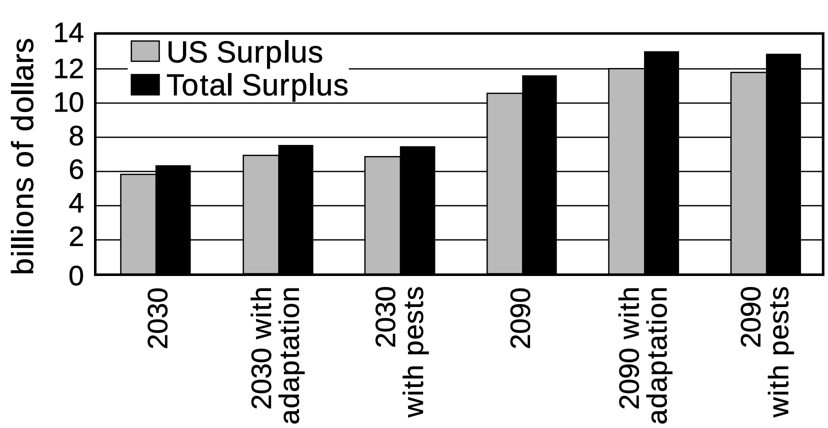


Figure 3.4b. Economic Impacts of Climate Change, Hadley Centre Climate



conclusively to a specific aspect of the climate scenarios is impossible. The pattern of results very likely reflects the fact that in the Canadian scenario, precipitation decreases in the United States in 2030 and then increases by 2090. Care must be taken to avoid overinterpreting this time path or any of the specific results. Climate models produce variability from year to year and decade to decade. Even for specific models such as the Canadian or Hadley models, a particular decade of climate drawn from a particular scenario must be considered only one possible draw from a distribution of possibilities. By 2030, the additional greenhouse gas forcing beyond that of current climate is relatively smaller compared with 2090, so the natural variability on a decadal scale can have a large effect relative to the signal from greenhouse gas forcing.

The distribution of benefits between foreign and domestic is notably different in the two scenarios. Much of the benefit goes abroad in the Canadian scenario, whereas relatively little flows abroad in the Hadley scenario. This difference occurs because of the differential effects on crops where exports are important versus those that are mainly consumed domestically.

As observed for the intermediate crop yield results, adaptation is considerably more important when the impacts are adverse than when they are beneficial. Although this effect shows up in the comparison of the two climate scenarios, more research is required to assess the robustness of this result. A more expansive exploration of adaptation options such as double cropping could reveal further gains in northern regions.

Net pesticide expenditures increase, thereby reducing total economic surplus. This effect is quite small. The size of the effect is not surprising, however, given that pesticide expenditures account for only a few percent of total costs. This estimate may understate losses, however, because it does not include any increase in damage that cannot be eliminated through increased use of pesticides.

Distributional Effects

The distribution of economic effects between producers and consumers and among regions varies. Figures 3.5a and 3.5b display the distribution of effects between domestic US producers and consumers. Across all scenarios, consumers generally gain from lower prices, whereas these lower prices cause producer losses despite the fact that climate change has improved productivity. The Canadian

Figure 3.5a. Producer versus Consumer Impacts of Climate Change, Canadian Centre Climate

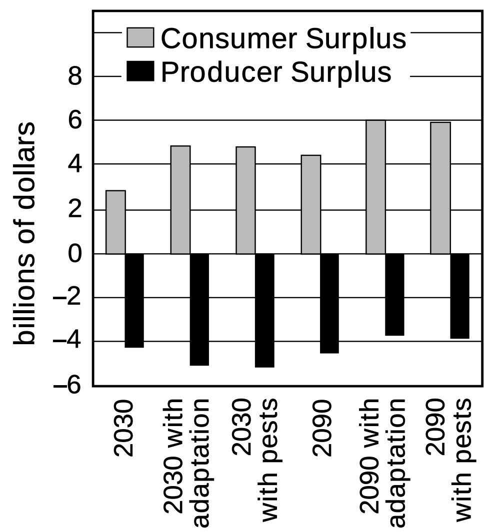
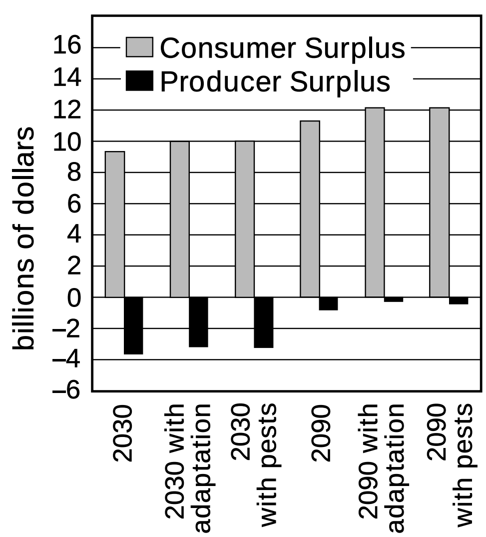


Figure 3.5b. Producer versus Consumer Impacts of Climate Change, Hadley Centre Climate



scenario produces an approximate balance in terms of domestic consumer gains and producer losses in most scenarios. In contrast, the Hadley scenario produces large consumer gains. The productivity gains are so substantial, however, that the output and export gains to producers nearly offset the price declines. Although the absolute level of change is comparable between producer and consumers, in percentage terms the changes to producers are much more substantial. For comparison purposes, the total economic benefit derived from food consumption in the base is estimated at approximately $1.1 trillion, whereas total producer surplus is on the order of $30 billion. Thus, the $4–5 billion surplus losses in the Canadian scenario represent 13–17 percent loss of surplus to producers, whereas the gains of $9–14 billion of consumer surplus in the Hadley scenarios represent only a 1.1–1.3 percent gain to consumers. We would expect producer losses to be realized ultimately as changes in the value of land. A 13–17 percent loss in this asset value is substantial; to place this in context, however, agricultural land values fell on the order of 50 percent between 1980 and 1983.

Figures 3.6a and 3.6b display the regional differences. We report an aggregate index of the production across crops, with prices used as weights in the

Figure 3.6a. Regional Production Changes, Canadian Centre Climate, Percentage Change in Output (crop and livestock production aggregated using price weights)

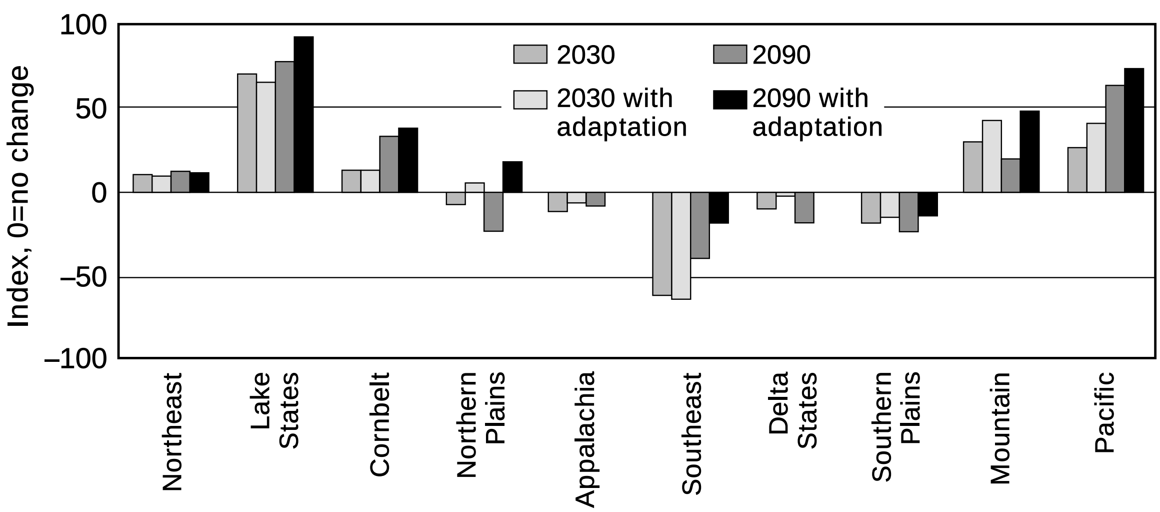
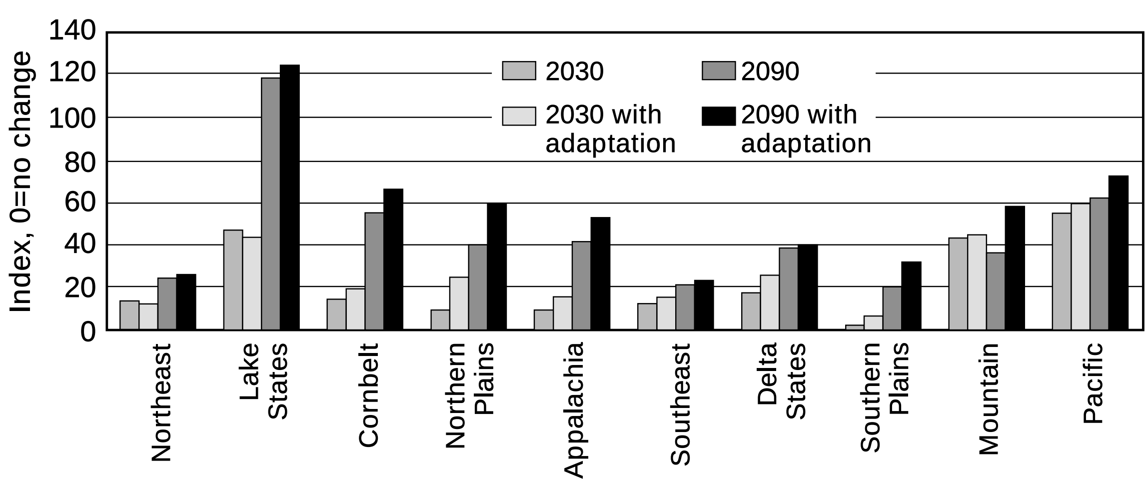


Figure 3.6b. Regional Production Changes, Hadley Centre Climate, Percentage Change in Output (crop and livestock production aggregated using price weights)



index. The plotted values are percentage changes from base production. The figures show substantial regional differences in both scenarios. The basic regional pattern is similar in both scenarios. The Lake, Pacific, Mountain, and the Corn Belt regions (in decreasing order) show large increases in production—generally between 50 and 150 percent increases in output. The pattern of absolute (or relative) losers varies more across the scenarios. The Southeast, Southern Great Plains, and Delta states lose absolutely in the Canadian scenario or show the smallest increases in production in the Hadley scenario. Appalachia also is more negatively affected. Impacts on the other regions vary substantially across the two climate scenarios and over the two time periods.

In the Hadley scenario, no region shows a production decline. With substantial overall producer losses in the United States as a result of declining commodity prices, however, farmers in regions that show only modest increases in production clearly are suffering substantial economic loss. In these cases, we expect economic losses to show up as decreases in the value of assets located in these regions—primarily agricultural land. In the Canadian scenario, several regions show absolute decreases in production. This adjustment process over the longer term explains why production can continue to increase even though the region experiences economic loss. Owners of land may be forced out of business, and the resulting price of land would reflect the reduced production potential resulting from degrading climatic conditions. A new buyer paying the lower price could then profit because the asset cost was lower. Thus, production continues despite the fact that owners of farmland take a significant economic loss. In the Canadian scenarios, regions with production losses also are suffering from price decreases, although not as severely as in the Hadley scenario.

Resource Use

Overall, measures of resource use generally decline across all categories, both climate scenarios, and both time periods (Figure 3.7). Irrigated land and water use decline most, reflecting the overall increase in production and decline in prices and the relative yield effects between irrigated and dryland agriculture. Overall, the results for these scenarios suggest considerably less pressure on resources as a result of the overall increase in productivity.

Trade Scenarios

Table 3.9 provides aggregate economic results for the three different trade scenarios for 2030 and 2090. All three foreign trade scenarios were run against the Canadian and Hadley domestic US scenarios. The trade scenarios generally do not lead to a substantial change in total surplus or total US surplus. This result reflects the fact that the United States is a substantial commodity exporter but also a substantial food consumer. Hence, global price changes have roughly offsetting effects—consumers gain from price decreases whereas producers lose. With price increases, these effects are in the opposite direction but again roughly offset one another. Thus, the biggest effect of the trade scenarios is reallocation of the total domestic effect between producers and consumers. The Darwin scenario

Figure 3.7. Changes in Resource Use, Canadian and Hadley Centre Climates, without Adaptation

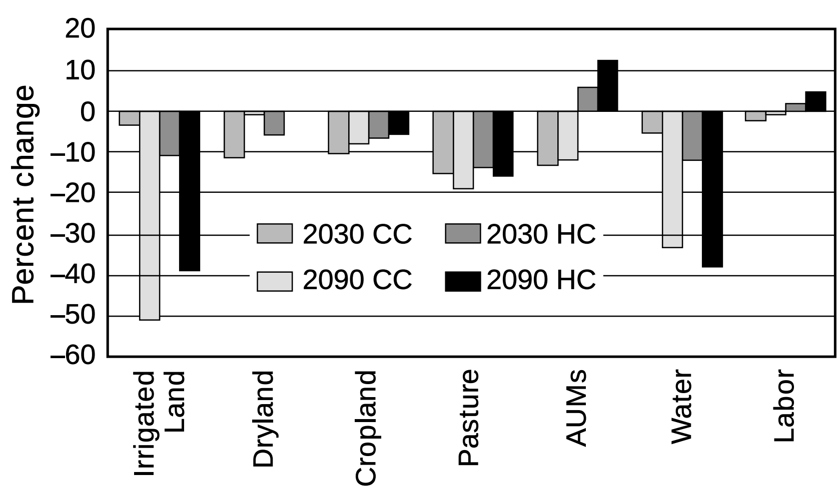


Table 3.8 Sensitivity to Trade Scenarios, Without Adaptation

Year	Scenario	Consumer Surplus	Producer Surplus	Foreign Surplus	Total Surplus
2030	Base, CC	2.8	-4.2	0.8	-0.6
2030	Darwin, CC	5.0	-6.4	0.8	-0.6
2030	GISS, CC	2.2	-3.7	0.8	-0.7
2030	UKMO, CC	2.8	-4.2	0.8	-0.6
2030	Base, HC	9.4	-3.6	0.6	6.4
2030	Darwin, HC	11.0	-5.2	0.5	6.3
2030	GISS, HC	9.3	-3.4	0.6	6.4
2030	UKMO, HC	9.4	-3.6	0.6	6.4
2090	BASE, CC	4.5	-4.5	1.1	1.1
2090	Darwin, CC	5.1	-5.5	1.1	0.7
2090	GISS, CC	4.2	-4.3	1.2	1.0
2090	UKMO, CC	4.5	-4.5	1.1	1.1
2090	BASE, HC	11.4	-0.8	1.0	11.5
2090	Darwin, HC	11.8	-1.5	1.0	11.3
2090	GISS, HC	11.3	-0.8	1.0	11.6
2090	UKMO, HC	11.4	-0.8	1.0	11.5

Note: Columns may not sum to total due to independent rounding.

creates somewhat greater losses for US producers—the implication being that the impact on production in the rest of the world for those goods in which the United States trades is positive with generally lower world prices than in comparable cases in which world production was left unchanged. For the GISS and UKMO scenarios, the effect is the opposite: World prices increase—very modestly in the GISS case and more substantially in the UKMO case—thereby shifting some of the gains from US consumers to US producers.

These trade scenarios were not developed consistently with the domestic impacts. If the results obtained for the United States with these climate scenarios—generally, more positive yield effects than in past assessments—were observed across the world, we would expect world prices generally to decline. The result would be further gains by US consumers and losses by producers—as observed in the Darwin scenario rather than in the GISS or UKMO scenario. On the other hand, a factor that is undoubtedly important in moderating the climate impacts on the United States is the cooling effect of sulfate aerosols in northern temperate regions. Earlier assessments used climate scenarios that did not include sulfate aerosol effects. Often these assessments showed warming benefits in more northerly regions and losses in tropical regions. Sulfate aerosol effects could produce a regional pattern of climate change that reduces benefits to some northern regions compared with earlier assessment, while leaving unchanged the losses in the tropical regions. If such a result obtained, the implication might be world price increases and a shift of benefits from US consumers to US producers. More complete global studies with newer climate scenarios are required to resolve this effect.

Alternative PNNL Crop Scenarios

Table 3.9 provides aggregate economic results for the alternative PNNL crop simulations. These results were produced only for the Hadley scenario and did not include adaptation. We did not include pest changes in this comparison because the primary purpose here is to evaluate scenarios for PNNL crop simulations versus core crop simulations for a comparable set of scenarios. In terms of aggregate consumer and producer surplus, the PNNL-based economic results were similar to the site-based economic results. The PNNL study did not cover all crops, however, so the PNNL-based economic results include the site-based yield results for crops not

Table 3.9 PNNL Crop Yield Simulations, Without Adaptation

	Consumer Surplus	Producer Surplus	Foreign Surplus	Total Surplus
HC 2030	9.4	-3.6	0.6	6.4
HC-PNNL 2030	11.2	-3.3	0.3	8.2
HC 2090	11.4	-0.8	1.0	11.5
HC-PNNL 2090	14.0	-4.0	0.7	10.6

considered by PNNL—thereby making the economic results more similar than they might have been if PNNL had different results for all crops. The total economic welfare gain is somewhat higher in 2030 and somewhat lower in 2090. Although the general result—increases in productivity for most crops in many places—obtained for the PNNL and for the site-based studies, there were some important differences in the results, such as the effect on irrigated crops of differences and denser coverage of sites. These differences did lead to differences at the regional level. In the PNNL scenarios, the Southeast does not show up as a particularly severely affected region; the Southern Plains and Northeast are affected considerably more positively than in the core scenarios. The Northern Plains appear to be the more negatively affected region in the PNNL scenario. The Lake States, Corn Belt, and Pacific regions are among the more positively affected regions in both scenarios.

Overall, this comparison is reassuring in the sense that the limited site selection in the core scenarios does not appear to have created a substantial bias in aggregate estimates. The aggregate effects offer a relatively weak test, however; several crops were left unchanged between the core and PNNL results because the crops were not simulated by PNNL. Clearly, some differences do occur at the regional level, emphasizing the uncertainties in producing consistent projections at the regional level.

Other Scenarios and Sensitivities

We were unable to generate yield changes for cotton with a cotton crop model. Instead, we adapted results from another study. We also simulated results by using soybeans as a proxy for cotton. Soybean results generally were quite negative in the South in the Canadian scenarios, whereas the alternative cotton scenarios showed more positive effects. As a result, this alternative assumption produced quite different results. Notably, under the Canadian scenarios the $0.6 billion total surplus loss in 2030 doubled, and the approximately $1 billion gain in 2090 changed to a $1 billion loss. Most of this change accrued to domestic and foreign consumers. Producers losses actually were slightly reduced in 2090 as a result of higher cotton prices. Negative production effects were most substantial in the Delta region.

The results derived by projecting the agricultural economy forward to 2030 and 2090 were not qualitatively different. Specific quantitative results depend crucially on highly uncertain forward projections. The two basic aspects of these projections are yield growth and demand. Projecting historical yield growth and increases in demand because of population growth increases the absolute size of the agricultural economy. If we consider yield changes in percentage terms as operating on the new higher yields, the percentage effect is similar. Differences can arise by virtue of different assumptions about yield and demand growth for different crops and differences in yield impacts among crops.

We also jointly considered the impacts of changes in agriculture and forestry. Because of the long growth cycle of forests, there is a far greater need to look forward and consider the present value of changes over many years. Forest yield scenarios were based on the Canadian and Hadley climate scenarios and use of two ecological process models (Joyce et al. 2001; Irland et al. 2001; McCarl 2000; Alig et al. 1997). The results suggest that when the agriculture and forestry sectors are considered together, the effects for the US economy are beneficial. Increased supplies from forests lead to reductions in log prices that decrease producers' welfare (profits) in the forest sector. At the same time, lower forest product prices mean that consumers generally benefit. This pattern of distributional impacts on forestry producers and consumers is similar to results in the agricultural sector. Increases in the net present value of total economic welfare (combined forestry and agriculture) ranged between 0.9 and 1.2 percent, with higher positive impacts under the Hadley climate change scenarios. More details on these results are provided in McCarl (2000).

Land-use changes between forestry and agricultural uses are an important avenue of adjustment to climate-induced shifts in production, and there are notable differences in these adjustments across climate change scenarios. Over the full projection period, the base and Canadian scenarios project a net shift of land from agriculture to forests—the latter at about half the rate of the former—whereas the Hadley scenarios project a net loss of forest land to agriculture. Yields from the land generally increase in both the forestry and agricultural sectors in all four scenarios. In the Canadian scenarios, these shifts are relatively more favorable for forestry profits compared to agriculture, whereas the opposite is true in the Hadley scenarios.

Summary of Main Economic Results

The main results of the economic analysis are as follows:

- Climate change as modeled under the climate scenarios that we considered is mostly beneficial for society as a whole in terms of agricultural impacts, particularly if adaptation is considered. This finding differs from the results of previous scenario analyses, in which results have been mixed and generally negative in the absence of adaptation.
- Climate change uniformly shows increases in crop production and exports and decreases in crop prices. Livestock production and prices are mixed.
- Climate change is largely detrimental for producers. Climate changes are beneficial for foreign surplus and for consumers. These results reflect the overall positive effect on production, which leads to decreasing prices.
- There are substantial shifts in regional production, with gainers and losers. The Lake states, Mountain states, and Pacific region show gains in production; the Southeast, the Delta, the Southern Plains, and Appalachia generally lose. Results in the Corn Belt are generally positive. Results in other regions are mixed, depending on the climate scenario and time period. Regional results show broadly that climate change favors northern areas and can worsen conditions in southern areas—a result obtained by many previous studies.
- Our analysis suggests increases in pesticide expenditures as a result of climate change—a partial offset to the overall benefits. The magnitude of this effect is relatively small.
- The overall benefits of climate change are greater in 2090s than in 2030 for the United States as a whole; even for regions with losses, these changes generally are less in 2090 than in 2030. Changes in precipitation and atmospheric CO_2 probably are the source of this result.
- Climate change largely causes a decrease in resource usage because of expanded productivity. In particular, dryland, total cropland, pasture land, and water usage decline.
- Farm-level adaptation increases the climate change benefits to society by about $1 billion. Producer losses generally are reduced by adaptation.
- Consideration of climate effects in other countries did not greatly alter the climate change benefits to society. It can have substantial distributional assumptions, depending on how climate affects the rest of the world.
- Changing the base year does not alter the sign of the climate change benefits to society as a whole.
- The results we obtained by using two different crop yield simulation approaches were quite similar in overall magnitude.
- Jointly considering forest and agricultural changes resulting from climate does not change the impacts substantially. The net effect on society of both changes is positive, and the distribution effects are similar; producers suffer surplus losses because of declining prices, whereas consumers benefit.

Chapter 4 Impacts of Variability on Agriculture

Introduction

Crop yield variability is the result of many different factors. These factors include changing production practices such as the introduction of new tools, new hybrids and varieties or cultivars, development of new diseases and pests, and government policy. Underlying many of these factors are extreme weather events and the variability of weather from year to year.

Extreme weather events such as hurricanes and droughts have obvious impacts and recently necessitated two disaster relief bills for farmers. In the past decade, large yield reductions were observed in 1988 because of severe drought throughout the midsection of the United States and again in 1993 when large areas of Illinois, Iowa, Missouri, and other Midwestern states experienced record rainfall from early spring through summer. In the early 1980s, corn surpluses were so large that in 1983 farmers were paid to remove large acreage from production.

In recent years, climate scientists have improved their ability to identify and predict seasonal to interannual climate phenomena such as ENSO 6 to 18 months in advance. This improved prediction capability has contributed to increased attention toward identifying how farmers would or could respond in anticipation of these events. Several studies suggest that one-fifth of the losses related to such events might be avoided if appropriate changes in cropping practices were made.

In this chapter, we review and evaluate the impacts of climate variability on crop yields and consequent impacts on the US agricultural economy, focusing primarily on how greenhouse gas-induced climate change could change variability. We first present the method by which the climate change scenarios were used in results discussed in Chapter 3 and later in this chapter. The purpose is to make clear the extent to which the approach already includes variability and extreme events as they affect agriculture. We also clarify the relationship among changes in the climate means, the variability of climate, and the frequency of climatic extremes.

The basic approach in the core site studies in Chapter 3 was to apply changes in mean monthly precipitation and temperature from the GCM scenarios to actual 40-year historical records for the sites. The PNNL approach used changes from the GCMs as seeds for a stochastic weather generator that is part of their model. Both approaches thereby include variable weather. For temperature in the site studies, we calculated absolute differences between the GCM-modeled mean monthly temperature in the scenario with greenhouse gas forcing and the GCM-modeled climate without forcing (often referred to as the control scenario). We added these differences to the daily values in the historical record for each site for the applicable month for the 40-year historical record. Thus, the variability of temperature remains the same as in the historical record, but the mean is higher.

For precipitation, the standard approach is to use ratios of the greenhouse gas-forced climate and the control climate—rather than absolute differences. Ratio adjustments for precipitation are widely used in crop studies because they avoid the problem of potentially negative precipitation. A negative precipitation estimate can result when there are errors in simulation of precipitation in the control run of the GCM combined with projected decreases in precipitation. Some studies have used absolute differences in precipitation, replacing negative values where they occurred with zero precipitation, and found that using absolute differences resulted in more precipitation than the ratio approach, particularly over desert regions (Alcamo et al. 1998; Darwin 1997). The ratio approach changes the variability of the daily intensity of precipitation. The variance changes as a function of the square of the ratio of the climate change to control climate projections (Mearns 1996). This change in variance is the coincidental result of using ratios rather than differences; it does not reflect an analysis of how variability might actually change on the basis of analysis of GCM results. These methodological differences could lead to different yield results and water-use results, particularly in more arid regions where the differences are greater. Yield increases in arid areas and reductions in water use would be expected to be larger if the same difference were observed with the Canadian and Hadley models. We were unable to consider this alternative method directly.

The PNNL stochastic weather generator also reproduces weather that varies like that observed in the past, but the stochastic aspect of the approach means that the realized weather has characteristics like historical weather but is different in each run. The mean and variance calculated over many years of simulation are the same across runs. These approaches have been developed because climate model results are still too inaccurate on a regional scale to be used directly.

Thus, the method used here for generating climate input for the crop models produces a weather record with climate change that includes storms, droughts, and extreme temperatures. In particular, because we used monthly mean changes, the seasonality of climate (e. g., distribution of precipitation and the pattern of warming over the year) can change. For example, if the GCM scenario projects a precipitation decrease of 90 percent in the summer and a precipitation increase of 90 percent in the winter for a location with seasonally balanced precipitation, the yearly total precipitation would not change but the seasonal distribution would be greatly altered. This scenario can be regarded as a change in the seasonal cycle (seasonal variability) of precipitation. This change is captured by methods applied in Chapter 3.

Changing the mean temperature and precipitation in this way also changes the frequency of extremes—for instance, the likelihood that the maximum temperature on any day in the summer will exceed 35°C. In fact, given the usual distribution of temperature highs for a day, the frequency with which the temperature exceeds an absolute threshold such as 35°C changes rapidly with a change in the mean. For example, based on the 30-year weather record for Des Moines, Iowa, there is an 11 percent chance that the maximum temperature on any day in summer will exceed 35°C. Moreover, based on the distribution of high temperatures for Des Moines, if the mean temperature were to increase by 1.7°C, the chance that it will exceed 35°C would rise to 22 percent. Thus, for a relatively small change in the mean maximum temperature, the likelihood that the temperature will exceed 35°C doubles. Again, this increase in the likelihood of extremes is captured in the methods applied in Chapter 3 as well as later in this chapter.

If the variability (i. e., the standard deviation or variance) of the temperature also changed, this variability would further affect the frequency of extreme events. For example, if the simulated distribution of highs became wider (i.e., the variance increased), the chance that the temperature will exceed 35°C in the foregoing example would increase by more than 22 percent. This aspect of change in variability was not incorporated in our scenarios. Similarly, some aspects of potential changes in variability in precipitation are excluded as a result of the methods applied in Chapter 3. For example, if the historical record shows on average 10 rain events in July and August, the climate change scenario developed with the method in Chapter 3 also will have, on average, 10 rain events in July and August. The method also does not account for changes in frequency of precipitation on a daily time scale. Therefore, the result of GCM projections of an increase in precipitation is that each rain event has more rain. The method used in Chapter 3, however, would not include a projected trend toward fewer rain events or rain coming in heavy downpours rather than slowly over the course of a day.

Common parlance recognizes that a drought is a drought regardless of whether it is caused by a change in the mean or a change in the variance. We can easily imagine, however, that two areas with the exact same climatic means can have very different agricultural potential. An area with even rainfall and temperatures through the year could be the breadbasket of a nation. If identical mean conditions occurred but precipitation fell in torrential downpours—followed by months with no rain—and temperatures varied from freezing to scorching, the region would become a wasteland with regard to agricultural potential.

A major point of this discussion is to make clear that our method produces changes in extremes but does not include changes in all aspects of climate variability that affect the frequency of extremes (e.g., variance). The intent of this chapter is to address more specifically the impacts of variability, extreme events, and changes in variability.

We begin by briefly reviewing the evidence from climate modeling on how variability could change. We then review the impact of weather on variability in crop yields and discuss possible future responses to changing variability. We consider the impacts of climate change and variability in the context of projecting extreme events, simulating the potential impacts of climate variability and extreme events on crops, relating crop yield variability to climate, and considering the economic implications of potential ENSO shifts.

We examine the impacts of climate on the variability of US corn, cotton, sorghum, soybean, and wheat yields. We chose these crops because of their widespread coverage and important economic value. Other regionally important crops also will be affected by climate change and variability but we did not analyze them.

Predicting Extreme Events

Most of our knowledge of possible changes in extremes comes from climate model experiments of futures with increased greenhouse gases and aerosols. Climate modeling capabilities have improved greatly in the past 10 years, and examination of changes in at least certain types of extremes simulated in climate models is more common now than it was in the past. The current generation of coupled atmosphere-ocean general circulation models (AOGCMs) has improved spatial resolution (about 2.5 degrees latitude), adopts more realistic land surface schemes, and includes dynamic sea ice formulations. These and other improvements, such as nesting of high-resolution (tens of kilometers) regional models within AOGCMs, have improved our ability to estimate possible changes in some extremes. In this section, we review what is known from climate models on possible changes in extreme events in the 21st century.

Temperature

One of the earliest and simplest analyses of possible changes in extreme events concerns increased frequency of extreme daily high-temperature events and decreased frequency of low daily temperature events. With an increase in mean (maximum and/or minimum) temperature—assuming no other changes in other aspects of temperature (e.g., variability)—there will be an increase in the likelihood of, for example, days with maximum temperatures exceeding 35°C. The change in the probability of extreme daily temperature events is nonlinear with the change in mean temperature—that is, a small change in mean temperature will produce a relatively large change in the probability of a temperature extreme (Mearns et al. 1984). Changes in temperature variance also contribute to changes in the frequency of extremes; on a per degree basis, these changes have a greater influence than the change in the mean (Katz and Brown 1992). In climate model experiments investigated to date, however, the mean usually changes more than the variance.

Within the literature on climate change, several climate simulations of the future have found that in northern mid-latitudes, the daily temperature variance increases in summer but tends to decrease in winter. These changes complement the effects of the changes in mean. The increased frequency of high-temperature events in summer is further increased by the increased variability, and decreases in low extremes in winter are further decreased by the decreasing variance (Meehl et al. 2000).

Precipitation

Earlier studies of climate models found a tendency for increased precipitation intensities; more recent studies continue to find this result. For example, Zwiers and Kharin (1998) found that mean precipitation increased by about 4 percent and precipitation extremes increased by 11 percent over North America in a doubled-CO_2 simulation. Another important and seemingly robust result from climate models is a tendency toward mid-continental drying in summers—as a result of higher temperature and reduced precipitation—with increases in CO_2 (e.g., Wetherald and Manabe 1999). Seasonal and regional changes in the pattern of precipitation and temperature are accounted for within crop studies described in Chapter 3; we use them as the basis for economic modeling. These general regional and seasonal patterns are reflected in the regional estimates presented in Chapter 3.

Extratropical and Tropical Storms

Although researchers have made steady improvements in the ability of climate models to adequately model tropical and extratropical storms, they still have relatively low confidence in model simulations of changes in these features. A growing number of studies address possible changes in extratropical storm activity, but little agreement is found among these studies. Moreover, no consensus has emerged among global models regarding changes in the frequency or intensity of tropical cyclones. Several studies have shown increased intensity of tropical cyclones, but the models are still too coarse to resolve many important features of such storms (e.g., the eyes of hurricanes).

El Niño/Southern Oscillation and La Niña

ENSO is a major coupled ocean-atmosphere phenomenon that determines the interannual variability of climate and thus will be a major determinant of the future variability of climate. El Niño is the part of the oscillation when Pacific waters off the coast of South America are warm; La Niña is the cool phase. Current climate models have much improved simulations of ENSO, but conclusive evidence of how ENSO might change remains elusive. Several studies suggest, however, that with a warmer base condition, precipitation extremes associated with El Niño events may become more extreme—that is, more-intense droughts and flooding conditions may be found (e.g., Meehl 1996). There has been considerable progress in the realm of seasonal forecasting of ENSO events and its connections with broader climate phenomena. The relevance of more-severe ENSO events to agriculture is discussed below.

Conclusions

The literature on predicting extreme events indicates that our knowledge of changes in extreme climate events in the future remains limited, with the exception of relatively simple single-variable extremes such as those related to daily temperature. Yet many types of extreme events certainly will change in frequency and possibly intensity in the future. Many of these events (temperature and precipitation extremes, droughts, floods) have important effects on agriculture. Even with little conclusive information on how such extremes may change, sensitivity analyses can illustrate how changes in extremes could affect cropping systems and agriculture in the United States, suggesting strategies that reduce losses. Although long-term prediction of changes in climate variability because of greenhouse gas accumulation may remain elusive, studies of response to variability are useful in identifying strategies that could be used as medium-term climate prediction improves.

Predicting the Impact of Climatic Variability and Extreme Events on Crops

Most research regarding potential changes in crop yield resulting from climate change has focused on the impacts of changes in long-term climatic averages, with the assumption that climate variability as technically defined will be the same as in the present climate. Changes in climate variability, however, will affect the frequency of extremes and could have important impacts on crop yields. We discuss below some of the effects of extreme events on agriculture (independent of whether their probabilities are changing), aspects of modeling extreme events in crop models, and the effect on interannual events such as ENSO. We then review some recent efforts that have attempted to separate changes in variability from changes in the mean. Finally, we discuss spatial variability.

Examples of Extreme Events Affecting Crops

Extreme events that affect crops occur on varying spatial and temporal scales. Events on the interannual time scale include seasonal droughts, floods, cold winters, and so forth. Well-known periods of drought in the 1930s and again in the 1950s severely decreased crop yields in the United States.

On time scales of hours to weeks, very short-lived extreme events within the cropping season can cause serious damage to crops. For example, many field crops suffer after consecutive days of high temperatures during sensitive phenological stages. Corn is a very sensitive crop, and several researchers have identified damaging events: Shaw (1983) reported that damage to corn occurs after 10 days of high maximum temperatures during silking, and Berbecel and Eftimescu (1973) identified daily maximum temperatures above 32°C during tasseling and silking as particularly damaging. Although soybeans are less vulnerable than corn, soybeans can suffer from maximum temperatures exceeding 40°C at the onset of flowering (Mederski 1983). Cotton plants abort bolls when the temperature exceeds 40°C for more than six hours; in rice, a temperature exceeding 30°C during anthesis causes spikelet sterility (Acock and Acock 1993). Short-term moisture deficits also can cause loss in yield, depending on the phenological stage during which they occur. Most often, reproductive stages are the most vulnerable. Excess precipitation also causes problems for crops in the form of lodging, lack of aeration, and increased insect pest infestation (Rosenzweig and Hillel 1998).

Extreme cold events affect fruit and citrus. Freezing temperatures (below 0°C) during the winter months result in catastrophic damage to the citrus crops in Florida, Texas, and California. Extreme winter temperatures affect the more cold-sensitive peach crop by killing the flower buds with temperatures below –18°C and killing the peach trees with temperatures below –30°C. A change in the frequency of these extreme events as a result of climate change could cause a contraction of the area in which these crops are grown—if extreme events occur more frequently—or an expansion of the production region with a less frequent occurrence of extreme cold temperatures.

Modeling of Extreme Events in Crop Models

In most crop models, the impact of temperature occurs on a daily basis. The simulation of temperature effects in crop models is almost always independent of the temperature of the preceding day. In other words, the impact of a warm day on growth is the same whether the day before was warm or very cold. Many models accumulate temperature stress days, based on high and low prescribed threshold temperatures. Given the relative success of most crop models, this approach appears to work reasonably well.

Occasionally, crop models simulate more complex sequences of extremes. One example is the modeling of winter kill in some crop models (e.g., CERES-Wheat), which takes into consideration the hardening of the crop (based on temperature accumulation at some prescribed low temperature) and exposure to very low extremes (killing temperatures). If the crop experiences a rapid oscillation between high and low minimum temperatures, winter kill can result (e.g. , Mearns et al. 1992).

Crop models generally are less successful, however, at modeling the effects of sequences of days, such as the effects of five consecutive days of above 35°C temperatures during silking in corn. The relatively small sample size of such events makes successful modeling of the physiology of this effect difficult. Being able to predict the effects of heat waves, for example, could be more important in a climate-changed world in which the mean and variability of day-to-day temperatures increased. Current state-of-the-art models probably underestimate the impact of resultant extremes of climate on crop growth. Thus, although the altered climate scenarios we use create a greater likelihood of such heat waves, existing crop models lack specific mechanisms to fully reflect these types of events.

On the other hand, crop models have long been constructed with a view toward modeling the effects of moisture stress (i.e., a deficit) on crops—and are relatively successful at doing so. Important differences in the details of how moisture stress is modeled can result in very different responses of crop models to the same climate change conditions, however. For example, the sensitivity of crops to moisture stress tends to be growth stage-specific. Although most crop models use the accumulated degree-day approach to represent the progressive phenology through a crop season, they can differ substantially with regard to how detailed this treatment is. EPIC, for example, has a relatively crude phenological submodel, whereas the CERES family of crop models tends to represent more detailed phases of phenological development. In a comparison of the response of CERES maize and wheat with EPIC maize and wheat for climate change scenarios in the Great Plains, Mearns et al. (1999) found that the models projected different magnitudes and directions of change in yield, primarily as a result of differences in the phenological stage at which simulated crops experienced moisture stress.

Although moisture deficit (drought) has been the principal concern of crop modeling efforts, excess moisture also causes significant crop damage. Some crop models (such as EPIC; Williams et al. 1989) include the modeling of stress from insufficient aeration, and at least one of the CROPGRO models (SOYGRO; Boote et al. 1998) includes an excess moisture factor. There is little information, however, on how realistically these models simulate excess moisture effects.

Infrequent combinations of weather variables also can lead to unusual crop responses. For example, moisture or high humidity after physiological maturity has been reached, in combination with warm temperatures, can cause grain to germinate or sprout before harvest. Waterlogging in combination with warm temperatures in spring can have particularly negative impacts on crop growth. Crop models often do not simulate the effects of these interactions. For example, the EPIC model calculates an aeration stress factor that is based on the water content of the top 1 m of soil, but this factor is not dependent on temperature.

Overall, a major direction of crop modeling is toward understanding of crop response to varying climate. Climate can vary in many dimensions, and not all potential effects are captured. Moreover, most of the testing and validation of crop models occurs in areas where these crops are grown. Although annual variability in climate creates a rich set of weather conditions against which to evaluate these models, climate change could produce combinations of climatic conditions that are only infrequently observed where these crops currently are grown; thus, our ability to capture these effects may be limited. Direct comparisons of different models of the same crops to the same climate conditions can produce widely varying results, and running a crop model at a new site can require considerable calibration before it can estimate realistic yields at the site. Overall, crop models capture some of the broad changes fairly well and on average perform well. As we begin to consider more detailed aspects of climate and attempt to make more precise predictions about how to respond to very specific climate conditions, we require more detailed models, experimental evidence, and site-level verification so that the model can reproduce actual responses to varying conditions.

Interannual Variability: ENSO Events

An example of an increase in climate variability on an interannual scale would be if precipitation extremes associated with the El Niño phenomenon become even more severe than they are now. Our understanding of the influence of ENSO—as well as other important couplings of ocean currents and atmospheric dynamics—on climate variability in specific regions has greatly increased in the past decade. This development has enhanced our ability to forecast events such as El Niño and La Niña years on a regional basis. The general impacts on crop yield of climate regimes associated with the El Niño phenomenon are reasonably well understood and are captured effectively in several crop simulation models. These models have been used to determine specific components of the climate that are responsible for yield variations. For example, a study of the impact of El Niño events on corn yield in the US corn belt, using crop growth simulation, indicated that water stress in July and August is the primary cause of lower corn yields in La Niña years, along with a shorter period of grain filling because of high temperatures (Phillips et al. 1999). The cooler temperatures and greater rainfall during El Niño years had less pronounced effects on yield than the dryer, warmer La Niña years.

Studies also have been undertaken to determine the value of El Niño forecasting to agriculture at the farm management and industry level. Hammer et al. (1996) compared a fixed management strategy for nitrogen fertilizer application rate and cultivar selection in a wheat cropping system in Australia to a tactical strategy that depended on the seasonal forecast, using the Southern Oscillation Index. An analysis of simulated results with the tactical strategy indicated significant increases in profits and reductions in risks compared to the fixed management strategy. In another Australian study, phases of the Southern Oscillation Index were used to make forward estimates of regional peanut production (Meinke and Hammer 1997). Because peanut yield varies greatly with rainfall, high variability in rainfall is a concern for peanut processors and marketers. One conclusion of this study was that the industry could profit by using yield forecasts made three to five months ahead of harvest to strategically adjust for expected volume of production.

The foregoing studies were conducted to evaluate the extent to which advanced warning of El Niño or La Niña events, as well as other important couplings of ocean currents and atmospheric dynamics, can significantly improve farm and agricultural industry management decisions. As these types of analyses improve, our ability to predict the impacts of changes in decadal-scale climate variability on agriculture will be enhanced. Future studies should take into account, on a regional basis, current agricultural systems and feasible alternative systems in the context of current and possible future economic and policy environments. This type of approach, linked with appropriate climate scenarios, should be useful in predicting the sensitivity of agricultural systems to changes in decadal-scale climate variability.

Intra-Annual Variability (Weather)

Climate change also may cause changes in the within-season variability of temperature and precipitation, although most studies of agricultural yields under future climate change scenarios have assumed that the nature of this variation will be the same as in the present climate. There could be important impacts, however, if within-season variability increases. Such changes would further shift the probability of extreme events and also might have less-obvious influences on crops, such as changing the rate of development.

Changes in Variability Alone

Several studies, encompassing a variety of crop simulation models and regions, have systematically investigated the impact of changing within-season variability of temperature and precipitation (e.g., Mearns et al. 1996; Riha et al. 1996). General conclusions from these studies are that crop yield decreases as temperature variability increases and that the capacity of the soil to store water strongly mediates crop response to changes in precipitation variability. Not surprisingly, sandy soils are far more vulnerable to increases in rainfall variability.

Riha et al. (1996), who applied EPIC corn and soybean models, found that increased variability of temperature or precipitation resulted in substantially lower mean simulated yields; decreased variability of temperature produced insignificantly small increases in yield. The implications of this asymmetric response to variability in temperature is that relatively low variability in temperature is one of the major factors that make these Corn Belt areas so productive. The year-to-year variability of yields also increased with increased variability of temperature and precipitation. The implication for climate change is that the main risk to these regions is likely to be the potential for increased variability.

Combined Effects of Mean and Variability Changes

Several studies (Mearns 1997; Semenov and Barrow 1997) have examined the effects of climate change scenarios that included changes in the mean and the variance of climate on simulated crop yields by altering parameters of stochastic weather generators. The negative effects of climate change on crops were exacerbated by including the effects of changes in climate variability.

Spatial Dimensions of Extremes

Extreme events can have spatial characteristics that have implications for appropriately simulating their impact on crop yields over relatively large spatial and temporal scales. Some extreme events are common when large areas are being considered but occur infrequently in a specific location (e.g., hail). Hail causes damage that can lower yield and, in the case of horticultural crops, lower the value of the crop. For a given location (such as an experimental farm) where data for crop model development and testing are being generated, the likelihood of hail in any given growing season may be quite low. Therefore, the impact of such a phenomenon is not considered in the simulation of climate impacts on crop yields. Clearly, if the frequency of occurrence of such a phenomenon were to increase, it would cause damage to a larger proportion of the cropped area and might reach a point at which regional yields were significantly affected.

Some extreme events are more likely to occur in certain areas rather than randomly over an area because of the interactions of weather with the landscape. Examples include cold air drainage that creates frost pockets, gusting winds that causes lodging, snow pack of variable depth that affects the winter survival of wheat, and flooding. Some current crop models can simulate the impact of such events on crop growth and field operations, but the more difficult challenge is to predict the spatial extent of these events from terrain and weather data. This variability in the spatial dimension usually is not explicitly included as input to crop models. For example, most agronomic crops cannot survive flooding. Changes in precipitation that result in more rain during short periods of time could lead to more flooding; clearly, however, the likelihood and extent will depend on terrain factors, as well as flood management policies.

Response of Future Crops to Extreme Events/ Climate Variability

Adaptation to Temperature Extremes

Crop varieties have been developed to avoid temperature extremes through selection of plants that can complete their life cycle more quickly than traditional varieties. In temperate climates, these varieties can be planted late and harvested early to avoid chilling and frost injury. In tropical climates, these varieties can be used to avoid periods of high temperatures. This type of adaptation generally is well simulated by crop models. Increases in temperature variability alone would be expected to further reduce the length of the growing season and therefore require growing a shorter-season variety or crop. For many crops, however, varieties have been developed that can tolerate (not just avoid) heat and cold. This type of adaptation is somewhat more difficult to simulate because tolerance often is limited to a particular stage of development, such as germination, emergence, flowering, or grain ripening. These adaptations, though limited, can have significant impact on growth and yield. For example, a seed's ability to germinate at temperatures that are even a few degrees cooler in many cases can significantly increase the region in which the crop can be grown. Breeding for cold tolerance during germination and heat tolerance during grain filling probably will mitigate some impacts of increases in temperature variability and some extremes. Crop simulation models vary in their ability to simulate these varietal adaptations.

Although selected varieties may tolerate temperature extremes better than more traditional varieties during specific life stages, if the mean seasonal temperature moves outside the optimum range for the crop, the yield of all varieties generally decreases significantly. In general, varieties that yield best under nonstressful environments also yield best under stressful environments, though the yield is reduced (Evans 1993). This finding suggests that current breeding strategies will be useful in selecting plants that can perform reasonably well even if temperature variability increases.

Adaptation to Drought

Similarly, crop varieties have been developed to avoid drought through selection of plants that can either complete their life cycle more quickly than traditional varieties or are not in phenological stages that are sensitive to stress (such as flowering) when drought is likely to occur. It is less clear that the ability of plants to tolerate drought stress has been significantly improved in the course of plant breeding, except that breeding for tolerance of high temperatures may improve yield under drought. The water use efficiency (WUE) of crops, expressed as the ratio of biomass of crop produced per unit mass of water transpired, decreases as temperature increases, assuming radiation and vapor density are similar.

Empirical Estimates of Crop Yield Variability as Related to Climate

Another approach for evaluating the impact of variability on crops is to use cross-section evidence. The availability of state-level detailed climate and yield data across the United States allowed us to examine how year-to-year and region-to-region climate variation alters crop yields (Chen et al. 1999b) as part of the agriculture sector assessment. Variability influences of climate were investigated with USDA-NASS (1999c) *Agricultural Statistics* state-level yields and acreage harvested for 25 years (1973–1997). State-level climate data matched to the agricultural output data were drawn from NOAA (1999), which includes time series observations for thousands of weather stations. The April-to-November average temperature for the published weather stations ina state was used.

The approach relies on the ability to separate changes in variability from changes in means (details of which are provided in Chen et al. 1999b). The basic results are in terms of elasticities—that is, how does a 1 percent change in temperature or precipitation affect yields in percentage terms? We can estimate how the 1 percent change in climate affects the mean yield and the variability of yield. Results can vary, depending on the functional form of the estimated equation.

Table 4.1 reports the mean yield elasticity estimates for a linear form and a multiplicative functional form (the specific form is commonly known as a Cobb-Douglas production function in economics). In terms of changes in the mean, the sign on precipitation is positive for corn, cotton, and sorghum crops and negative for temperature. This result indicates that crop yields increase with more rainfall and decrease with higher temperatures. Elasticities for soybean and wheat crops are mixed. Sorghum had the highest elasticities for rainfall and temperature.

The impact of climate change on variability is reported in Table 4.2. In terms of variability, the clearest

Table 4.1. Response of Mean Crop Yields to Changes in Means of Climate Variables (measured as percentage change in mean yield for a percentage change in climate variable, temperature in ˚C)

Production Function Form	Corn Precipitation % Change	Corn Temperature % Change	Cotton Precipitation % Change	Cotton Temperature % Change	Sorghum Precipitation % Change	Sorghum Temperature % Change
Linear	0.3273	-0.2433	0.0371	-1.5334	2.8844	-2.0866
Cobb-Douglas	1.5148	-2.9792	0.4075	-0.7476	1.8977	-2.6070

Production Function Form	Soybean Precipitation % Change	Soybean Temperature % Change	Wheat Precipitation % Change	Wheat Temperature % Change
Linear	-0.2068	0.0002	-0.1309	-0.5076
Cobb-Douglas	0.34640	N.S.	1.4178	-0.3721

N.S. = not significant.

Table 4.2. Response of Crop Yield Variability to Changes in Means of Climate Variables (measured as percentage change in yield variability for a percentage change in climate variable, temperature in ˚C)

Yield Variability Function	Corn Precipitation % Change	Corn Temperature % Change	Cotton Precipitation % Change	Cotton Temperature % Change	Sorghum Precipitation % Change	Sorghum Temperature % Change
Linear	-9.7187	7.5058	-0.3028	-10.9386	0.5230	-5.3517
Cobb-Douglas	-1.4461	0.8923	-0.0212	-3.5800	0.4802	-2.5633

Yield Variability Function	Soybean Precipitation % Change	Soybean Temperature % Change	Wheat Precipitation % Change	Wheat Temperature % Change
Linear	-0.7932	-0.2739	-2.1572	-0.1035
Cobb-Douglas	0.8194	0.0586	-1.6473	5.0875

results are obtained for corn, cotton, and sorghum. The results are the same for both functional forms tested. Increases in rainfall decrease the variability of corn, cotton, and wheat yields. Corn yields are predictably more variable with higher temperatures. Cotton and sorghum rainfall variability elasticities are small; a 1 percent increase in rainfall leads to a 0.5 percent or less increase or decrease in yield variability. Cotton and sorghum have high temperature variance elasticities: a 1 percent increase in temperature produces as much as an 11 percent decrease in yield variability. Similarly large elasticities are obtained for rainfall effects on corn and wheat yield variability. All of these results are consistent across functional forms. Soybean elasticities are all less than one, but sign inconsistency across functional forms confound interpretation of these results.

We used regional estimates of climate change arising under the Canadian and Hadley climate model simulations to estimate whether, based on these climate projections and the statistical models estimated here, crop yield variability would increase or decrease using the estimated Cobb-Douglas functions. The results (see Table 4.3) show fairly uniform decreases in corn and cotton yield variability, with mixed results for other crops. Wheat yield variability tends to decrease under the Hadley Center model and increase under the Canadian model. Soybean yield variability shows a uniform increase with the Hadley model.

The basic conclusion is that these mean climate changes can produce fairly large changes in variability, but these changes can be increases or decreases. This analysis considers only the potential for changes in the mean climate conditions to change yield variability; it does not consider how changes in climate variability itself might affect mean yields or the variability of yields.

Table 4.3. Percentage Change in Crop Yield Variability for 2090, Selected States*

	Canadian Climate Change Scenario					Hadley Climate Change Scenario				
	Corn	Soybeans	Cotton	Wheat	Sorghum	Corn	Soybeans	Cotton	Wheat	Sorghum
CA			-12.84					-11.81		
CO				34.43					-10.60	
GA			-10.35					-6.92		
IL	-25.71	21.28				-24.73	18.90			
IN	-8.73	8.06				-26.31	20.30			
IA	-36.89	33.14				-26.83	20.90			
KS				-14.39	-0.75				-18.16	3.38
LA			-13.03					-7.97		
MN		4.01					10.60			
MT				32.86					-6.36	
MS			-13.92					-7.73		
NE	15.30	-4.74		48.22	-16.15	-15.05	11.65		-5.57	-1.72
OK				16.34	-9.27				-17.07	2.83
SD	-21.75			-6.94		-24.37			-19.10	
TX			-13.21	27.86	-10.83			-8.05	2.26	-3.10

*Percent change in the variance of the yield expected if the change in the simulated mean climate conditions simulated were observed for a series of years.

Estimates of Economic Implications of Potential ENSO Shifts

Some researchers argue that global climate change may alter the frequency and strength of extreme events. One marker for extreme events that has received considerable public attention is the ENSO climatic phenomenon. Timmermann et al. (1999) presented results from a climate modeling study implying that global climate change would alter ENSO characteristics, causing

- the mean climate in the tropical Pacific region to change toward a state corresponding to present day El Niño (warm) conditions;
- stronger inter-annual variability, with more extreme year-to-year climate variations; and
- more skewed inter-annual variability, with strong cold events becoming more frequent.

There is much debate about these results. We use them here to illustrate the sensitivity of agriculture to such shifts. Details of the analysis are provided by Chen et al. (1999a), a study conducted as part of the agriculture sector assessment. The Chen et al. analysis examines the economic implications of a shift in ENSO frequency and intensity by using the quantitative definition of the shift as developed by Timmermann et al. (1999). Specifically, Chen et al. presents estimates of the economic consequences of shifts in ENSO frequency and strength on the world agricultural sector.

According to Timmermann et al. (1999), the current probability of ENSO event occurrence (with present-day concentrations of greenhouse gases) is 0.238 for the El Niño phase, 0.250 for the La Niña phase, and 0. 512 for the neutral (non–El Niño, non–La Niña) phase. They project that the probabilities for these three phases, under increasing levels of greenhouse gases, will be 0.339, 0.310, and 0.351 for El Niño, La Niña, and neutral, respectively. In other words, they project that the frequency of the El Niño and La Niña phases would increase, and the frequency of the neutral phase frequency would decrease. Although they do not offer specific evidence, they argue that such a frequency change could be expected to have strong ecological and economic effects.

Our analysis investigates more formally and quantitatively whether such a change would have strong economic impacts on the agricultural economy. The ENSO impacts are based on a time series statistical analysis of ENSO impacts on each region of the world. Thus, we are able to consider how ENSO changes affect agricultural production across the world. (For details, see Chen et al. 1999a.) ENSO events influence regional weather and, in turn, crop yields.

Several studies have estimated the value to farmers of adapting to ENSO events. The question is, if farmers knew ahead of time the ENSO phase, what could they do to improve their economic outcome compared to the situation in which they operate only on long-term average climate conditions? Results indicate that there is economic value to the agricultural sector in using information on ENSO events. In terms of aggregate US and world economic welfare, the estimated benefits of using ENSO information in agricultural decision making have been in excess of $300 million annually for current ENSO frequencies.

The model experiments conducted to study these events involve different assumptions about the information with which farmers operate. To consider the value of knowing which event would occur, two fundamentally different situations were simulated in the Agriculture Sector Model (ASM):

- Producers were assumed to be operating without any information concerning ENSO phase and thus choose a crop plan (a set of crops to be planted on their land base) that represents the most profitable crop mix across a uniform distribution of weather events, based on data for the past 22 years. We refer to this analysis as the "Without use of ENSO Phase Information" scenario.

- Producers were assumed to incorporate information regarding the pending ENSO phase and thus choose a set of crops that perform best economically across that individual phase. Thus, crop mixes that are optimized for ENSO events are selected across a distribution of the ENSO states, as are crop mixes for other states. Initially, each ENSO event is assumed to be equally likely. We refer to this analysis as the "With use of ENSO Phase Information" scenario.

For the analysis conducted here, we assumed that forecast information for ENSO is correct. The economic analysis assumes that all farmers make the optimal choice, given this correct information. Failure to produce correct forecasts, failure by farmers to adjust planting in response to the forecast, or lack of knowledge on the part of farmers about responses to ENSO would reduce the value of forecasts. Losses could increase if forecasts are subject to error, if farmers respond to wrong forecasts, or if farmers do not respond unless they see evidence of sufficient accuracy. In many ways, this analysis therefore considers the greatest potential value of forecasts, although the management choices included in the economic model used may not include all possible management responses.

This analysis was conducted separately from any change in mean conditions resulting from climate change (i.e., separate from the analysis conducted in Chapter 3) to isolate the effect of change in ENSO intensity and frequency. Like the Chapter 3 analysis, the scenarios are all imposed on an agricultural economy as it exists in the year 2000—but as if different ENSO phases had occurred in that year.

In addition to structuring the analysis to vary the response of farmers to ENSO information, a second key component is varied in the model experimentation. In particular, three ENSO phase event probability conditions are evaluated.

- The first probability condition represents current conditions. Specifically, we assume El Niño phases occur with a probability of 0.238, La Niña with a probability of 0.250, and neutral phases with a probability of 0.512. Within an El Niño phase, we assume that individual crop yields for five El Niño weather years contained in our data set are each equally likely (i.e., the same strength), with a comparable assumption for the four La Niña events and the 13 neutral yield states.
- The second probability condition incorporates frequency shifts suggested by Timmermann et al. (1999). Here, the El Niño phase occurs with a frequency of 0.339, the La Niña phase with a probability of 0.351, and the neutral phase with a probability of 0.310. Within each of the phases, we again assume that cropping yield data states are equally likely.
- The third probability condition considers the impact of stronger or weaker ENSO events. The three event types were reclassified into five different ENSO events: strong El Niño, weak El Niño, neutral, weak La Niña, and strong La Niña. The frequency shifts used in this experiment are from Timmermann et al. (1999). To evaluate event strength shifts, we assume that the stronger El Niño and La Niña events occur with a 10 percent higher frequency. Specifically, if the 1982–1983 and 1986–1987 El Niños each occur with a 0.20 probability within the set of five El Niño events observed in the data set (assuming a uniform distribution across the five observed El Niños in our data set), we shift those probabilities to 0.25 and reduce the probabilities of the three other El Niño years to 0.167. Similarly, the two strongest (in terms of yield effects) La Niña events have their probabilities raised from 0.25 to 0.30, and the weaker two La Niñas have their probabilities reduced to 0.20.

The results of this analysis appear in Tables 4.4 and 4.5. Table 4.4 provides estimates of aggregate economic welfare before and after the ENSO probability shifts. Table 4.5 contains a more disaggregated picture of these economic effects. The economic consequences are evaluated for both situations regarding producer decision making (i.e., ignore or use ENSO forecasts). As in Chapter 3, the economic effect is measured in terms of changes in welfare. The aggregate changes in Table 4.4 are the sum of domestic consumer, domestic producer, and foreign surplus. Table 4.5 provides a breakdown of these results between producers, consumers, and foreign interests. Four major results can be drawn from this work:

- First, an increase in ENSO event frequency and intensity causes significant increases in crop losses. Specifically, the welfare loss from the frequency shift where farmers operate without information on ENSO event probability is estimated to be $414 million. When both frequency and strength shifts are considered the welfare loss increases to $1,008 million. This figure is about 5 percent of typical US agricultural net income, or about 0.15 percent of total food expenditures in the United States. If the strength shift were more substantial than the one assumed here, it could have substantially larger effects.

- Second, there is considerable value to farmers in operating with better information about ENSO events, and the value increases if the frequency and intensity of these events increase. The value of ENSO forecasts under current ENSO frequency and strength is estimated at $453 million. This value is very similar to previous work, as estimated by Solow et al. (1998). The value of ENSO forecasts increases to $544 million with the frequency shift and to $556 million if both frequency and intensity shift.

- Third, the additional damage from these more intense and frequent ENSO shifts is only partially offset by better forecasting. The forecasting gains are greater with a more frequent and stronger ENSO than under the current ENSO frequency and strength, but the gains do not offset the additional losses from the ENSO shifts. The use of ENSO forecasts mitigates some of the negative economic effects of the shift.

Table 4.4. Change in Aggregate Economic Welfare With Shifts in ENSO Frequencies and Strength

	Without use of ENSO information	With use of ENSO information	Gain from of ENSO use information
		($ millions)	
Current probabilities	–	–	453
Phase frequency shift	-414	-323	544
Phase frequency and strength shift	-1008	-905	556

Specifically, the figures in Table 4. 4, column 2 show an increase in damage from the current ENSO event frequency and intensity of $323 and $905 million, respectively, when ENSO information is used compared to the figures in column 1 which show an increase in damages of $414 and $1,008 million, respectively when ENSO information is not used.

- Fourth, there are winners and losers from changes in ENSO frequency and intensity (Table 4.5). Specifically, the total welfare loss from the shift in ENSO frequencies results in domestic producer and foreign country welfare losses but gains to domestic consumers. Most of these welfare losses occur in the foreign markets. These differences across groups arise from changes in US and world prices for the traded commodities. For example, for the commodities evaluated here, there are price declines as a result of slight increases in worldwide production when phase frequency shifts. Price declines result in losses to producers and exporting countries but gains to consumers.

The referenced ENSO case of Chen et al. (1999b) that is summarized here confirms the analysis by Timmermann et al. (1999) that climate change-induced shifts in ENSO frequency will have economic consequences. We further find that

Table 4.5. Change in Welfare, by Component, With Use of ENSO Information ($ millions)

	Phase frequency shift	Phase frequency and strength shift
	($ millions)	
US Producers	-307	-321
US Consumers	591	326
Foreign interests	-607	-910
Total	-323	-905

those consequences involve changes in agricultural prices and welfare. Prices and welfare fall, but these effects are reduced as producers anticipate and react to forthcoming El Niño and La Niña events. The projected changes of Timmermann et al. (1999) can be partly offset by producer reactions to ENSO information. Again, we caution that there is much uncertainty and controversy with regard to whether or how global climate change would affect ENSO. Our intent here was simply to consider the ENSO shifts as a "what if" scenario.

Implications

The importance of extreme events in the context of the impacts of climatic change and variability on agriculture has received increased attention in recent years. Extreme events and climate variability have documented impacts on agriculture. Farmers have many financial mechanisms with which to address variability and extreme events, ranging from crop insurance and savings to forward contracting, and an emerging market for weather derivatives. They also can change production practices to make themselves less vulnerable to variability. These mechanisms, however, cannot eliminate the real effects of variability on costs. Moreover, in the case of mechanisms such as insurance and forward markets, the costs of variability are merely pooled or spread, not eliminated or reduced. As demonstrated by analysis of possible changes in ENSO events, better forecasting can reduce the effects of increased variability, but it cannot eliminate all the additional costs. The greatest limitation in our understanding of the impacts of variability on agriculture is our very limited ability to predict how variability will change. Our knowledge regarding possible shifts in the frequencies of extreme events with a new climate regime is limited. Work also remains to be done to incorporate current information on changes in variability, as represented in climate models, into methods for assessing impacts on agriculture.

Investigators must distinguish among the relevant time scales and spatial scales of extreme events important to agriculture. In general, crop models adequately handle extreme events that are longer than their time scale of operation. For example, crop models operating on a daily time scale can simulate fairly well the effects of a seasonal drought (lasting a month or more), but they will have more difficulty properly simulating responses to very short-term extreme events, such as daily temperature or precipitation extremes. Another difficulty for crop models is properly representing composite extreme events such as a series of days with high temperatures combined with precipitation extremes. Therefore, in considering the possible effects of extremes and climate variability on crops from a policy point of view, extreme caution must be exercised in interpreting the analyses of climate models regarding what types of changes in extremes might occur in the future and in interpreting the responses of crop models to extreme climate events. Research in these areas is likely to continue to develop rapidly, however.

Although predicting the future climate with great accuracy is impossible, the analysis presented in this chapter provides an indication of the more-favorable and less-favorable future climates. For corn, a wetter and cooler climate is the more favorable; a hotter and drier climate is the less favorable than current climate, resulting in decreased yield and greater year-to-year yield variability A wetter and warmer climate would result in the greatest decrease in year-to-year yield variability; conversely, a drier and cooler climate would result in increased year-to-year yield variability. Sorghum year-to-year yield variability would be reduced most by a drier and warmer climate.

The US consumer wins in the case of a future climate with a change in the ENSO phase frequency and an ENSO phase frequency shift with a change in the strength of the phases. Agricultural producers, on the other hand, are losers as a result of lower prices for their crops. Foreign interests also lose. The United States generally is a winner when producers and consumers are considered.

This analysis does not include all of the potential effects of changes in climate; added together, these changes may have more profound effects on agricultural production than changes to the ENSO phase frequency and phase frequency shift. Again, the ENSO shifts are based on a single study, and much uncertainty remains about how global climate change would affect ENSO.

In summary, this chapter documents many of the ways in which variability can affect crops and how it may change in the future. The difference, in terms of agricultural productivity, between a moderate and even climate and one of extremes of hot and cold, wet and dry, can be stark. Challenges also remain for the agricultural assessment community in evaluating the impacts of variability changes.

Chapter 5

Agriculture and the Environment: Interactions with Climate

Introduction

Many previous assessments of the potential impacts of climate change and variability on agriculture have focused solely on agricultural production, food prices, and farm incomes. Our nation's interest in agriculture is broader than these issues, however. People in rural and urban areas value agricultural land as open space and a source of countryside amenities. Agricultural land is an important habitat for many remaining wildlife species. Agriculture also is a source of negative environmental impacts in some areas. Nutrients, pesticides, pathogens, salts, and eroded soils are leading causes of water quality problems in many parts of the United States. In many parts of the western United States, irrigated agriculture is a major user of scarce water resources. Our nation also has an interest in agriculture because of its potential to serve as a sink for greenhouse gases.

Agriculture has many environmental impacts—some occurring on the farm and others off the farm. For example, cultivation of crops increases the exposure of the land to the forces of wind and water erosion, which has on-farm and off-farm effects. Soil erosion reduces on-farm soil productivity by depleting soil nutrients and altering the structure of the soil in ways that reduce the soil's capacity to filter and hold water. Farmers bear the costs of lower soil productivity in the form of diminished production and sales. Thus, farmers can make economic decisions about how much of this productivity loss to avoid, given the costs of doing so. That is, farmers have a direct financial stake in the on-farm impacts of soil erosion and other environmental problems.

Off-farm environmental impacts of agricultural production, such as surface water sedimentation from eroded soils, are an entirely different matter. These impacts generally do not show up on any farmer's bottom line. Farmers may be as concerned about the environment as anyone else (or even more concerned), but expecting them to voluntarily reduce their own incomes for the sake of protecting the environment is asking a great deal—particularly when they have no reason to believe that their fellow farmers will follow suit or when the links between their individual actions and water quality are poorly understood. Off-farm environmental impacts have been a motivation for major federal conservation programs such as the Conservation Reserve Program (CRP), Environmental Quality Incentives Program (EQIP), and the Wetland Reserve Program (WRP), as well as voluntary conservation compliance that is based on farmers' assessment of the payments the programs offer for participation.

For these reasons, the off-farm environmental impacts of climate change could be more important from a public policy perspective than the impacts on agricultural production, food prices, or farm incomes. Farmers (as well as seed companies, fertilizer distributors, and other firms that sell products and services to farmers) will have strong financial incentives to adapt to climate change by minimizing negative impacts on production and exploiting positive impacts. For off-site effects of agricultural practices where environmental and conservation "goods" are not priced in markets, federal, state, and local governments will have to decide if environmental regulations must be strengthened if climate change worsens environmental problems.

Consideration of all potential agriculture-environment interactions and how they might be affected by climate change was beyond the scope of the agriculture assessment. Much more research and model development is needed on these interactions before the capacity exists to quantitatively and completely assess them. Whereas, relatively well-developed data on current conditions exist for market impacts, for environmental concerns we often have very incomplete information on the extent of current problems and their causes. We considered some specific case studies that help illuminate the environmental risks that climate change may present. In most cases, we sought to produce new, quantitative results with models that allowed us to simulate results using the Hadley and Canadian climate scenarios. The hazard with case studies is that the cases may not be representative of what might happen elsewhere or under different climate conditions. Indeed, many environmental problems depend on very specific and precise dimensions of climate. Erosion and runoff are highly nonlinear with rainfall intensity. There may be little or no erosion with moderate storm events; most erosion may occur during one or two extremely heavy and intense storms. Similarly, water recharge and water supply are highly dependent on the specific character of regional rain events.

We considered the relationship between agriculture and water quality in the Chesapeake Bay region (Abler, Shortle, and Carmichael 2000), potential changes in pesticide use that might occur as a result of changing climate (Chen and McCarl 2000), the interaction of urban and agriculture demand for groundwater in the Edwards' aquifer region near San Antonio, Texas (Chen, Gillig, and McCarl 2000), and the potential impacts of climate change on soils (Paul and Kimble 2000). These environmental issues are important in their own right. In addition, these environmental and conservation concerns are quite different from a physical, biological, economic, and policy perspective; they are illustrative of the range of environmental and conservation issues that would be affected by climate change.

The Chesapeake Bay has been seriously degraded over the years by agricultural production and other human activities. In the following section, we analyze the potential impacts of climate change on nutrient runoff into the Chesapeake Bay, based on new results from an integrated economic-environmental model of corn production in the Bay region. Nutrient runoff during heavy rainfall is the primary mode by which corn production affects the Bay. This dynamic is a case of an environmental externality related to agricultural production. There are no direct market incentives for farmers to control runoff of residues into the Bay. The Bay is an open-access, public resource.

In the next section, we examine the interaction between climate change and pesticide use. We address how changes in climate might alter pest populations and the costs of pest treatment. Decisions to control the effects of pests are internal to the farmer's decision making, and incentives to control pests are market-driven. Pesticide use raises many environmental concerns—such as residues on food, contamination of water, and consequences for wildlife. We therefore consider here the extent to which climate change could change the use of pesticides. We do not attempt to relate the change in pesticide use to particular changes in exposure of people or wildlife to these chemicals, nor do we consider all chemicals used on all crops. That would be an immense task. Attempts to estimate the relationship between current levels of chemical use and exposure levels are very uncertain. Even with known levels of exposure, the health and ecosystem effects are very uncertain. Nevertheless, we believe the results suggest the possible direction of the environmental effect.

In the next section we consider intersectoral water reallocation in the water scarce region around San Antonio, Texas. Groundwater is a resource that often is not well-managed, although recognition that uncontrolled access to groundwater will lead to excessive depletion has increasingly led states in arid regions of the country, which rely on groundwater, to step in and manage withdrawals. Drawdown of water levels in aquifers can have effects on wetlands and water levels in rivers and lakes, thereby threatening wildlife and recreation as well as increasing the cost of pumping water for urban and agricultural users. Climate change can affect the demand for water and the recharge rate of the aquifer.

In the final section of this chapter, we examine interactions between climate change and soil properties. We discuss many interactions of soil and climate, including the relationship between soil organic matter and climate. Soil organic matter consists largely of carbon; hence, the effects of climate on soil organic matter are a feedback into the climate system. Increases in soil organic matter reflect removal of carbon dioxide by plants and incorporation of the residue into the soil. Decomposition of organic matter, on the other hand, releases carbon into the atmosphere. The rate of decomposition versus incorporation of organic matter determines whether the soil of a given area is a net source or net sink for carbon. Increases in organic matter itself improve soil quality, provide a source of nutrients, and thus can improve crop productivity. The principal goal of this section, however, is to discuss the many ways that climate affects soil and hence the productivity and sustainability of agricultural production. Soil quality and crop productivity are largely on-site issues; farmers normally would have incentives to maintain soil quality in an economic manner. Considerable uncertainty about the cropping practices that best maintain soil and the long-term effect of existing practices remain. In view of this lack of information, there is a need for data, technical assistance, testing, and monitoring so that farmers can better manage their soils toward their own interest of maintaining the long-term profitability of their farm.

Agriculture and the Chesapeake Bay

In this section we examine agriculture in the Chesapeake Bay region as it exists today and as it might evolve in the first few decades of the 21st century. We also examine the potential impacts of climate change on agriculture and water quality in the Chesapeake region, based on new results from an integrated economic-environmental model of corn production.

We begin with an overview of the Chesapeake region; then we consider agriculture as it currently exists in the region, sketch a possible future for agriculture in the region, and identify how climate may change in the region. With this background, we then briefly describe the simulation model we developed and used to investigate the impacts of climate, present the principal results, and offer some implications for current decisions.

Introduction

The 64,000-square-mile Chesapeake Bay watershed is the largest estuary in the United States (Chesapeake Bay Program 1999). The watershed includes parts of New York, Pennsylvania, West Virginia, Delaware, Maryland, and Virginia, as well as the entire District of Columbia. More than 15 million people currently live in the Chesapeake Bay watershed.

The Chesapeake Bay is one of the nation's most valuable natural resources. It is a major source of seafood, particularly the highly valued blue crab and striped bass. It also is a major recreational area; boating, camping, crabbing, fishing, hunting, and swimming are all very popular and economically important activities. The Chesapeake and its surrounding watersheds provide a summer or winter home for many birds—including tundra swans, Canada geese, bald eagles, ospreys, and a wide variety of ducks. In total, the Chesapeake region is home to more than 3,000 species of plants and animals (Chesapeake Bay Program 1999).

Human activity within the Chesapeake Bay watershed during the past three centuries has had serious impacts on this ecologically rich area. Soil erosion and nutrient runoff from crop and livestock production have played major roles in the decline of the Chesapeake. The Chesapeake Bay Program (1997) estimates that agriculture accounts for about 39 percent of nitrogen loadings and about 49 percent of phosphorus loadings in the Bay. Thus, agriculture is the single largest contributor to nutrient pollution in the Chesapeake. Other contributors include sources such as wastewater, forests, urban areas, and atmospheric deposition.

Agriculture within the Chesapeake Bay region also is a major source of pollution, compared to agriculture in other parts of the country. Of 2,105 watersheds (defined at the 8-digit hydrologic unit code level) in the 48 contiguous states, watersheds in southern New York, northern Pennsylvania, southeastern Pennsylvania, western Maryland, and western Virginia rank in the top 10 percent in terms of manure nitrogen runoff, manure nitrogen leaching, manure nitrogen loadings from confined livestock operations, and soil loss from water erosion (Kellogg et al. 1997). Watersheds in southeastern Pennsylvania also rank in the top 10 percent in terms of nitrogen loadings from commercial fertilizer applications (Kellogg et al. 1997).

Agriculture in the Chesapeake Bay Region

Agriculture in the Chesapeake region is characterized by smaller farms and a wider range of crops and livestock products than in many other parts of the United States. Average farm size in the region is less than 200 acres, compared with more than 500 acres for the rest of the country (USDA National Agricultural Statistics Service 1999b). Poultry and hog operations within the region tend to be as large and intensive, however, as those in other parts of the country (USDA National Agricultural Statistics Service 1999b).

Major sources of farm cash receipts within the Chesapeake region include dairy products, poultry, eggs, hogs, mushrooms, other vegetable and nursery products, apples, and peaches. There also is significant production of corn, soybeans, and hay; these commodities, however, are mainly consumed on the farm as livestock feed rather than sold.

Crop production in the Chesapeake Bay region is overwhelming rainfed rather than irrigated. Less than 3 percent of crop acreage in the region is irrigated, compared with about 13 percent in the rest of the United States (USDA National Agricultural Statistics Service 1999b).

Forests are the largest category of land use in the Chesapeake region, accounting for about 60 percent of total land use. Agriculture is the second-largest category, accounting for nearly 30 percent of total land use. Urban areas, residential areas, wetlands, and other land uses account for the remainder. Production agriculture accounts for about 2 percent of the total labor force in the Chesapeake region.

Future Agriculture in the Chesapeake Bay Region

Agriculture in the Chesapeake region—like US agriculture as a whole—has changed radically during the past century, and there are few reasons to expect this rapid pace of change to slow. Tractors and other farm machinery have virtually eliminated the use of draft animals and enable a single farmer to cultivate tracts of land that are orders of magnitude larger than a century ago. The introduction of synthetic organic pesticides in the 1940s revolutionized the control of weeds and insects. Similarly, there has been tremendous growth in the use of manufactured fertilizers and hybrid seeds. Farmers have become highly specialized with regard to the livestock products and crops they produce; they also have become much more dependent on purchased inputs. Crops that were virtually unheard-of 100 years ago, such as soybeans, are of major importance today. As agricultural productivity has risen and as real (inflation-adjusted) prices of farm commodities have fallen, substantial acreage in the Chesapeake region has been taken out of agriculture and either returned to forest or converted to urban uses.

The basic science of biotechnology is progressing very rapidly; tens of millions of crop acres in the United States already have been planted with genetically modified organisms (GMOs). Plant biotechnology has the potential to develop crops with significantly greater resistance to many pests and greater resilience during periods of temperature and precipitation extremes—and even cereal varieties that fix atmospheric nitrogen in the same manner as legumes. Work also is underway to engineer pest vectors into beneficial insects as part of integrated pest management (IPM) strategies. GMOs with tolerance to specific herbicides also are being developed and released, and concerns have been raised that these new crops may promote herbicide usage.

Animal biotechnology has the potential to yield livestock that process feed more efficiently, leading to reduced feeding requirements and fewer nutrients in animal wastes. Feed also may be genetically modified to reduce nutrients in livestock wastes. Genetically engineered vaccines and drugs could significantly reduce livestock mortality and increase yields.

Another development already underway is precision agriculture, which uses remote-sensing, computer, and information technologies to achieve very precise control over agricultural input applications (e.g., chemicals, fertilizers, seeds). Precision agriculture has the potential to significantly increase agricultural productivity by giving farmers much greater control over microclimates and within-field variations in soil conditions, nutrients, and pest populations (National Research Council 1997). This technology may be accompanied by significant improvements in computer-based expert systems to aid farmers with production decision making (Plucknett and Winkelmann, 1996). The environment could benefit insofar as precision agriculture permits fertilizers and pesticides to be applied more precisely where they are needed at the times of the year when they are needed.

Future population increases in the Chesapeake Bay region may lead to additional conversion of farmland to residential and commercial uses. Future increases in per capita income could manifest themselves in larger homes and lot sizes and thus more residential land use—a tendency that has become evident over the past 30–40 years. Studies of land use confirm that population and per capita income are important determinants of conversion of farmland and forestland to urban uses (Hardie and Parks 1997; Bradshaw and Muller 1998). Probable futures for the spatial pattern of development within the Chesapeake region are more difficult to assess than an overall tendency toward urbanization. One possible future involves a "fill in" of areas between existing major urban centers, such as the area between Baltimore and Washington, D.C. (Bockstael and Bell 1998). Increases in per capita income also increase the demand for environmental quality.

Economic conditions facing agriculture in the Chesapeake Bay region can be expected to continue to change for many other reasons, including changes in global agricultural commodity prices and stricter environmental regulations toward agriculture (Abler and Shortle 2000). There probably will be fewer commercial crop and livestock farms within the region in the future than there are today, and some of the region's agricultural production will shift to other regions and countries (Abler and Shortle 2000). There may be growth in "weekend," "hobby," and other noncommercial farms within the region. Such farms, however, account for only a small fraction of total agricultural output. Production per farm and yields per acre on the remaining commercial farms within the Chesapeake Bay region also are likely to be significantly higher than they are today.

Future Climate in the Chesapeake Bay Region

Climate in the Chesapeake region also is likely to change. Climate projections for the region differ significantly, however, depending on the climate model used. Projections that use the Hadley and GENESIS models for the Mid-Atlantic region—which includes the Chesapeake Bay region—suggest increases in average daily minimum and maximum temperatures and increases in average annual precipitation (Polsky et al. 2001). Projections that use the Canadian model, however, suggest a much warmer and drier climate than the Hadley or GENESIS model (Polsky et al. 2001).

Predicting whether extreme weather events (such as droughts, floods, heat waves, hurricanes, ice storms, blizzards, and extreme cold spells) will occur more or less often is very difficult. Current trends for the mid-Atlantic region suggest a change toward fewer extreme temperatures but more-frequent severe thunderstorms and severe winter coastal storms (Yarnal 1999). Whether these trends will continue is unclear.

Simulation Model of Climate Change, Agriculture, and Water Quality

To assess the potential impacts of climate change on agriculture's contribution to water quality problems in the Chesapeake Bay region, we constructed a simulation model of corn production and nutrient loadings in six watersheds within the region. The model contains economic and environmental modules that link climate to productivity, production decisions by corn farmers, and nonpoint pollution loadings. Corn is an important crop to study because of its importance to the region's agriculture and because it is a major source of nutrient pollution; it accounts for more than half of all nonpoint nitrogen loadings. Corn is the most nitrogen-intensive of all major crops currently grown within the region. In addition, livestock farms within the region often dispose of manure on corn land.

The economic module projects the choices that farmers make with respect to the amount of land devoted to corn and the usage of fertilizer and other inputs into corn production. Precipitation, temperature, and atmospheric carbon dioxide levels affect the uptake of fertilizer and the productivity of land used in corn production. The economic module is based on previous economic models we constructed to examine nonpoint agricultural pollution (Abler and Shortle 1995; Shortle and Abler 1997). We calibrated the module to the six watersheds with available state-, county-, and watershed-level data on farm production, land use, nutrient applications, and other inputs. Details on the model and the results appear in Abler, Shortle, and Carmichael (2000).

Using the farmer decisions projected by the economic module, the environmental module projects nitrogen loadings from corn production within each of the six watersheds. The environmental module is based on the Generalized Watershed Loading Functions (GWLF) model (Haith et al. 1992). The GWLF model uses precipitation and temperature data, combined with data on land use, topography, and soil types, to estimate water runoff and pollutant concentrations flowing into streams from several types of land use, including corn. The GWLF model was calibrated to field conditions in the six watersheds by Chang, Evans, and Easterling (2000). The GWLF model projects nitrogen and phosphorous loadings. We found, however, that phosphorous loadings from corn production were very highly correlated with nitrogen loadings from corn production in each watershed. Thus, we focus here on nitrogen loadings.

The locations of the six watersheds (Clearfield Creek, Conodoquinet Creek, Juniata/Raystown River, Pequea Creek, Pine Creek, and Spring Creek) within the Chesapeake Bay region are shown in Figure 5.1. Statistics on land cover and land use for the watersheds are provided in Table 5.1, and statistics on nitrogen loadings are provided in Table 5.2. The watersheds are diverse in terms of the percentage of land devoted to agriculture as a whole and to corn. They are similar, however, in that agriculture accounts for the vast majority of nonpoint nitrogen loadings. Corn alone accounts for more than half of all nonpoint nitrogen loadings in each watershed. Across the six watersheds, corn accounts for an average of 69 percent of all nonpoint loadings.

In the simulation model, the weather is random in the sense that farmers do not know what temperature and precipitation during the growing season will turn out to be. Therefore they must make planting and production decisions on the basis of average (more precisely, expected) temperature and precipitation patterns. Farmers in the model are aware of climate change, however, in the sense that they know how average temperature and precipitation patterns are evolving over time in their area.

We consider three climate scenarios in the model. The first is present-day climate (temperature and precipitation averages for the 1965–1994 period), which serves to establish a reference point. The second climate scenario is based on projections from the Hadley climate model for the 2025–2034 period. The Hadley model suggests increases in average daily minimum and maximum temperatures and increases in average annual precipitation (Polsky et al. 2001). The third climate scenario is based on projections from the Canadian model for the

Chesapeake Bay Region and Study Watersheds

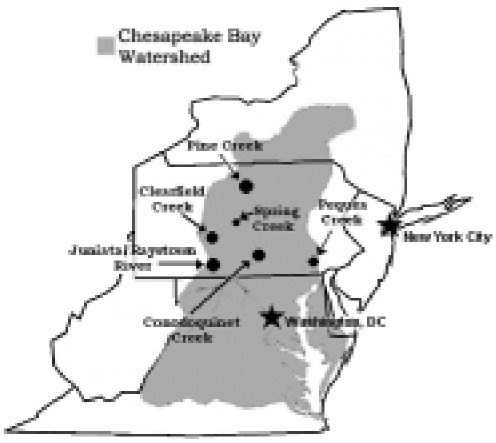


Figure 5.1: Sources: Chesapeake Bay Program (1997) and Chang, Evans, and Easterling (1999).

2025–2034 period. The Canadian model suggests a much warmer and drier climate than the Hadley model (Polsky et al. 2001). Because the weather is random in the model, the climate scenarios involve changes in the means and variances of the model's temperature and precipitation variables.

We also consider two future baseline scenarios in the model. These scenarios describe what might happen to corn production in the Chesapeake Bay region in coming decades independent of climate change. Shortle, Abler, and Fisher (1999) discuss procedures to use in constructing future baseline scenarios. These procedures develop scenarios that establish probable upper and lower bounds on economic and environmental impacts. Although pinpointing the exact magnitude of an impact is

Table 5.1. Land Cover/Use in the Six Study Watersheds

Watershed	Land Area (1,000 acres)			Percentage of Total Land Area	
	Total	**All Agriculture**	**Corn**	**All Agriculture**	**Corn**
Clearfield Creek	240	33	8	14	3
Conodoquinet	321	199	24	62	7
Juniata/ Raystown	458	154	40	34	9
Pequea Creek	98	70	9	71	9
Pine Creek	629	66	27	11	4
Spring Creek	44	21	13	49	31
All Six Watersheds	1,789	543	120	30	7

Table 5.2. Nonpoint Nitrogen Loadings in the Six Study Watersheds

Watershed	Nonpoint Inorganic Nitrogen Loadings (1,000 pounds)			Percentage of Total Nonpoint Nitrogen Loadings	
	Total	**All Agriculture**	**Corn**	**All Agriculture**	**Corn**
Clearfield Creek	2,057	1,852	1,453	90	71
Conodoquinet	5,102	5,023	2,914	98	57
Juniata/ Raystown	4,359	4,261	3,661	98	84
Pequea Creek	1,335	1,327	940	99	70
Pine Creek	1,623	1,317	981	81	60
Spring Creek	709	697	587	98	83
All Six Watersheds	15,192	14,481	10,536	95	69

Note: Figures for six watersheds may not add to column totals in the row because of rounding.
Sources: Chang, Evans, and Easterling (1999) and authors' own calculations.

impossible, we can say that the impact is likely to fall within a certain range.

With an eye toward establishing probable upper and lower bounds on changes in nitrogen loadings from corn production in the Chesapeake region between now and the 2025–2034 period, we consider two future baseline scenarios. These two scenarios—a continuation of the status quo (SQ) and an "environmentally friendly," smaller agriculture (EFS)—are detailed in Table 5.3. The EFS scenario is much more probable than any scenario approximating a continuation of the status quo, but both scenarios are needed to establish probable bounds on climate change impacts. The EFS scenario establishes a lower bound on any increase in nitrogen loadings resulting from climate change because biotechnology and precision agriculture help to minimize loadings from any given level of agricultural production. In addition, stricter environmental regulations in the EFS scenario lead farmers to adopt less nitrogen-intensive corn production practices. None of these factors occurs in the SQ scenario; therefore, the SQ scenario establishes an upper bound on increases in nitrogen loadings resulting from climate change.

With three climate scenarios and two future baseline scenarios, we must analyze a total of six scenario combinations. Because the weather is random, we analyzed each combination by using a Monte Carlo experiment in which we took 100,000 random draws for the model's temperature and precipitation variables. Each of these random draws could be considered an alternative possible growing season within a particular climate scenario. The results are the means of 100,000 random draws.

Results from the Simulation Model

Results from the simulation model for each watershed and for the six watersheds as a whole are presented in Table 5.4. Results for the six watersheds as a whole also are illustrated in Figure 5.2. The results for the SQ baseline scenario suggest that climate change could lead to significant increases in nitrogen loadings from corn production. For the six watersheds as a whole, nitrogen loadings are more than 3 million pounds higher in the Hadley climate scenario than with the present-day climate—an increase of 31 percent. In the Canadian climate scenario, nitrogen loadings for the six watersheds as a

Table 5.3. Baseline Agricultural Scenarios for the 2025–2034 Period

Scenario	Scenario Details[a]
"Environmentally Friendly," Smaller Agriculture (EFS)	• Significant decline in corn production in Chesapeake Bay region • Significant decrease in number of commercial corn farms in region • Substantial increase in agricultural productivity via biotechnology and precision agriculture • Major increase in corn production per farm and corn yields on remaining commercial farms • Significant decrease in agriculture's sensitivity to climate variability through biotechnology and precision agriculture • Continued conversion of agricultural land to urban uses, with some abandonment of unprofitable agricultural land • Significant decrease in commercial fertilizer and pesticide usage through biotechnology • Less runoff and leaching of agricultural nutrients and pesticides via precision agriculture • Stricter environmental regulations facing agriculture
Status Quo (SQ)	• Agriculture as it exists today in the Chesapeake Bay region

[a]Note: For greater detail, see Abler, Shortle, and Carmichael (2000).

whole are nearly 2 millions pounds higher than with the present-day climate—an increase of 17 percent.

The results for the EFS baseline scenario, on the other hand, suggest that climate change would lead to more modest increases in nitrogen loadings from corn production. For the six watersheds as a whole, nitrogen loadings are about 400,000 pounds higher in the Hadley climate model scenario than with the present-day climate, an increase of 19 percent. In the Canadian climate model, nitrogen loadings for the six watersheds as a whole are about 200,000 pounds higher than with the present-day climate—an increase of only 8 percent.

The results for the SQ and EFS baseline scenarios differ significantly in part because the EFS scenario starts from a much lower level than the SQ scenario. Under the present-day climate, total loadings for the six watersheds as a whole are about 2 million pounds in the EFS scenario, as opposed to more than 10 million pounds in the SQ scenario. Many forces cause fertilizer usage and environmental impacts to be much lower in the EFS scenario than in the SQ scenario. The results for the SQ and EFS scenarios also differ because agriculture is less climate-sensitive in the EFS scenario than in the SQ scenario.

The SQ and EFS baseline scenarios are in agreement, however, regarding the direction of change in nitrogen loadings from corn production. In both scenarios, climate change leads to increases in loadings. In percentage terms, the increase for the six watersheds as a whole ranges from 8 percent (EFS scenario/Canadian climate model) to 31 percent (SQ scenario/Hadley climate model).

Loadings increase because climate change makes corn production in the six watersheds more economically attractive. As corn production becomes economically more attractive, farmers devote more

Nitrogen Loadings from Corn Production

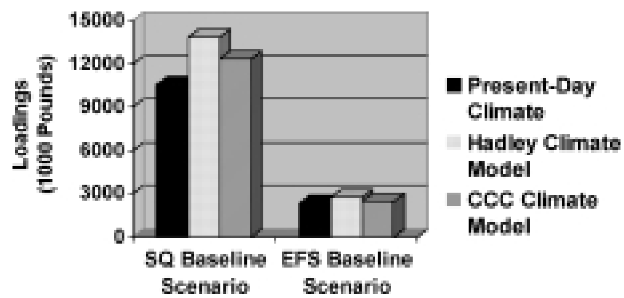


Figure 5.2: Nitrogen loadings from corn production for the six watersheds are presented here for the continuation of status quo (SQ) baseline scenario and the environmentally friendly (EFS) baseline scenario.

Table 5.4. Nitrogen Loadings from Corn Production under Alternative Scenarios (1,000 pounds)

Watershed	Baseline/Climate Scenario Combination					
	SQ			EFS		
	Present-Day Climate	Hadley Climate Model	Canadian Climate Model	Present-Day Climate	Hadley Climate Model	Canadian Climate Model
Clearfield Creek	1,453	1,913	1,710	313	374	340
Conodoquinet	2,914	3,835	3,426	629	750	681
Juniata/ Raystown	3,661	4,803	4,294	788	938	855
Pequea Creek	940	1,242	1,108	203	243	221
Pine Creek	981	1,285	1,150	211	251	229
Spring Creek	587	771	689	126	151	137
All Six Watersheds	10,536	13,848	12,377	2,270	2,706	2,462

Note: Figures for each scenario are averages across 100,000 random samples. Figures for six watersheds may not add to column totals in the row because of rounding.

land to corn compared with the baseline (no climate change) and increase their use of inputs per acre to raise yields. As they take these steps, their usage of nitrogen fertilizer increases—leading to increases in nitrogen loadings.

Leaving aside for a moment the economic responses by farmers, the increase in growth potential of corn because of climate change in and of itself leads to greater uptake of nitrogen by crops, leaving less nitrogen to run off into surface waters or leach into groundwater. To take full economic advantage of the growth potential of crops, however, farmers apply more nitrogen fertilizer. These increased nitrogen applications result in overall greater nitrogen loadings.

In the Hadley climate model scenarios, nitrogen loadings also increase because average precipitation during the growing season increases—washing more nutrients into streams, rivers, and groundwater. In the Canadian climate model scenarios, on the other hand, average precipitation during the growing season falls. Nevertheless, because of the increased nitrogen applications by farmers in response to the yield effects of climate change, nitrogen loadings from corn production still increase in the Canadian climate model scenarios.

Pesticide Use and Climate

An open issue in the climate change arena involves the following question: How might changes in climate alter pest populations and, in turn, the costs of pest treatment? We use an approach that is similar to that employed by Mendelsohn, Nordhaus, and Shaw (1994). In that study, the authors used geographic variation to consider the implications of climate for land values and to draw conclusions from the statistical model for projected changes of climate in the future. We statistically estimate a relationship between pesticide costs and climatic conditions. We use the estimated statistical model to consider the impact of future climate change on pesticide costs. We estimated a panel data version of the production function laid out by Just and Pope (1978) that allowed us to estimate average pesticide costs and the variance of pesticide costs. For more detail, see Chen and McCarl (2000).

State-level pesticide usage for corn, wheat, cotton, soybeans, and potatoes was drawn from USDA (1991-1997; 1999a). These data give statistical survey-based averages for various insecticide, herbicide, and fungicide compounds by crop and year. The states for which data were available vary by crop; they are listed in Table 5.5. We computed a total cost of pesticides by multiplying the pesticide use by category by annual prices from the USDA (1997). We use aggregate total cost data to reflect pesticide substitution as climate and pesticide prices vary. Climate data were drawn from the US National Oceanographic and Atmospheric Administration (NOAA, 1999). Rainfall data were cropping year totals, to reflect not only cropping season supply but also water stored in soil or irrigation delivery systems. Temperature data were the March–September average for all crops except for winter wheat areas. In winter wheat areas, we used October–April temperature data. We derived state-level temperature and rainfall data by averaging all data for weather stations in a region.

Table 5.5. States for Which Pesticide Data Are Available by Crop

Crop	State
Corn	IL, IN, IA, MI, MN, MO, NE, OH, SD, WI
Cotton	AZ, AR, CA, LA, MS, TX
Soybeans	AR, IL, IN, IA, LA, MN, MS, MO, NE, OH, TN
Wheat	CO, ID, KS, MN, MT, ND, NE, OK, OR, SD, TX, WA
Potatoes	CO, ID, ME, MI, MN, NY, ND, OR, PA, WA, WI

Results

The estimated impacts of rainfall and temperature on pesticide cost and its variability by climate are displayed in Tables 5.6 through 5.9. The estimation results in Table 5.6 show the relationship between pesticide usage costs and climate. Table 5.7 contains the computed percentage change in cost resulting from the percentage change in climate characteristics, using the data in Table 5.6. The impacts of precipitation on pesticide usage cost for these five crops are all positive and significant, except for cotton. This result indicates that increased rainfall increases pesticide costs. For example, when rainfall increases by 1 percent, we compute that corn pesticide costs increase by 1.49 percent. We find mixed effects from temperature. A 1 percent temperature increase (measured in degrees Fahrenheit) increases pesticide costs for potatoes by 2.67 percent. Pesticide costs for corn, cotton, and soybeans also increase with temperature, but wheat costs decrease.

The impacts of climate on the variability of pesticide usage cost are more complicated (see Tables 5.8 and 5.9). We found that a hotter temperature increased the variance of pesticide cost for corn, cotton, and potatoes but decreased the cost variance for soybeans and wheat. For example, a 1 percent increase in temperature will increase the year-to-year cost variance for corn by 6.96 percent. A rainfall increase also increases the pesticide cost variability for cotton but decreases the variance for soybeans, wheat, and potatoes.

Under a warmer and wetter climate (and given the estimated relationships), we generally would expect climate change to increase pesticide use. Some regions may have less rainfall, however, and not all crops show positive relationships between the climate variables and pesticide usage. For perspective, then, we used the regional estimates of the Canadian and Hadley climate scenarios for 2090 to obtain estimates of the effects of projected climate change on pesticide usage cost for selected crops in selected regions (Table 5.10). The results for states with significant production of each crop are given in Table 5.10. They show increases in pesticide use on corn generally in the range of 10–20 percent, on potatoes of 5–15 percent, and on soybeans and cotton of 2–5 percent. The results for wheat varied widely by

Table 5.6. Regression Results for Effects of Climate on Per Acre Pesticide Cost

Crop	Precipitation	Temperature	Constant
Corn	0.7351 (25.85)	0.9222 (19.00)	–30.183 (–11.30)
Cotton	0.0059 (0.26)	0.9730 (8.39)	–17.213 (–2.27)
Soybeans	0.0632 (3.78)	0.5523 (13.22)	32.343 (15.04)
Wheat	0.1211 (29.25)	–0.1160 (–21.30)	7.7950 (24.41)
Potatoes	1.3684 (22.76)	2.5914 (11.99)	–89.564 (–7.54)

Note: Temperature is measured in degrees Fahrenheit and rainfall is measured in inches. T-statistics in parentheses indicate significance of all estimates except for cotton, where precipitation and temperature coefficients are insignificant at 5 percent level.

Table 5.7. Percentage Change in Pesticide Cost for a 1 Percent Change in Average Climate Measures

Crop	Precipitation	Temperature
Corn	1.49	1.87
Cotton	–	1.94
Soybeans	0.09	0.78
Wheat	2.86	–2.74
Potatoes	1.41	2.67

Note: Percentage change for pesticide cost is computed by dividing coefficient parameters in Table 5.6 by US average pesticide cost for a crop across all years and places. Results are computed only for estimated parameters with t ratios that exceed 1.9. Temperature percentage change is based on degrees Fahrenheit; rainfall percentage is based on inches.

state and climate scenario, with changes ranging from approximately –15 percent to +15 percent.

Pesticides and Climate: Some Conclusions and Limitations

Regional pesticide cost data show systematic variations that can be related to climate characteristics. Average per-acre pesticide usage costs for corn, soybeans, wheat, and potatoes increase as precipitation increases. Similarly, average pesticide usage costs for corn, cotton, soybeans, and potatoes increase as temperature increases, although the pesticide usage cost for wheat decreases. Climate also affects the year-to-year variability of pesticide cost. More rainfall decreases the variability of pesticide costs for soybeans, wheat, and potatoes but increases the variability of pesticide costs for cotton. Increased temperature reduces the variability of pesticide cost for soybeans and wheat but increases it for corn, cotton, and potatoes.

This study is one of the first investigations of the relationship of pests and climate, conducted so that the results could be integrated into an economic assessment. There are several limitations in the study. For example, we do not consider how altered CO_2 could effect pests. Moreover, the approach considers how pesticide use changes but not how pest damage itself changes, implicitly assuming that the cost implications of any change in pests is fully captured by changes in pesticide expenditures. In general, statistical analyses are limited by data availability in their ability to capture some of the detailed structural interactions or to trace increased pesticide use to specific pest infestations—in this case, specific pesticides that have different environmental consequences. Projections of changes in pesticide use under future climates are highly speculative because few areas of agriculture change as rapidly as pesticides. Pests can quickly develop resistance to particular control methods, and new control methods are developed. In the future, pest resistance may be increasingly introduced directly into crops. Nevertheless, these results indicate that for most of the crops we considered and for most locations, the future climate is likely to increase pest problems and create the need for more effective control methods. The environmental implications clearly will depend on the types of methods developed to control pests. The likelihood of increased pest problems creates an added incentive to ensure that pest control methods that do not create environmental harm are developed and used.

Table 5.8. Regression Results on Influence of Climate on Variance of Pesticide Usage Cost

Crop	Precipitation	Temperature	Constant
Corn	-0.0008	0.1179	-6.2453
	(-0.22)	(19.56)	(-19.93)
Cotton	0.0093	0.0497	-2.1377
	(4.03)	(3.65)	(-2.42)
Soybeans	-0.0190	-0.0500	4.4399
	(-7.52)	(-8.96)	(16.33)
Wheat	-0.0489	-0.0225	0.4838
	(-25.45)	(-7.15)	(2.83)
Potatoes	-0.0372	0.1273	-3.4946
	(-12.00)	(8.25)	(-4.02)

Note: Temperature is measured in degrees Fahrenheit and rainfall is measured in inches.

Table 5.9. Percentage Change in Variance of Pesticide Usage Cost for a One percent Change in Average Climate Measures

Crop	Precipitation	Temperature
Corn	–	6.96
Cotton	0.39	3.44
Soybeans	-0.83	-3.20
Wheat	-1.33	-1.34
Potatoes	-1.15	7.14

Note: Percentage change for pesticide variability cost is computed by multiplying coefficient parameters in Table 5.8 by average precipitation and temperature across all years and places. Results are computed only for estimated parameters with t ratios that exceed 1.9. Temperature percentage change is based on degrees Fahrenheit and rainfall percentage is based on inches.

Effects of Climatic Change on a Water-Dependent Regional Economy: A Study of the Edwards Aquifer

Global climate change portends shifts in water demand and availability. In areas where water already is a severely limited resource, potential reductions in supply can pose significant questions with regard to allocation of the remaining resource. Agriculture is the major user of water in most regions. In this section we summarize the results of an analysis we carried out as a part of this assessment (described in greater detail in Chen, Gillig, and McCarl 2000). The study examines the implications of climate change projections for the San Antonio, Texas, Edwards Aquifer (EA) region, concentrating on the economy and the water use pattern.

We begin with a discussion of the Edwards Aquifer area; we then provide a summary of the methods we used to estimate the various impacts of climate on water use in the region, describe the model and methods we used to consider the implications of these effects for the region, discuss the results, and offer some broader conclusions on the basis of the study.

The Edwards Aquifer

The Edwards Aquifer supplies the needs of municipal, agricultural, industrial, military, and recreational users. The Edwards Aquifer is a karstic aquifer. A karstic aquifer is one that has many characteristics in common with a river. Annual recharge over the period 1934–1996 averaged 658,200 acre feet; discharge averaged 668,700 acre feet (USGS 1997). Edwards Aquifer discharge is through pumping and artesian spring discharge. Pumping rose by 1

Table 5.10. Percentage Increase in Crop Pesticide Usage Cost from Reference Levels for Year 2090, by Scenario

	Canadian Climate Change Scenario					Hadley Climate Change Scenario				
	Corn	Soybeans	Cotton	Wheat	Potatoes	Corn	Soybeans	Cotton	Wheat	Potatoes
CA			5.16					4.69		
CO				-10.29	7.33				9.15	13.25
GA			4.23					2.66		
ID					21.03					15.42
IL	18.19	3.26				14.23	2.00			
IN	10.01	2.72				15.07	2.04			
IA	26.07	3.94				15.66	2.17			
KS				13.60					12.93	
LA			5.36					3.12		
MN		2.25			8.10		1.90			9.67
MT				-9.85					6.28	
MS			5.83					3.01		
ND					5.54					10.67
NE	3.35	2.69		-14.54		10.72	2.16		5.83	
OK				-3.48					12.34	
SD	17.08			8.88		14.73			13.96	
TX			5.41	-8.78				3.15	0.81	
WA					13.19					10.68

percent per year in the 1970s and 1980s (Collinge et al. 1993) and now accounts for 70 percent of total discharge. Pumping in the western Edwards Aquifer is largely agricultural (AG), whereas eastern pumping is mainly municipal and industrial (M&I). Spring discharge—mainly from San Marcos and Comal springs in the east—supports a habitat for endangered species (Longley 1992), provides water for recreational use, and serves as an important supply source for water users in the Guadalupe-Blanco river system. The aquifer is now under pumping limitations as a result of actions by the Texas Legislature and because of a successful suit by the Sierra Club to protect endangered species (Bunton 1996).

Reduced water availability or increased water demand because of climate change could exacerbate the regional problems that arise in dealing with water scarcity. This study utilizes an existing Edwards Aquifer hydrological and economic systems model known as Edwards Aquifer Simulation Model (EDSIM) (McCarl et al. 1998), to examine the implications of climate-induced changes in recharge and water demand.

Effects of Climatic Change in the Edwards Aquifer Region

The Canadian and Hadley model results for the Edwards Aquifer region climate are listed in Table 5.11. Changes in regional climatic conditions would alter water demand and supply. An increase in temperature would cause an increase in water demand for irrigation and municipal use but would also increase evaporation lowering runoff and in turn Edwards Aquifer recharge. A decrease in rainfall would increase crop and municipal water demand, lower the profitability of dryland farming, and reduce available water for recharge.

Table 5.11. Projected Percentage Climate Changes for Edwards Aquifer Region, by Scenario

Climate Change Scenario	Temperature (°F)	Precipitation
Hadley 2030	3.20	-4.10
Hadley 2090	9.01	-0.78
Canadian 2030	5.41	-14.36
Canadian 2090	14.61	-4.56

Recharge Implications

To project climatic change effects on Edwards Aquifer recharge, we used regression analysis to estimate the effects of alternative levels of temperature and precipitation on historically observed recharge. We drew US Geological Survey (USGS) estimates of historical recharge data by county from the Edwards Aquifer Authority annual reports for the years 1950–1996. We obtained county climate data for the same years from the Office of the Texas State Climatologist and a University of Utah Web page. We concluded that the preferred regression model for this data set was a log-linear model. The significant recharge regressions coefficients all exhibited the expected sign. Summary measures of the effect of the projected climate changes on annual recharge for the years 2030 and 2090 under different climate scenarios are displayed at the top of Table 5.12; these data show that the projected climate change causes large reductions in recharge for drought years (21–33 percent) and wet years (24–49 percent).

Municipal Water Use Implications

Griffin and Chang (1991) present estimates on how municipal water demand is shifted by changes in temperature and precipitation. In particular, they estimate the percentage increase in municipal water demand for a 1 percent increase in the number of days that temperature exceeds 90°F and precipitation falls below 0.25 inches. To obtain the anticipated shifts for the 2030 and 2090 climate conditions, we took the daily climate record from 1950 to 1996 and adjusted it by altering the original temperature and precipitation by the projected climate shifts from the climate simulators. We then recomputed the municipal water demand accordingly. The results are given in Table 5.12; the forecast climate change increases municipal water demand by 1.5–3.5 percent.

Crop Yields and Irrigation Water Use

Changes in climatic conditions influence crop yields for irrigated and dryland crops, as well as irrigation crop water requirements. For this study, we estimated the shift in water use and yield under projected climate changes by using the Blaney-Criddle (BC) procedure (Heims and Luckey 1983; Doorenbos and Pruitt 1977, following Dillon 1991). In particular, we used the BC procedure to alter yields and water use for the nine recharge/weather states of nature present in the EDSIM model, an economic and hydrological simulation model of the Edwards Aquifer region (McCarl et al. 1998). Summary measures of the resultant effects are presented in Table 5.12; the data show a decrease in crop and vegetable yields and an increase in water requirements. For example, under the Hadley scenario in 2090, the irrigated corn yield decreases by 3.47 percent, whereas the irrigation water requirement increases by 31.32 percent.

Methods for Developing Regional Impact

These effects were combined in EDSIM. The model depicts pumping use by the agricultural, industrial, and municipal sectors while simultaneously calculating pumping lift, ending elevation, and springflow. EDSIM simulates the choice of regional water use, irrigated versus dryland production, and irrigation delivery system (sprinkler or furrow) such that overall regional economic value is maximized. Regional value is derived from a combination of perfectly elastic demand for agricultural products, agricultural production costs, price-elastic municipal demand, price-elastic industrial demand, and lift-sensitive pumping costs.

In terms of its implementation, EDSIM is a mathematical programming model that employs two-stage stochastic programming with recourse formulation. The multiple stages in the model depict the uncertainty inherent in regional water-use decision

Table 5.12. Selected Effects in Terms of Percentage Changes from Base Scenario

	Hadley		Canadian	
	2030	2090	2030	2090
Recharge in drought year	-20.6	-32.9	-29.7	-32.0
Recharge in normal year	-19.7	-33.5	-29.0	-36.2
Recharge in wet year	-23.6	-41.5	-34.4	-48.9
Municipal Water demand	1.5	2.5	1.9	3.5
Irrigated Corn Yield	-1.9	-3.5	-4.3	-5.6
Irrigated Corn Water Use	12.0	31.3	23.5	54.0
Dryland Corn Yield	-3.9	-6.8	-8.2	-10.8
Irrigated Sorghum Yield	-1.8	-3.4	-2.8	-4.2
Irrigated Sorghum Water Use	15.1	38.2	42.7	79.4
Dryland Sorghum Yield	-5.9	-13.1	-10.8	-16.8
Irrigated Cotton Yield	-9.1	-15.8	-19.8	-24.6
Irrigated Cotton Water Use	16.9	40.8	34.6	71.5
Dryland Cotton Yield	-7.1	-11.6	-14.0	-17.8
Irrigated Cantaloupe Yield	-1.3	-2.3	-2.9	-3.6
Irrigated Cantaloupe Water Use	19.0	46.5	41.4	82.7
Irrigated Cabbage Yield	-5.6	-12.1	-9.6	-14.7
Irrigated Cabbage Water Use	14.8	31.0	36.4	71.3

making. Many water-related decisions are made before water availability is known. For example, the decision about whether to irrigate a particular parcel of land and the choice of crops to put on that parcel are decided early in the year, whereas the true magnitude of recharge is not known until much later in the year.[1]

Model Experimentation, Regional Results, and Discussion

We considered five scenarios in this study:

- base without climatic change
- change projected by the Hadley model for the year 2030
- change projected by the Canadian model for the year 2030
- change projected by the Hadley model for 2090
- change projected by the Canadian model for 2090.

Table 5.13 displays EDSIM results on the economic and hydrological effects of climate change under the base scenario as actual values; results under the other scenarios are displayed as a percentage change from the base results. The total water usage is held less than or equal to a 400,000 acre-feet pumping limit mandated by the Texas Senate for years after 2008. Under the base condition, agriculture uses 38 percent of total pumping, and M&I pumping usage accounts for the rest. Total welfare for the region is $355.69 million—$11.39 million from agricultural farm income and $337.65 million from M&I surplus. In addition, $6.64 million accrues to the Edwards Aquifer Authority for the water-use permits. This authority surplus can be regarded as rents to water rights to use some of the 400,000 acre-feet available. Comal and San Marcos springflows are 379.5 and 92.8 thousand acre-feet, respectively—greater than recent average historical levels.

The strongest effect of climate change falls on springflow and the agricultural sector. Under the climatic change scenarios, the Comal (the most sensitive spring) springflows decrease by 10–16 percent in 2030 and by 20–24 percent in 2090. This change could require additional springflow protection (see below). In terms of agriculture, the change results in a reallocation of water away from agriculture. It adds to the cost of pumping because the water must be pumped from greater depths, and it increases water demand for irrigation because of higher temperatures and less rainfall. Overall yields are lower. The result is a reduction in farm income of 16–30 percent in 2030 and 30–45 percent in 2090. Regionally, income falls by $2.8–5 million per year in 2030 and $5.8–8.8 dollars in 2090. The projected shift in agricultural water to M&I indicates that city users are purchasing water that otherwise is allocated to agriculture through water markets.

Despite an increase in M&I water use, the M&I surplus decreases because of an increase in pumping costs that result from an increase in pumping lift deriving from lower recharge. In contrast to the welfare decrease for agricultural and nonagricultural pumping users, rents to the authority or water permits increases by 5–24 percent. The increased demand for water increases water permit prices. Water use in the nonagricultural sector is less variable, and a shift to that sector actually makes water use slightly greater—with corresponding decreases in springflow.

The large reduction in springflow would put endangered species in the spring emergence areas in additional peril. The projected climate change therefore would require a lower pumping limit to offer the same level of protection for the springs, endangered species, and other environmental amenities now provided by the 400,000 acre-foot limit. Table 5.14 presents the results of an examination of the pumping limit that would be needed to preserve the same level of Comal and San Marcos springflows as in the current situation. The results indicate that a decrease in the Edwards Aquifer pumping limit of 35,000–50,000 acre-feet in 2030 and 55,000–75,000 acre-feet in 2090 would be needed. These further

[1]This uncertainty may be best illustrated by referring to the Irrigation Suspension Program implemented by the Edwards Aquifer authority: Early in the year an irrigation buyout was pursued, but the year turned out to be quite wet in terms of recharge.

Table 5.13 Aquifer Regional Results under Alternative Climate Change Scenarios

		Base	2030		2090	
Variable	Units	Value	Hadley (%)	Canadian (%)	Hadley (%)	Canadian (%)
AG Water Use[a]	1000 af	150	-0.9	-1.4	-2.4	-4.2
M&I Water Use[b]	1000 af	250	0.6	0.9	1.5	2.6
Total Water Use[c]	1000 af	400	0.1	0.1	0.1	0.1
Net AG Income[d]	$1,000	11391	-15.9	-29.4	-30.3	-45.0
Net M&I Surplus[e]	$1,000	337657	-0.2	-0.4	-0.6	-0.9
Authority Surplus[f]	$1,000	6644	3.8	7.1	12.7	21.6
Net Total Welfare[g]	$1,000	355692	-0.6	-1.2	-1.3	-1.9
Comal Flow[h]	1000 af	379.5	-10.0	-16.6	-20.2	-24.2
San Marcos Flow[i]	1000 af	92.8	-5.1	-8.3	-10.1	-12.1

a Agricultural water use.
b Municipal and industrial water use.
c Total water use, including agricultural and nonagricultural water use.
d Net farmer income.
e Net municipal and industrial surplus.
f Surplus accruing to pumping or springflow limit.
g Net total welfare, including agricultural and nonagricultural welfare.
h Comal springflow.
i San Marcos springflow.

Table 5.14. Results of Analysis on Needed Pumping Limit to Preserve Springflows at Base, without Climate Change Levels

		Base	2030		2090	
Variable	Units	Value	Hadley (%)	Canadian (%)	Hadley (%)	Canadian (%)
Pumping Limit	1000 af	400	365	350	345	320
AG Water Use	1000 af	150	-16.5	-22.7	-23.7	-46.1
M&I Water Use	1000 af	249	-4.0	-6.3	-7.7	-4.3
Total Water Use	1000 af	400	-8.7	-12.5	-13.7	-20.0
Net AG Income	$1,000	11391	-18.4	-33.4	-34.6	-58.3
Net M&I Surplus	$1,000	337657	-0.8	-1.3	-1.9	-1.9
Authority Surplus	$1,000	6644	32.3	52.5	73.7	68.3
Net Total Welfare	$1,000	355692	-0.8	-1.4	-1.6	-2.5
Comal Flow	1000 af	379.5	1.5	0.5	1.2	-1.1
San Marcos Flow	1000 af	92.8	-0.3	-1.1	-1.1	-2.5

Note: Pumping limit under each scenario represents amount of water restriction in Edwards Aquifer regions.

decreases in pumping impose substantial additional economic costs beyond those imposed by climate change alone; welfare would fall by $0.5–0.9 million in 2030 and $1.1–1.9 million in 2090. The additional pumping reduction causes a large impact on agriculture and a substantial municipal cutback.

Concluding Remarks

Changes in climatic conditions projected by the Canadian and Hadley models cause a reduction in available water resources, as well as a demand increase in the Edwards Aquifer region. The change largely manifests itself in reduced springflows and a smaller regional agricultural sector. The regional welfare loss was estimated to be $2.2–6.8 million per year. If springflows are to be maintained at the currently desired level to protect endangered species, pumping must be reduced by 10–20 percent below the limit currently set, at an additional cost of $0.5–2 million per year.

Global Climate Change: Interactions with Soil Properties

Soil and Society

Soil processes operate on time scales that range from thousands of years (e.g., breakdown of rock substrate) to hours (e.g., erosion). For much of North America, the climate is naturally highly variable, and this variability has punished us badly when we have not been good stewards of the land. Land abandonment after excess growth of cotton in the Southeast, the loss of soil fertility and acidification in the Northeast, and the dust bowl of the Prairies can be attributed to soil management practices. These instances stem from failure to recognize soil as a resource that is subject to degradation and failure to develop practices that maintain soil under climate conditions that vary from decade to decade.

Atmospheric Constituents and Soil Processes

Carbon, nitrogen, oxygen, and hydrogen are the building blocks of life on earth. They also are the most important constituents of soil organic matter. The earth's carbon and nitrogen cycles have the ability to restore and even increase soil organic matter content and tilth if properly established scientific principles are applied to implement good land stewardship and sustainable agriculture during a time of global change.

Global change scenarios are associated most often with projected increases in temperature and climate instability associated with increased atmospheric concentration of gases of carbon and nitrogen. These radiative gases consist of CO_2, CH_4, and N_2O, which are produced by microbial activities in soils, sediments, surface waters, and animal digestive systems or through the burning of fossil fuels. Soil microorganisms produce CO_2 by breaking down plant and animal residues in environments that contain oxygen. This process returns to the air the

Table 5.15. Trends in US Greenhouse Gas Emissions (MMT carbon equivalents)

Category	1990	1996
CO_2		
Fossil fuel combustion	1,330	1,450
Other industrial sources	20	20
CH_4		
Transportation and industry	60	60
Land use and agriculture	50	50
Landfills and waste	60	70
N_2O		
Transportation and industry	30	30
Land use and agriculture	65	70
HFCs, PFCs, SF_6	20	35
Total	**1,635**	**1,785**

Source: US Environmental Protection Agency.

carbon that has been fixed by photosynthesis and in the past has kept the carbon cycle in near balance. Where oxygen is lacking—such as in peat bogs, rice fields, and the stomachs of ruminants—methane (CH_4) is produced instead of CO_2.

Soil inorganic nitrogen is produced when microorganisms "burn off" the carbon of plant and animal residues or organic matter in their never-ceasing search for energy. Other microorganisms oxidize, by the nitrification process, inorganic nitrogen that is produced on mineralization or added as fertilizer. This process is leaky and produces N_2O. The oxidized form of nitrogen, NO_3, that is produced during nitrification can again be reduced under anaerobic processes where there is no oxygen. This process also can result in N_2O leakage to the atmosphere.

Methane is 20 times as effective as CO_2 in retaining atmospheric heat; N_2O is 300 times as effective as CO_2. The relative effect of these gases in causing greenhouse effects is best seen by expressing the emissions as carbon equivalents. In 1996, the United States released 1,450 million metric tons (MMT) of carbon into the atmosphere from fossil fuel consumption. This amount is less than one-tenth of the amount released annually from our soils by decomposition; the carbon of decomposition is offset, however, by a nearly equal amount of photosynthesis, whereas the equivalent of about one-half of the carbon from fossil fuels accumulates in the atmosphere.

A total of 180 MMT of CH_4 in carbon equivalents using 100-year Global Warming Potentials (GWPs) is released from US transportation, industry, wetlands, landfills, and waste. Aerobic terrestrial sites absorb CH_4, but cultivated, fertilized soils consume only about one-quarter that of undisturbed sites and wildlands. Agriculture is the predominant source of N_2O; transportation and industry supply about one-third as much as agriculture. All soils release some N_2O, but highly managed soils release more than wildlands (especially if they have trees). CO_2 is increasing in the atmosphere at 0.5 percent per year; CH_4 is increasing at 0.75 percent, and N_2O is increasing at 0.75 percent.

The clearing of forests, the draining of wetlands, and the plowing of prairies for agriculture led to significant increases in atmospheric CO_2 as organic carbon was decomposed. The carbon content of most agricultural soils is now about one-third less than it was in its native condition as either forest or grassland. Using computer simulation models of cropland in the central United States, Bruce et al. (1998) suggest that soil carbon losses have diminished and soils are starting to accumulate carbon again, reversing the trend of carbon loss that had occurred since cultivation began. This reversal has come about through higher yields, the return of greater proportions of crop residue to the land, conservation tillage such as cover crops, and no till (Lal et al. 1998). The return of considerable acreage to grass in conservation reserve programs and to trees in afforestation of formerly plowed lands also is returning atmospheric CO_2 to the land. The eastern United States now has 110 million acres of afforested lands that are storing carbon (Fan et al. 1998). This carbon storage occurs as tree growth and in increased soil organic matter contents (Morris 2001). The other greenhouse gases—CH_4 and N_2O—also can be removed from the air by soil microorganisms. Improved pastures and cover crops on cultivated land lower the amount of inorganic nitrogen in soil and can lower atmospheric radiative gases. Higher-quality cattle feeds can reduce CH_4 emissions from domestic livestock.

Soil-Biological and Chemical Interactions in Global Change

A large number of agronomic-ecological interactions could occur in a world with more CO_2, higher temperatures, and a more variable climate. There is a great diversity of soil organisms, many of which have similar functions and general decomposition reactions. This situation enables us to project the future effects of changes in soil temperature and moisture on the basis of overall controls that apply to most soil types within a major climatic area. Climate change and accompanying extreme events undoubtedly will alter soil microbial populations and diversity. Over time, populations of soil biota can adapt, although cataclysmic occurrences such as floods and erosion will affect the diversity of microbial populations in local areas.

The CO_2 content of soil is higher than that of the atmosphere; atmospheric concentrations of CO_2 are not expected to directly alter soil nutrient cycling. Indirect effects have to be considered, however. The additional available substrate—the symbiotic partners consisting of nitrogen fixers such as rhizobia and mycorrhizal fungi—may be able to obtain a greater food supply and grow more effectively, with a consequent benefit to the plant, although the benefits vary depending on the fungi type. This process could be especially important in forests and native grasslands that are not normally fertilized as they adapt to global change.

Plants are more sensitive than microorganisms to specific temperatures. Increased temperature will move the growth requirements of specific plants 200–300 km north for each degree Celsius rise in temperature (equivalent to 60–90 miles for each degree Fahrenheit). This factor, along with breeding for cold tolerance, is moving the Corn Belt into the Prairie provinces of Canada. Insect activity of cold-sensitive insects has been observed to move northward with even the slight rise in measured temperatures that scientists have observed recently. With increased temperatures, we may see cold-temperature soil pathogens and weeds as well as fire ants in areas of what is now the Corn Belt, although pest interactions with climate and weather depend on a variety of factors, including moisture and weather variability.

Many soils contain inorganic carbon as carbonates. The pedogenic phases of these compounds can release and sequester CO_2. Agriculture is acidifying in nature; on some soils it requires the addition of lime, which on solubilization releases CO_2 to the atmosphere. Soils with carbonate horizons are common in arid and semi-arid regions. Calcium is added as lime through deposition of wind-blown dust and during weathering of parent materials. This calcium reacts with CO_2, based on the carbonate-bicarbonate (HCO_3^-) reactions, to produce carbonates. Soil inorganic carbon constitutes approximately 1,700 Pg C in the surface layers. This amount is similar to values for organic carbon (Nordt et al. 2000); soil inorganic carbon is being leached out of soils at an estimated rate of 0.25 Pg per year, whereas rivers are thought to transfer 0.42 Pg C to the oceans annually—providing a net CO_2 sink. Although irrigation water releases some trapped CO_2, researchers estimate that on a worldwide basis soils sequester 0.16–0.27 Pg C yr^{-1} of atmospheric CO_2 (Holland 1978; Bouwman and Lemans 1995).

Soil formation will be slowly altered by changes in moisture and temperature. The United States is now receiving 10 percent more rainfall than in previous decades. If this increase were to continue over hundreds of years, higher moisture and temperature would result in deeper profiles with more clay eluviation to lower horizons. These effects are slow and will be overshadowed by changes in management or erosion. A single extreme event, over the course of 24 hours, can erode away soil that would take hundreds of years to form, with the amount eroded highly dependent on management practices. The Dust Bowl of the 1930s is one such example. Agriculture has changed drastically since then, in response to the damage caused; nevertheless, precautions are needed in susceptible areas where multiple-year droughts, associated poor crops, and high winds could again combine to create conditions for severe wind erosion (regardless of whether this erosion is associated with specific climate change events).

Flooding affects agricultural and nonagricultural areas. For example, a wetter climate in California with increased temperatures—as occurs in the Hadley and Canadian scenarios—and more oceanic evaporation could result in massive soil movement (as in soil slippage) and local flooding from more severe local storms. Lal et al. (1998) estimate that 0.5 Pg C yr^{-1} are lost from local soils by erosion. Although much of this soil is deposited within associated landscapes, 20 percent is thought to be lost to the atmosphere through accelerated decomposition. The fate of the transported carbon is not well-known, however; Trimble (1999) estimates that recent water erosion is only one-sixth as severe as the erosion that occurred during the early years of agriculture in the Midwest.

Erosion and leaching can move extensive nutrients to rivers and eventually to estuaries. These nutrients—especially nitrogen and phosphorous—can create local high-nutrient and thus anoxic events, with serious pollution and local fish kills. This situation now exists in the Mississippi Delta and the Gulf of Mexico, as well as the Chesapeake Bay. The contribution of agriculture to such pollution must be determined. Potential nutrient losses in a climate-change scenario also must be considered. Nutrient management will have to include lower inputs on nitrogen and phosphorus and more containment of local floodwaters so nutrients can soak back into the land. It also must consider the effects of extensive concentrations of human and animal waste products on small land areas. This concentration removes nutrients from areas where crops are grown and often concentrates them in erosion- and flood-prone areas, with the potential for eutrophication and local contamination if flooding increases with climate change.

Soil Organic Matter and Global Change

Organic matter constitutes 1–8 percent of most soils (by weight) and nearly all of the dry weight of organic soils such as peats. Because of the great weight of soils to the plant rooting depth at which carbon accumulates, the world's soils store 1,670,000 MMT (16.7 Pg) of carbon. This amount represents a carbon storage capacity that is twice that of the atmosphere. The annual global rate of photosynthesis generally is balanced by decomposition; the annual flux is about one-tenth of the carbon in the atmosphere or one-twentieth of the carbon in soils. The United States accounts for about 5 percent of this storage; because of its higher proportion of peat soils, Canada accounts for up to 17 percent (Lal et al. 1998).

Soil carbon is composed of a wide range of compounds that decompose at different rates depending on their chemistry, the soil temperature and moisture, which organisms are present, the association with soil minerals, and the extent of aggregation (Paul et al. 1996). Plant residues in agricultural soils do not represent a large storage pool; their management influences water penetration, erosion, and the extent of formation of soil organic matter—thus affecting long-term soil fertility and carbon storage.

Decomposition by soil organisms is relatively insensitive to dryness on an annual basis. Most soils have some periods of time when decomposition can occur. Decomposition is very sensitive to excess wetness, however, which causes anaerobiosis. In the past, this decomposition has created high–organic-matter peat soils. Changes in moisture content resulted in increased decomposition of soil organic matter when the millions of acres of wetlands in the Corn Belt were tile drained (Lal et al. 1998). Warmer temperatures often are associated with drier climates. Researchers have postulated that this relationship greatly affects peat soils that contain so much of North America's soil organic carbon. Drying of peat soils to below water saturation would greatly increase decomposition rates and CO_2 evolution to the atmosphere. Water saturation of soils is controlled as much by drainage and topography as by rainfall and temperature. Projections that are based on temperature and rainfall alone will not necessarily be valid relative to decomposition in peats. One can control the soil moisture of tile-drained soils in the winter by controlling (plugging) tile drainage flows. This plugging creates temporary wetlands and thus retards decomposition. It should have the additional benefit of decreasing nitrates and possibly pesticides in the groundwater, as well as helping in flood control. Wetland restoration in general has potential for future carbon sequestration—providing greater diversity and havens for wildlife and reducing nitrates in ground water. It will lead to some increases in methane, however, and possibly N_2O evolution from flooded soils.

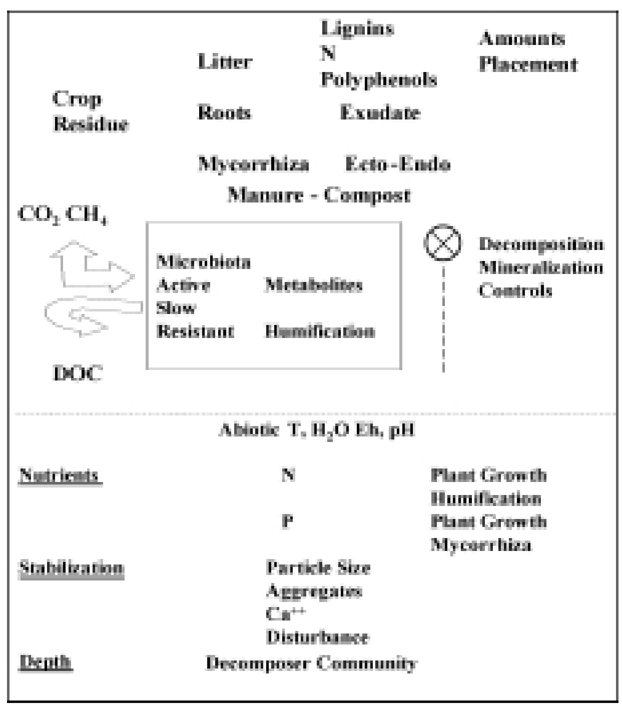
Grasslands contain approximately one-fifth of the world's global carbon reserves; many of the world's grasslands have been degraded by overgrazing. This overgrazing has resulted in a loss of plant cover, reduced protection against wind and water erosion, and loss of production potential. Soil organic matter degradation in such conditions has contributed to the rise in atmospheric CO_2. Grazing and other management practices that lower overgrazing have the potential to increase global carbon sequestration substantially (0.46 Pg C yr^{-1}). This management also should result in increased methane utilization. Fertilizer nitrogen is one suggested means—along with better grazing management—of increasing grassland production and soil carbon sequestration. Production of nitrogen fertilizer uses fossil fuels, however, and application of fertilizer could lead to increased N_2O evolution. Closer coupling of grazing with intense animal-feeding operations that returns nutrients for pasture improvement would greatly reduce problems with pollution when excess rainfall causes flooding.

The increased CO_2 in the atmosphere probably has enabled farmers to greatly increase yields through plant breeding, fertilizer additions, and pest control. The continued increase in plant yield of 1.25 percent per year (Reilly and Fuglie 1998) will produce a similar increase in the crop residue applied to soils. At equivalent nitrogen levels, production of carbohydrates and possibly lignin and polyphenols will increase. Polyphenols should slow down decomposition rates and help build organic matter. The changed composition of leaves and roots will affect the insects and microbiota that feed on plant parts. These insects are a part of a complex food web, often involving numerous layers of predators; thus, the insect response to CO_2 should be considered in climate change scenarios.

The large size of the soil carbon pools and their slow turnover rate mean that they are fairly well buffered against change and that short-term effects—unless they involve erosion and thus removal of carbon from the landscape—do not have immediate effects. Normally, 7–15 years of management effects would be required to produce measurable differences in carbon and associated soil fertility and soil tilth. The large size of the carbon pool and the fact that soil carbon is very unevenly distributed across the landscape make accurate measurement of any changes that occur over a few years very difficult.

Total soil carbon is very difficult to measure with the accuracy required for decision making in global change calculations. Soil heterogeneity and changes in bulk density further confound the problem of measuring short-term changes in soil organic matter. Calculation of soil carbon sequestration must be based on long-term plots that have been under a specific plant management scheme for 10–30 years. Soil fractions that are sensitive indicators of soil carbon changes are best used in conjunction with modeling that is based on a knowledge of the controls on soil carbon dynamics (Figure 5.4). This approach enables researchers to project the effect of specific management on other soil types and landscape areas.

Figure 5.3 Controls on Soil Carbon Turnover and Accumulation



Indicators that have been useful for estimating soil carbon include the light fraction obtained by floating soil in water or a more dense liquid. This light fraction reflects partially decomposed plant residues that make up a portion of the active fraction of soil organic matter. The microbial biomass that feeds on the residues and on the active and slow fraction of soil organic matter is another measurable fraction that changes rapidly enough to be an indicator of total changes.

The partially altered plant materials that are held within aggregates and thus slowly decompose over a period of years constitute part of the slow fraction that is so essential to soil fertility. This fraction—known as particulate organic matter—can be measured by disrupting the aggregates; it has potential as an indicator of the overall size of the slow pool in management for sustainable agriculture and in carbon sequestration calculations. Laboratory incubations of soils from various management treatments on different soil types and under representative climatic conditions enable the natural population of soil fauna and soil microorganisms to decompose the different available fractions over time. Analysis of CO_2 evolution curves enables researchers to determine the size and turnover rate of the active fraction and the slow fraction if the size of the resistant pool has previously been determined.

The foregoing biophysical techniques are best utilized on well-documented and characterized long-term plots with known management histories, where total carbon and soil bulk density can be measured to the rooting depth. If these plots are representative of the different soil types, climate, and management, mathematical models can project the carbon content of other soils as well as the landscape. Projections of future carbon levels are based on modeling that utilizes information from long-term plots. Continuation of research on long-term plots, together with measurements on an array of well-distributed validation plots would enable researchers to plan new approaches and support policy decisions that must be made as we adapt to global change.

Soils in a North American Context

The warming of North America is noticeable already in increased growing seasons and the northward movement of the limits of corn and soybean growth. The Corn Belt may move into the Canadian Prairies. The soils of northern parts of Minnesota, Wisconsin, Michigan, New York, Vermont, and Maine could be utilized for corn, soybeans, and specialty crops. The present soils in these areas are not especially fertile; from an agroforestry viewpoint and from the aspect of removal of carbon from the atmosphere, they might better be left in trees. Canada does not have a great deal of potentially useful agricultural land in the east, unless the climate becomes so warm that Hudson Bay lowlands would be suitable for agriculture. Warming of western Canada will produce more agricultural land. Alberta and northern British Columbia could develop significant underutilized acreage that would be far from markets.

Sandy soils are much more sensitive to climatic fluctuations than loams and clay soils. Fortunately, many drought-sensitive, sandy soils of the Great Plains already have been removed from cultivation. Public policy as well as management by individual operators should continue to protect these fragile soils. The extent and distribution of rainfall is the greatest unknown in future climate scenarios. Researchers project that because of higher temperatures there will be more moisture in the atmosphere and thus more rainfall on land. What is not known is where this moisture will fall. Warm periods generally have been associated with drought on the prairies. If that relationship continues to be the case, increased decomposition of soil organic matter because of higher temperatures will be offset somewhat by decreased decomposition from lower moisture.

Field Validation

The overall requirements for soil organic matter research and field validation of the role of soil carbon in global change are as follows:

- Provide analytical background and knowledge concerning the effects of agronomic management on different soil types to project and model their effect on soil organic matter contents and other greenhouse gases.

- Establish benchmark sites, on a national level, that can provide verification of treatment effects. This effort requires field measurements, under different management, of soil types and climates that are representative of most agricultural production; these measurements must be accurate enough that possible future CO_2 emission debits/credits can be validated.
- Provide national inventories of soil carbon storage and fluxes of CO_2, N_2O, and CH_4 into and out of soils.
- Participate with available informational systems—such as industry consultants and university and government extension systems—to provide necessary information to the public and the agricultural industry concerning the present and future role of soils in global change.

Adapting to Global Change: Policy Implications

Agriculture has had and will continue to have the ability to adapt to new conditions. The ability to change with a changing climate will depend on a strong research base that can supply required information. Some of the areas that may benefit most are as follows:

- Crops vary in their response to enriched CO_2 in several growth characteristics. Research that utilizes plant breeding and molecular techniques in conjunction with studies of physiological responses to increased CO_2 would increase productivity. It also would result in increased crop residue additions to the soil. Improved soil organic matter levels will sequester CO_2, enhance sustainability and reduce soil erosion. Similar techniques could be used to produce plants with increased roots and biological nitrogen fixation, as well as plants with higher capacities to take up nutrients through more efficient mycorrhyza.
- Increased phenolic and lignin contents of plant residues could decrease decomposition rates and result in more crop residues at the surface. They also should enhance the formation of slow and resistant carbon pools that are important to carbon storage. The growth of more perennial crops could have many benefits, especially when such crops are utilized as a biological, non-fossil fuel energy supply.
- Irrigation efficiency could be improved. Increased oceanic temperatures should result in more rainfall overall. This rainfall could be utilized more efficiently by drip irrigation, water harvesting, and other techniques.
- Farmers should develop more-efficient nitrogen and phosphorus fertilizer usage, especially in flood-prone areas. Precision farming holds promise for better nutrient control and pesticide application. The nitrogen, phosphorus, silicon, and carbon cycles need to be considered in an ecosystem context.
- The movement of intensive animal feeding operations to the source of the animal feeds would enhance the placement of nutrients and organic residues back on the soil and stop the development of these facilities on flood-prone areas.
- Increased soil organic matter would store more atmospheric carbon and result in greater soil fertility, better soil tilth, and greater water-holding capacity. It also would make plant/soil systems more stress-resistant and thus better able to withstand the greater projected climatic fluctuations.
- Control of water levels on hydric soils when crops are not being grown could result in carbon sequestration, improved water quality, flood control, and better wildlife habitat. Potential losses of CH_4 and N_2O would have to be avoided.
- Soil pathogen and pest control in a warmer, often more humid climate would have to be considered in future management scenarios.

- Agricultural research and practice should work to improve pasture management for better carbon sequestration.
- The agriculture sector should integrate farm woodlots and riparian strips into overall land management and farm policy programs that enhance water quality and offer a positive response to global change.

Conclusions

Each of the cases presented in this chapter offers specific conclusions. In addition, five broader conclusions also emerge. First, environmental impacts can be highly dependent on the specific character of climate change. For the Chesapeake Bay, nitrogen loadings from corn production in the Chesapeake region differ significantly depending on whether the Hadley or Canadian climate scenarios is used. Similarly, Chen, Gillig, and McCarl (2000) find that available water resources in the Edwards Aquifer region of Texas differ significantly depending on whether they use projections from the Hadley model or the Canadian model. In the Chesapeake Bay region and the Edwards Aquifer region, the Hadley model projects more precipitation and less warming than the Canadian climate scenario.

Second, environmental impacts also are highly dependent on the ability of crops to productively use higher atmospheric levels of CO_2. The optimistic conclusion for soils is that climate change could enhance agricultural sustainability, increase water-holding capacity, and reduce soil erosion depends on increases in crop growth as a result of additional CO_2. Results for the Chesapeake Bay region that show increased nitrogen loadings from corn production also hinge on crop responses to additional CO_2. In and of itself, a higher level of CO_2 increases nitrogen uptake by corn plants, leaving less nitrogen to run off into surface waters or leach into groundwater. Higher levels of CO_2 may make corn production in the Chesapeake region economically more attractive. If corn production becomes more attractive, farmers may devote more land to corn and increase their use of inputs per acre to raise yields. If they do these things, their usage of nitrogen fertilizer may increase, leading to increases in nitrogen loadings.

Third, additional research is needed on interactions between climate, agriculture, and the environment. The vast majority of research on climate change and agriculture to date has focused on agricultural production impacts. Very little work has been done on how climate change might affect the environmental impacts of agricultural production and land use. Given the magnitudes of environmental effects in many areas of the country, this area should be a high priority for research. In addition, research is needed to understand climate impacts on agriculture's contributions to wildlife habitat, rural landscape amenities, and carbon sequestration.

Fourth, particular effort is needed to investigate the potential for changes in extreme events and their consequent environmental effects. Current climate models do not adequately represent extreme weather events such as floods or heavy downpours that can wash large amounts of fertilizers, pesticides, and animal manure into surface waters. Changes in extreme events could easily overwhelm the environmental effects of changes in average levels of precipitation or temperature, as well as the effects of changing atmospheric CO_2 levels.

Fifth, many of these environmental and conservation concerns involve nonmarket, off-farm effects and require actions by local, regional, or federal governments if these resources are to be protected. The first step in many cases is that adequate measures are needed to protect environmental resources under current climate conditions. Climate change may mean that managers must be prepared to adapt protection measures if climate change makes them inadequate. The Chesapeake Bay study indicates that current management of these resources may be inadequate. The long-term quality of these resources may be affected by climate change, but improving agricultural practices under current climate would offer significant improvement under the current climate. Such changes also greatly reduce pollution under both climate change scenarios we considered. The other side of this story is illustrated in the Edwards Aquifer study: A pumping limit imposed with the expectation of maintaining the health of ecosystems and protecting endangered species may prove inadequate by a significant margin if the climate changes projected by the scenarios we considered come to pass.

Chapter 6 Conclusions and Implications

Introduction

This study was conducted as part of a National Assessment effort that was designed to evaluate the impacts of climate change and climate variability on the United States across its various regions and including sectors beyond agriculture. We set out to understand the potential implications of climate change for agriculture. In chapter 1 we provided an overview of the goals of the assessment and a broad-brush portrait of forces shaping US agriculture over the past 100 years, where US agriculture finds itself today, and some of the major forces that will shape agriculture into the next century. In chapter 2 we reviewed previous studies on the impacts of climate change on agriculture, including some of the key findings, how the literature has developed, and where some of the major gaps remain.

We reported the substantive new work of the agriculture sector assessment in chapters 3 through 5. In chapter 3 we considered the impacts of future climate change on production agriculture and the US economy. We reported a series of crop modeling studies that examine in detail the impacts of climate change on crop yield, with the intent of providing a representative estimate of climate impacts on US crop yields under two climate scenarios for climates: with a CO_2 concentration projected to represent the decade of the 2030s and the 2090s. We then combined these results with estimates of changes in water supply, pesticide expenditures, livestock, and international trade resulting from climate change to understand the combined impacts on the US agricultural economy, resource use, and the distribution of impacts in the United States by producer and consumer and by region.

In chapter 4 we considered the question of climate variability and extreme events, the chance that climate change may cause the probability of extreme events to change, and the potential consequences for agriculture. Many books discuss climate variability, yield variability, and how farmers cope with variability apart from climate change. Crop insurance, futures markets, weather derivatives, and technological options such as irrigation, storage facilities, and shelter for livestock are intricate parts of the agricultural system because of weather variability. In no way have we covered this broad literature; we have tried to understand the extent to which climate change could exacerbate or reduce variability.

The subject of chapter 5 was one of the poorly researched areas of climate impacts on agriculture: the arena of environmental and resource implications. Soil erosion, the fate of chemical residuals, and the quality and quantity of soil and water resources are highly dependent on climatic conditions. In chapter 5 we began the process of examining some of these interactions. We focused on some case studies to illustrate the issues and problems that could arise as we try to manage resource use and agriculture's relationship with the environment under a changing climate. We examined the upper portion of the Chesapeake Bay drainage area that extends through Maryland, Delaware, and Pennsylvania; the San Antonio, Texas, area where the Edward's Aquifer provides most of the water supply; pesticide use and its relationship to climate; and the direct impact of climate on soil. This list leaves many problems unexplored, including issues such as soil erosion, the potential for climate to change the level of pollutants such as ozone that are detrimental to crops, the interaction of agriculture with wildlife habitat, livestock waste issues, and many others.

One of the goals of the assessment has been to respond directly to questions that stakeholders felt were important. A considerable gap remains between the questions of the stakeholder community with whom we interacted and the answers we were able to provide. Answering many of these questions would require a modeling capability and precision that we do not possess. The most fundamentally difficult conceptual problem is to represent completely the dynamics of social, economic, and physical interactions in their full complexity. If we could understand and model these dynamics, we could address issues such as when climate change will begin to affect the agricultural sector, when it will be noticed, by whom, and how they will react to it. As individuals, organizations, and local governments react—or not—how will the reactions change the relative economic position of one farm versus another or one region versus another? Almost any change provides an opportunity for people who are prepared for it and adjust early—and a threat for those who fail to adjust. Technological change—a force that generally improves economic performance—creates losers along with winners. Although pollution regulation usually is regarded as increasing the cost of production in the industries targeted, it can create winners among companies that have or can create innovative solutions to meet the environmental regulation, allowing them to win market share against their slower-to-respond rivals. Regardless of whether climate change generally improves agricultural productivity in the United States—as projected in the scenarios we investigated—or leads to losses in productivity, as some previous forecasts have projected, there will be winners and losers.

In this chapter we review our principal findings and try to draw out the implications of these findings for adaptation and adjustment. We make only a small start in this direction. In this regard, the research and assessment team we assembled for the task of assessing climate impacts on agriculture was best suited to describing the impacts of climate change. Understanding what to do requires a far more detailed engagement of those who are directly involved—the farmers, legislators, research managers, government program managers, and local communities who will be affected and whose incomes, livelihoods, and jobs are on the line. Thus, this report is a start in that process, from a team of researchers. We organize this chapter to answer the four questions we identified in Chapter 1:

- What are the key stresses and issues facing agriculture?
- How will climate change and climate variability exacerbate or ameliorate current stresses?
- What are the research priorities that are most important to fill knowledge gaps?
- What coping options exist that can build resiliency into the system?

Key Stresses and Issues

Agricultural production is very diverse. This diversity bespeaks an industry that is undergoing rapid change. The enterprise of farming appears to have divided into several broad categories, and the stresses facing each group are different. Most commodities are produced on large commercial farms with large revenues, whose operators rely principally on the farm as a source of income, and who earn a family income above the average of the US household. A second group of farm operators run small farms where net income from the farm is very small or negative; the income of the household is determined by off-farm earnings of household members. Another group of farmers are near retirement or in semi-retirement. Farmers in this group typically own outright all the land they operate; in fact, they may rent most of their land or have it enrolled in a long-term easement program such as the Conservation Reserve Program, which pays farmers of highly erodible land to maintain permanent cover on the land. A fourth group comprises farmers who own mid-sized farms (chapter 1).

The important features of future agriculture are more like "forces" than "stresses." At least in common parlance, stress connotes a negative effect. Change in agriculture has proved to be an opportunity for some farmers, although it threatens the financial survival of others. In this regard, we identify four broad forces that will shape the future for American agriculture over the next few decades (see chapter 1):

- Changing technology. Biotechnology and precision agriculture are likely to revolutionize agriculture over the next few decades—much as mechanization, chemicals, and plant breeding revolutionized agriculture over the past century—although public concerns and environmental risks of genetically modified organisms could slow development and adoption of crops and livestock containing them. Biotechnology has the potential to improve adaptability, increase resistance to heat and drought, and change crop maturation schedules. Biotechnology also will give rise to entirely new streams of products and allow the interchange of characteristics among crops. Precision farming—the incorporation of information technology (e.g., computers and satellite technology) in agriculture—will improve farmers' ability to manage resources and adapt more rapidly to changing conditions.

- Global food production and the global marketplace. Increasing linkages are the rule among suppliers around the world. These links are developing in response to the need to assure a regular and diverse product supply to consumers. Meat consumption is likely to increase in poorer nations as their wealth increases, which will place greater pressure on resources. Climate change could exacerbate these resource problems. Trade policy, trade disputes (e.g., over genetically modified organisms), and the development of intellectual property rights (or not) across the world could have strong effects on how international agriculture and the pattern of trade develops.
- Industrialization of agriculture. The accelerating flow of information and the development of cropping systems that can be applied across the world will transcend national boundaries. Market forces are encouraging various forms of vertical integration among producers, processors, and suppliers, all of whom are driven, in part, to produce uniform products and assure supply despite local variations induced by weather or other events.
- Environmental performance. The environmental performance of agriculture is likely to be a growing public concern in the future, and it will require changes in production practices. Significant environmental and resource concerns related to agriculture include water quality degradation resulting from soil erosion, nutrient loading, pesticide contamination, and irrigation-related environmental problems; land subsidence resulting from aquifer drawdown; degraded freshwater ecosystem habitats resulting from irrigation demand for water; coastal water degradation from run-off and erosion; water quality and odor problems related to livestock waste and confined livestock operations; pesticides and food safety; biodiversity impacts from landscape change (in terms of habitat and germplasm); air quality, particularly particulate emissions; and landscape protection. Tropospheric ozone is increasingly recognized as an industrial/urban pollutant that negatively affects crops. Agricultural use of land also can provide open space; habitat for many species; and, with proper management, a sink for carbon. These positive environmental aspects are likely to be valued increasingly highly.

Climate Change and Current Stresses

Climate change is unlikely to alter the driving forces of agriculture over the next century in any fundamental way (see chapter 1). Regional relocation and response to climate variability has been a part of agriculture over the past century (chapter 1). We cannot predict the specific consequences of climate change with great detail (chapter 2). The regional and resource impacts of climate change may vary considerably (chapter 3). The new quantitative work we undertook confirmed in many ways the broad results of previous studies (reviewed in chapter 2). We therefore have reached the following conclusions:

- The next 100 years. Over the next 100 years and probably beyond, human-induced climate change as currently modeled is unlikely to seriously imperil aggregate food and fiber production in the US, nor will it greatly increase the aggregate cost of agricultural production. Our quantitative results—which are based on newer climate scenarios and include a broader range of impacts, including effects of CO_2 fertilization, changes in water resource, pesticide expenditures, and livestock—confirm the emerging consensus in the literature and, if anything, suggest significantly more positive results than previous studies (chapter 2, chapter 3).

- Regional effects. There are likely to be strong regional production effects within the United States; some areas will suffer significant loss of comparative (if not absolute) advantage to other regions of the country. In the scenarios we evaluated the Lake states, the Mountain states, and the Pacific region showed gains in production, whereas the Southeast, the Delta, the Southern Plains, and Appalachia generally lost. Results in the Corn Belt were generally positive. Results in other regions were mixed, depending on the climate scenario and time period. The regional results show broadly that climate change favors northern areas and can worsen conditions in southern areas—a result shown by many previous studies (chapter 2, chapter 3).

- Global markets. Global market effects can have important implications for the economic impacts of climate change. The position of the United States in the world agricultural economy as both a significant food consumer and exporter means that changes in production outside the United States lead to consumer benefits from lower prices that roughly balance producer losses. The situation is reversed if global production changes cause world prices to rise. As a result, the net effect on the US economy did not change much under different global impact assumptions. The main effect was to change the distribution of impacts among producers and consumers. We were unable to conduct a new assessment of impacts on the rest of the world. Trade scenarios drawn from previous work showed both small increases and decreases in world prices (chapter 2, chapter 3)

- Effects on producers and consumers. Effects on producers and consumers often are in opposite directions, which often is responsible for the small net effect on the economy. In the Canadian climate scenario, the absolute effects on producers and consumers were nearly balanced. In relative terms, the $4–5 billion losses to producers in the Canadian scenario represent a 13–17 percent loss of producers income, whereas the gains of $9–14 billion to consumers in the Hadley scenarios represent only a 1.1–1.3 percent gain in consumer welfare. These losses to producers are substantial; to place these figures in context, however, a good comparison is historical changes in land values—the asset that ultimately would be affected by changes in climate. In the early 1980's farmland values fell by 50 percent. Losses because of climate change are projected over the course of three to four decades or more and thus would likely inflict far lower adjustment costs than experienced in the early 1980's (chapter 2, chapter 3).

- Adaptation. US agriculture is a competitive, adaptive, and responsive industry that will adapt to climate change; all of the assessments we have reviewed have factored adaptation into the assessment (chapter 2). Adaptation improved results substantially under the Canadian scenario but much less so under the Hadley scenario, in which climate change was quite beneficial to productivity without adaptation (chapter 3).

- Policy environment. The agriculture and resource policy environment can affect adaptation. This conclusion is based primarily on our review of the literature. We did not extensively consider the policy environment and its impact on adaptation in the new work we conducted. Among the policies to consider are water markets, agricultural commodity programs, crop insurance, and disaster assistance (chapter 1, chapter 2)

Several limitations have been present in past assessments (chapter 2). We addressed some of the most serious of these limitations:

- We used more realistic "transient" climate scenarios that simulated gradual climate change as a result of gradually increased atmospheric

CO_2 and included the cooling effect of sulfate aerosols.

- Past studies have often considered only the major grain crops. We considered a broader set of crops including vegetable and fruit crops. We also considered livestock, pasture, and grazing effects.
- We used site-level crop model results combined with a spatial equilibrium economic model to generate national and regional results that included more than a dozen crops. We compared this approach with other approaches that had less crop detail but had other strengths. We investigated trade links and implications by using sensitivity analysis, based on previous estimates of impacts around the world.
- Previous studies have not considered changes in variability. We examined scenarios of change in variability and implications for the agricultural economy, as well as the extent to which climate is a factor in existing variability in crop yields.
- We considered a more complete interaction of effects such as changes in water resources and pesticide expenditures on production agriculture.
- We conducted case studies of environmental-agricultural interactions to examine the potential effects of climate change on the Chesapeake Bay drainage area and groundwater use in the Edward's aquifer area.

The most important changes in this study of the effects of climate change on production agriculture are the direct effects on crop yields (chapter 3) as these contribute most to the aggregate economic impacts we estimated. We conducted crop simulations studies at 45 sites across the United States that we selected to be representative of major production regions and areas that potentially could be important under climate change. We also compared these results to a more limited investigation that used a model to estimate yields at more than 300 representative sites, using a simpler crop modeling methodology. These results reflect changes in climate and atmospheric concentration of CO_2. Effects on crop yields varied by climate scenario and site but overall were far more positive than for many previous studies. Specific results that we found from the two climate scenarios we investigated include the following:

Effects on crop yields varied by climate scenario and site but overall were far more positive than for many previous studies.

- *Winter wheat*. Yields increased by 10–20 percent under the Hadley scenario but decreased by more than 30 percent at many sites under the Canadian scenario; yields also were more variable under the Canadian climate scenario. Adaptation helped to counterbalance yield losses in the Northern Plains but not in the Southern Plains. Irrigated wheat production increased under all scenarios by 5–10 percent, on average.
- *Spring wheat*. Yields increased by 10–20 percent in 2030 under both climate scenarios. Under the Hadley scenario, yields generally increased up to 45 percent higher by 2090; under the Canadian scenario, however, yields in 2090 showed declines of up to 24 percent. Irrigated yields of irrigated crops were negatively affected by higher temperatures. Adaptation techniques, including early planting and new cultivars, helped to improve yields under all scenarios.
- *Corn*. Dryland corn production increased at most sites, as a result of increases in precipitation under both climate scenarios. Larger yield gains were simulated in the northern Great Plains and in the northern Lake region, where warmer temperatures also were beneficial to production. Irrigated corn production was negatively affected at most sites.
- *Potato*. Irrigated potato yields generally fell—quite substantially at some sites—by 2090; under rainfed conditions, however, yield changes were generally positive. Adaptation of planting dates mitigated only some of the predicted losses.

There was little room for cultivar adaptation because predicted warmer fall and winter temperatures negatively affected tuber formation.

- *Citrus*. Yields largely benefited from the warmer temperatures predicted under all scenarios. Simulated fruit yield increased by 20–50 percent, while irrigation water use decreased. Crop losses from freezing diminished by 65 percent in 2030 and by 80 percent in 2090.
- *Soybean*. Soybean yields increased at most sites we analyzed; the increases were 10–20 percent for sites of current major production. Larger gains were simulated at northern sites, where cold temperatures now limit crop growth. The Southeast sites we considered in this study experienced significant reductions under the Canadian scenario. Losses were reduced by adaptation techniques involving the use of cultivars with different maturity classes.
- *Sorghum*. Sorghum yields generally increased under rainfed conditions—by 10–20 percent—as a result of increased precipitation predicted under the two scenarios we considered. Warmer temperatures at northern sites further increased rainfed grain yields. By contrast, irrigated production was reduced almost everywhere because of negative effects of warmer temperatures on crop development and yield.
- *Rice*. Rice yields under the Hadley scenario increased by 1–10 percent. Under the Canadian scenario, rice production was 10–20 percent lower than current levels at sites in California and in the Delta region.
- *Tomato*. Under irrigated production, the climate change scenarios generated yield decreases at southern sites and increases at northern sites. These differential regional effects were amplified under the Canadian scenario as compared with the Hadley scenario.

The factors behind these more positive results varied but, because the same crop models were used as in many previous studies, some of the more important differences are due to aspects of the climate scenarios.

- Increased precipitation in these transient climate scenarios is an important factor that contributes 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 warmer temperatures for dryland crops, whereas increased precipitation had little yield benefits for irrigated crops because water stress is not a concern for crops that already are irrigated.
- Another important factor that contributes to the more positive effects for crops is the high concentration (660 ppm) of atmospheric CO_2 in the 2090 transient climate scenarios. Earlier studies typically used a doubled-CO_2 concentration of around 555 ppm. Thus, one feature that appears important in considering the transient scenarios with continuing increases in atmospheric concentration of CO_2 is that the temperature change lags behind the CO_2 increase, due to heat uptake by the ocean.
- The coincidence of geographic patterns of precipitation and crop production contributed to differences among crops. Crops grown in the Great Plains—where drier conditions were projected, at least under the Canadian model—and crops grown in the Southern portion of the country, which already sometimes suffer heat stress, were more negatively affected. Heat-loving crops such as citrus benefited, whereas crops that do well under cool conditions (such as potatoes) suffered.
- Another factor behind the more positive results is that previous studies have been based on doubled-CO_2 equilibrium climate scenarios with larger temperature increases than those exhibited by these transient scenarios through 2100.
- The crop models and crop modeling approaches were substantially the same as in previous studies.

We combined the crop results with impacts on water supply, livestock, pesticide use, and shifts in international production to estimate impacts on the US economy (chapter 3). This analysis allowed us to estimate regional production shifts and resource use in response to changing relative comparative advantage among crops and producing regions.

- The net economic effect on the US economy was generally positive, reflecting the generally positive yield effects. The exceptions were simulations under the Canadian scenario in 2030, particularly in the absence of adaptation. Foreign consumers gained in all scenarios as a result of lower prices for US export commodities. The total effects (net effect on US producers and consumers plus foreign gains) were on the order of a $1 billion loss to $14 billion gain.
- Producers' incomes generally fell because of lower prices. Producer losses ranged from about $0.1 billion to $5 billion. The largest losses were under the Canadian scenario. Under the Hadley scenario, producers lost because of lower prices but enjoyed considerable increase in exports; the net effect was for only very small losses.
- Economic gains accrued to consumers through lower prices in all scenarios. Gains to consumers ranged from $2.5 to $13 billion.
- Different scenarios of the effect of climate change on agriculture abroad did not change the net impact on the United States very much but redistributed changes between producers and consumers. The direction of these changes depended on the direction of the effect on world prices. Lower prices increased producer losses and added to consumer benefits. Higher prices reduced producer losses and consumer benefits.
- Livestock production and prices are mixed. Increased temperatures directly reduce productivity, but improvements in pasture and grazing and reductions in feed prices resulting from lower crop prices counter these losses.

These production changes had important implications for demand on natural resources. We found that:

- Agriculture's demand for water resources declined nationwide by 5–10 percent in 2030 and 30–40 percent in 2090. Land under irrigation showed similar magnitudes of decline. The crop yield studies generally favored rainfed over irrigated production and showed declines of water demand on irrigated land (chapter 3).
- Agriculture's pressure on land resources generally decreased. Area in cropland decreased 5–10 percent, and area in pasture decreased 10–15 percent. Animal unit months (AUMs) of grazing on western lands decreased on the order of 10 percent in the Canadian scenario and increased by 5–10 percent under the Hadley scenario (chapter 3).

We conducted case studies of interactions of the environment and agriculture in the Chesapeake Bay drainage basin and in the Edward's aquifer region of Texas. The Chesapeake Bay is one of nation's most valuable natural resources, but it has been severely degraded in recent decades and is further threatened by climate change (chapter 5). Soil erosion and nutrient runoff from crop and livestock production have played a major role in the decline of the Bay. Potential effects of climate change on water quality in the Chesapeake Bay must be considered very uncertain because current climate models do not adequately represent extreme weather events such as floods or heavy downpours, which can wash large amounts of fertilizers, pesticides, and animal manure into surface waters. In our simulations, we found that under the two 2030 climate scenarios, nitrogen loading from corn production increased by 17–31 percent compared with current climate. Changes in farm practices by then could reduce loadings by about 75 percent from current levels under today's climate or under either of the climate scenarios.

The Edward's aquifer area is another region of the country where agriculture and resource interactions are critical, and these interactions could be intensified with climate change (chapter 5). Agricultural uses of water compete with urban and industrial uses, and tight economic management is necessary to avoid unsustainable use of the resource. Again, detailed regional predictions of climate are highly uncertain but our case study illustrates the potential vulnerabilities of a region dependent on groundwater for urban, agriculture, and habitat protection. We found that climate change causes slightly negative welfare changes in the San Antonio region as a whole but has a strong impact on the agriculture sector. The regional welfare loss—most of which is incurred by agricultural producers—was estimated to be $2.2–6.8 million per year if current pumping limits are maintained. A major reason for the current pumping limits is to preserve springflows that are critical to the habitat of local endangered species. If springflows are to be maintained at the currently desired level to protect endangered species, we estimate that under the two climate scenarios pumping would need to be reduced by 10–20 percent below the limit currently set, at an additional cost of $0.5–2 million per year. Welfare in the nonagricultural sector is only marginally reduced by the climate change simulated by the two climate scenarios. Increasing scarcity of water is reflected in steeply rising values of water permits and a shift of water from agricultural to nonagricultural uses.

Another important resource consideration is the impact of climate change on soil organic carbon. We were not able to conduct quantitative analysis of this interaction and it remains a topic that should be addressed in future assessments. The concern is that soil carbon may be reduced because warming speeds up decomposition of organic matter; increased yields predicted in many areas may counter this effect, however, if residue is retained on the soil surface through reduced or minimum tillage. We judged that changes in soils from climate change are unlikely to have significant effects on crop productivity (chapter 5). Moreover, microbial activity in soils is diverse and therefore probably resilient to changes in climate. With warming one might expect a shift northward into Canada for many crops but poor soils in Canada limit the extent of movement of cropping into these areas. Still another concern is soil erosion if precipitation becomes more intense. Soils that are managed with sustainable production practices, such as reduced tillage and retaining residues on the soil, produce more under either drought or excessively wet conditions and therefore could be a viable adaptation measure if weather becomes more variable. This was illustrated, in part, in our Chesapeake Bay case study, where erosion and nutrient run-off was reduced by 75 percent with a change in production practices.

Still another environmental concern is that increased pests and increased use of pesticides could result in more environmental damage. We conducted new analysis that allowed us to estimate that pesticide expenditures were projected to increase under the climate scenarios we considered for most crops and in most states we considered. Increases on corn generally were in the range of 10–20 percent; increases on potatoes were 5–15 percent, and increases on soybeans and cotton were 2–5 percent. The results for wheat varied widely by state and climate scenario, with changes ranging from approximately –15 to +15 percent. 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 continual evolution in the chemicals and control methods used.

The increase in pesticide expenditures results in slightly poorer overall economic performance, but this effect is quite small because pesticide expenditures are a relatively small share of production costs. The approach we used did not consider increased crop losses from pests; we implicitly assumed that all additional losses were eliminated through increased pest control measures. This approach may underestimate pest losses.

Another substantial additional contribution of this assessment was consideration of the potential effects of climate variability on agriculture (chapter 4). A 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 planting at different times. The value of improved forecasts of ENSO events has been estimated at approximately $500 million.

ENSO can vary intensity from one event to the next; thus, prediction—particularly of the details—of ENSO-driven weather are not perfect. And, ENSO has widely varying effects across the country. The temperature and precipitation effects are not the same in all regions; in some regions the ENSO signal is relatively strong, whereas others it is weak. Moreover, the changes in weather have different implications for agriculture in different regions because climate-related productivity constraints differ among regions under neutral climate conditions. At least one (highly controversial) study projected changes in ENSO as a result of global warming. We simulated the potential impacts of these changes on agriculture and found that

- an increase in the frequency of ENSO could cause a loss equal to about 0.8–2.0 percent of net farm income,
- an increase in frequency and intensity could cause a loss of 2.5–5.0 percent of net farm income, and
- there are differential effects on domestic producers, foreign economies and domestic consumers. We find gains to domestic consumers from increased ENSO frequency and intensity but losses to domestic producers and to foreign economies.

More generally, climate variability is responsible for significant losses in agriculture and it is changes in these extremes beyond what is captured in current methods of agricultural impact assessment that might significantly change our results. Droughts, floods, extreme heat, and frosts can damage crops or cause a complete loss of the crop for the year. Sequential years of crop loss can seriously affect the viability of a farm enterprise. Unfortunately, climate models do not predict extreme events and changes in variability well, so producing meaningful estimates of impacts is difficult. There also are limits to the ability of crop models to predict the effects of climate variability because yields can depend on very specific aspects of climate—including, for example, how many consecutive days of high temperatures are experienced or whether the crop has been subject to gradual hardening against cold temperatures. Even changes in mean conditions can change the variability of crop yields because changes in means change the chance of extreme events. We were able to examine this phenomenon explicitly and found mixed results:

- For corn and cotton, under the climate scenarios we used, yield variability decreased—largely as a result of the increase in precipitation.
- Wheat yield variability decreased under the Hadley scenario and increased under the Canadian scenario.
- Soybean yield variability shows a uniform increase under the Hadley scenario but mixed results in the Canadian scenario.

Will these predicted changes exacerbate or ameliorate current stresses? Before answering this question directly, we need to add three important caveats. First, we consider only two climate scenarios in the new work we conducted. Although the results of these scenarios confirmed broad patterns that are evident in previous studies, there are large differences even in the two scenarios we used. Second, the ability to predict climate at the detail required for agriculture assessment (i.e., in terms of regional predictions and in terms of specific features such as extreme event probabilities) is extremely limited (chapter 2, chapter 4). Third, we have not been able to completely study all of the ways in which climate can affect agriculture. We were particularly limited in our ability to consider environmental interactions and the impacts of climate variability (chapter 4, chapter 5).

Given these limits, climate change as currently modeled seems more likely to put downward pressure on commodity prices, with negative consequences for farm income. This development could put greater pressure on farmers in marginal crop-producing regions, particularly if they are adversely affected by climate change through increased drought. An important consideration is what will happen to foreign demand for US exports as a result of climate change or—probably of more importance—agricultural production and population growth abroad. Some scenarios of climate change suggest deteriorating conditions abroad, thus conferring an advantage to US farmers; other scenarios suggest the opposite (chapter 3). With regard to other factors, a review of 20- to 30-year forecasts of global production by major food agriculture organizations found continuing trends toward declining agricultural commodity prices. Although these conditions would create further stress on farm income, they could reduce stress on resource demands (water and land), providing more opportunities for devoting these resources to wildlife, recreation, or urban residential uses—all of which are likely to grow in the future. Thus, these changes would ameliorate what might otherwise be increasing competition over these resources.

Although climate change is highly uncertain, its greatest stress on agriculture may be how it affects water quality in areas that remain under intensive production. This threat could come from increased use of pesticides, increased competition for water in some local areas, nitrogen loading of coastal areas, and soil erosion and runoff of manure and agricultural chemicals (chapter 1, chapter 5). Such changes would exacerbate existing environmental problems.

Changes in climate variability also are not well predicted. If variability increased (e.g., if there were heavier rains and longer or more frequent periods of drought), it would further exacerbate these environmental problems. Increased variability is also the greatest threat to production agriculture. Increases in the intensity and frequency of ENSO or other changes in variability would increase losses. On the other hand, we found that changes in mean conditions had mixed effects on the variability of crop yield: For several crops, yield variability decreased under the climate scenarios we studied. This result is extremely dependent on the specific scenarios examined, however.

Research Priorities

Further research is needed in three broad areas: integrated modeling of the agricultural system; research to improve resiliency of the agricultural system to change; and several areas of climate-agriculture interactions that have not been extensively investigated.

Integrated Modeling of Agricultural System

The main methodology for conducting agricultural impact models has been to run detailed crop models at a selected set of sites and to use the output of these site models as input to an economic model. Although this approach has provided great insights, future assessments will have to integrate these models to consider interactions and feedbacks, multiple environmental stresses (tropospheric ozone, acid deposition, and nitrogen deposition), transient climate scenarios, and global analysis and to allow study of uncertainty where many climate scenarios are used. The present approach, whereby crop modelers run models at specific sites, severely limits the number of sites and scenarios that can be considered feasibly.

The boundaries of the agricultural system in an integrated model must 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 should 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 that address multiple changes and risks—including climate change and climate variability.

There is also great need for research to better predict and to make better use of short-term and intermediate-term (i.e., seasonal) weather changes.

New Areas of Research

Much of the existing research has focused more narrowly on the effects of changes in moisture, temperature and elevated ambient CO_2. Many other important interactions remain under-researched in comparison. Experimentation and modeling of interactions of multiple environmental changes on crops (jointly changing temperature, CO_2 levels, ozone, soil conditions, moisture, etc.) are needed. Experimental evidence is needed under realistic field conditions, such as FACE experiments for CO_2 enrichment. Far more research is needed on agricultural pests and their response to climate change, particularly in the development of models that could project changing ranges and incidences of pests. There remains a need for economic analysis to better study the dynamics of adjustment to changing conditions.

Climate-agriculture-environment interactions may be one of the more important vulnerabilities, but existing research is extremely limited. Soil, water quality, and air quality should be included in a comprehensive study of interactions.

Perhaps one of the most serious and potentially most important is the need to consider changes in variability. This has proved difficult both because it demands improved projections from climate models and detailed and carefully validated models of crop growth. To move forward, agricultural modeling must be more closely integrated with climate modeling so that modelers can develop better techniques for assessing the impacts of climate variability. This work 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.

Coping Options

The ultimate question for US agriculture over the next several decades is,"Can agriculture become more resilient and adaptable given the many forces that will reshape the sector—of which climate change is only one?" US agriculture has, in fact, been very adaptable and resilient along many dimensions; to stay ahead in a competitive world, however, we can always ask: "Can it do still better?" The individual farmer, agribusiness company, agronomist, or farm-dependent community is not concerned with whether prices are low because of climate change, technological change, or a market collapse in Asia. Similarly, if commodity prices rise sharply because of demand pressures, production failure in Russia, or worsening climatic conditions across the world, the impact on farmers and resources will be similar. Each of these scenarios represents a change in the relative economic conditions across regions. These types of events and forces create short-term variability and shape long-term trends. They present changed conditions that are potential opportunities for those that act quickly (and in the right direction) and threats to those who are slow to respond. Of course, there can be real losses and real gains to different regions; in this assessment, we have tried to illustrate such changes resulting from climate change. The challenge for adaptation is to do as well as possible with what the world presents. Limiting climate change is another option for avoiding negative impacts involved with climate change, but that approach involves much more than what happens to US agriculture. Coping options for climate change can be divided into two broad categories: the market and policy environment for agriculture and technological response options.

The Market and Policy Environment for Agriculture

Over the past half-century, federal farm policy has aimed to boost farm and rural incomes, smooth out the ups and downs of commodity prices, insure farmers against the inevitable disasters of droughts and floods, feed the poor, improve productivity, protect natural resources, and come to the aid of the small farmer. There have been great successes: since 1950, US agricultural productivity has doubled; real world food prices have fallen by two-thirds, so feeding the world is cheaper; and the average US farm household is now wealthier than the average nonfarm household. There also have been contradictory and costly policies such as supply control with production-based payments and "conservation" programs that idled land with only minimal environmental benefits.

In this new century, we must be realistic about inevitable market and global forces that are simply too powerful to change and avoid the policy pitfalls of the past half-century. As our assessment shows, the probability that climate change will increase agricultural productivity in the United States is at least as good as—if not better than—the probability that climate change will decrease productivity. Although improved productivity is good for US consumers, it generally reduces income and wealth among farmers and agricultural landholders.

Given the current structure of agriculture (chapter 1) and the forces that are likely to shape agriculture over the next several decades, four broad considerations with regard to the market and policy environment for agriculture will affect its ability to cope with climate change.

First, successful adaptation to climate change will require successful R&D. Traditional public R&D is part of the research portfolio, but the engine of invention now is in private firms. Basic research remains the province of the public sector. The important element for the future is how to encourage and direct the power of the private research engine to improve environmental performance. Science-based environmental targets implemented with market-based mechanisms can provide sound incentives for innovations that improve environmental performance. Designing market-based mechanisms to deal with nonpoint pollution has proved difficult; more attention is needed to assure that whatever mechanisms are chosen, they provide incentives for the private sector to develop and commercialize agricultural technologies and practices with improved environmental performance.

Second, the lesson from the last 50 years of agricultural policy is that use of broad-based commodity policy to fight rural poverty is an extremely blunt instrument. These payments often end up disproportionately in the hands of the wealthiest farmers. Fifty years ago, when the farm population was much poorer than the general population, the regressive aspects of these policies were minimal, but that is no longer true today. A goal could be to target income assistance far more carefully to disadvantaged people in rural areas—many of whom are not actually farmers on any significant scale. Tying aid to the business of farming also tends merely to inflate the value of assets (mainly land) tied to farming. Ultimately, the next generation of farmers pays a higher price for the land and faces a higher cost structure than if the payments had not been in place. This situation sets the stage for another income crisis when inevitable commodity price variability leads to a downturn in prices. The 1996 farm legislation eliminated most of these elements, replacing them with payments that ultimately were to be phased out after seven years. Farm sector euphoria over the program when prices were high turned to disenchantment when prices fell. This disenchantment risks a drift back to programs that pay people to produce product that depresses prices, forcing government to buy it up to prop up prices, dump stocks on the market and depress prices, and pay people not to produce. These lessons are broadly relevant to disadvantages and dislocations that may result from climate change.

Third, climate variability and its potential increase necessarily focus attention on risk-management strategies. Contract production, vertical integration, forward markets, private savings, household employment decisions, and weather derivatives are market responses to risk. These strategies are likely to evolve further, and farmers who are not adept at using them will have to become so. Farmers can adopt technological solutions to risk—such as irrigation as insurance against drought or shorter maturing varieties against frost. If farmers adopt these solutions primarily to reduce variability in income, however, these strategies can increase costs and make the farm uncompetitive with other farms that have accepted the risk and pooled income variability through savings, contract production, or other market mechanisms.

Crop insurance is another response, for which the federal government now takes some responsibility. Federal crop insurance contains a devilish public policy dilemma. One aspect of insurance is what is known in economics as "moral hazard." The existence of insurance reduces the incentive to undertake technological solutions to risks. A second aspect of insurance is that under a pure insurance program, the enrollee pays insurance premiums each year but over several years should expect to get back in loss payments no more than he or she paid. If the farmer can expect more, the insurance program also is a subsidy program. This situation may involve cross-subsidization among enrollees; the subsidizers then tend to drop out, however, or—where federally managed—the entire program can run a deficit with tax dollar support. There is a risk, then, that the desire to create a federal insurance program that enrolls a large proportion of farmers will end up as largely a subsidy program. If climate change causes a drift toward more frequent disasters in an area, the premiums for farmers in the area would have to be adjusted upward to maintain the program as a pure insurance program. Failure to adjust premiums ultimately could mean that insurance is paying out almost every year. A federal program would have difficulty, however, raising premiums substantially on areas that have suffered repeated disaster years. Ultimately, crop insurance or a broader form of producer insurance cannot offer much protection if an area is drifting toward reduced viability.

Fourth, environmental and resource policies need to be realistic, tough, and market-based and adapt as conditions change and put the ultimate objectives of the programs at risk. These situations can be "win-win." In the climate scenarios we examined increased yields and lower prices led to a reduction in resource use. In the past, acreage-reduction programs took vast tracts of land out of production to boost prices. In the same way, environmentally targeted programs that reduce production—through land retirement or through other types of constraints on production practices—can offset climate-induced productivity increases, raise commodity prices, and restore income levels. These programs also can be beneficial for the United States overall if the programs are targeted to generate substantial and real environmental gains. If—as projected in our analysis—use of water and land resources declines because of climate change, reallocating resources to environmental and conservation goals may be more feasible. Keep in mind, however, that we project reduced resource use compared with a reference. If far greater demand for resources occurs for other reasons (e.g., demand growth abroad), we will not see these reductions compared to current levels. Thus, again, climate change is just one of the factors that needs to be considered.

Technological Response Options

In addition we can think about some specific technological response options that could be useful in adapting to climate change. Considerable caution is needed in recommending specific technological solutions or directions for agricultural research, however, because of the remaining high degree of uncertainty in climate projections. A decade ago, the main fear of climate change was drought; in the scenarios we examined, however, precipitation over much of the country increased, reducing the number of irrigated acres and the demand for water. Flooding and excessively wet field conditions may pose a greater threat, at least as currently projected. Rather than bet on one scenario or another, a distributed portfolio of research, representing a variety of perspectives on how the future might evolve, is needed.

The surprising finding in our analysis is that the impact of climate change on agriculture may well be beneficial to the US economy through the next century. It will, however, create winners and losers and contribute to dislocation and disruption that imposes costs on localities. Our case studies of the Chesapeake Bay drainage area and the Edward's Aquifer region in Texas illustrated that local and regional effects and issues can differ substantially. Agriculture—or some types of agriculture—may well become nonviable in some areas under climate change. The truly difficult aspect of adaptation and adjustment is to decide when to make further investments in a particular farming practice or farming region and when conditions have become so adverse that the sensible strategy is to find another line of work.

Although identifying specific technological responses to climate change is difficult in view of the level of uncertainty in predictions of climate at a local and regional level, we found that adaptations such as changing planting dates and choosing longer season varieties offset losses or further increase yields. Adaptive measures are likely to be particularly critical for the Southeast because of large reductions in yields projected for some crops under the more severe climate scenarios (chapter 3). Breeding for response to CO_2 probably will be necessary to achieve the strong fertilization effect assumed in the crop studies. This technology is an unexploited opportunity; the prospects for selecting for CO_2 response are good. Attempts to breed for a single characteristic often are unsuccessful, however, unless other traits and interactions are considered. Breeding for tolerance to climatic stress already has been heavily exploited, and varieties that do best under ideal conditions usually outperform other varieties under stress conditions as well (chapter 4). Breeding specific varieties for specific conditions of climate stress therefore is less likely to be successful.

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 found increased pressure on groundwater resources that would threaten endangered species that rely on spring flows supported by the aquifer. Another example relates to agricultural chemical use. An increase in the use of pesticides 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 have to adapt broadly to changing conditions in agriculture—of which changing climate is only one factor. Some potential adaptations that are more directly related to climate include the following:

- Sowing dates and other seasonal changes. Planting 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. In many areas, however, economic incentives to reduce wasteful practices do not exist. Increased precipitation and more-intense precipitation probably will mean that some areas will have to increase their use of drainage systems to avoid flooding and waterlogging of soils.

In Summary

Climate and weather are intimately connected with agriculture. We have only scratched the surface of understanding how climate might change and how those changes would affect agriculture. While we found generally positive effects on the country as a whole even these changes will require adjustment and change. Southern portions of the US could suffer substantial losses if some of the more severe climate changes projected actually occur even as Northern regions benefit. Nearly all of the researchers involved in this effort have been studying climate and agriculture interactions intensely for 15 years or more. Even after this period of study, research, and analysis, we recognize that our ability to foresee the future with great resolution is limited.

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Appendix A: Agriculture Sector Assessment Working Papers

This volume contains the principal findings of the agricultural assessment. Detailed reports of results and methods are reported in the following working paper reports. All of these are available at http://www.nacc.usgcrp.gov/sectors/agriculture/workshop-report.pdf. Most of the substantive new modeling and statistical analysis in these reports has now been accepted for publication or is in review in peer-reviewed scientific journals.
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Appendix B: Abbreviations

AOGCM	atmosphere-ocean general circulation model
ASM	Agriculture Sector Model
AUM	animal unit month
BC	Blaney-Criddle procedure
CAST	Council on Agricultural Science and Technology
CCC	Canadian Climate Center
CRP	Conservation Reserve Program
CV	Coefficient of Variation
DOC	dissolved organic carbon
DOE	US Department of Energy
DSSAT	Decision Support Systems for Agrotechnology Transfer
EA	Edwards Aquifer
EDSIM	Edwards Aquifer Simulation Model
EFS	environmentally friendly, smaller agriculture
ENSO	El Niño Southern Oscillation
EPA	US Environmental Protection Agency
EPIC	erosion productivity impact calculator
EPRI	Electric Power Research Institute
EQIP	Environmental Quality Incentives Program
ERS	Economic Research Service
FAIR	Federal Agricultural Improvement Reform Act of 1996
GCM	general circulation model
GCRA	Global Change Research Act
GDP	gross domestic product
GHG	greenhouse gas
GISS	Goddard Institute for Space Studies
GMO	genetically modified organism
GPS	global positioning system
GWLF	Generalized Watershed Loading Functions
GWP	Global Warming Potential
IPCC	Intergovernmental Panel on Climate Change
IPM	integrated pest management
M & I	municipal and industrial
MINK	Missouri, Iowa, Nebraska, Kansas
MMT	million metric tons
NOAA	US National Oceanographic and Atmospheric Administration
NRC	US National Research Council
NREL	Natural Resource Ecology Laboratory
OTA	US Office of Technology Assessment
Pg C	Petagrams of carbon
PNNL	Pacific Northwest National Laboratory
R&D	research and development
SQ	status quo
t/ha	tonnes per hectare
UKMO	United Kingdom Meteorology Office
USDA	US Department of Agriculture
USGCRP	US Global Change Research Program
USGS	US Geological Survey
WRP	Wetland Reserve Program
WUE	water use efficiency

Color Plates

Figure 3.2: Simulated yield changes from baseline for dryland corn grown in (a) 2030 and (b) 2095 under climate scenarios projected with the HadCM2 general circulation model.

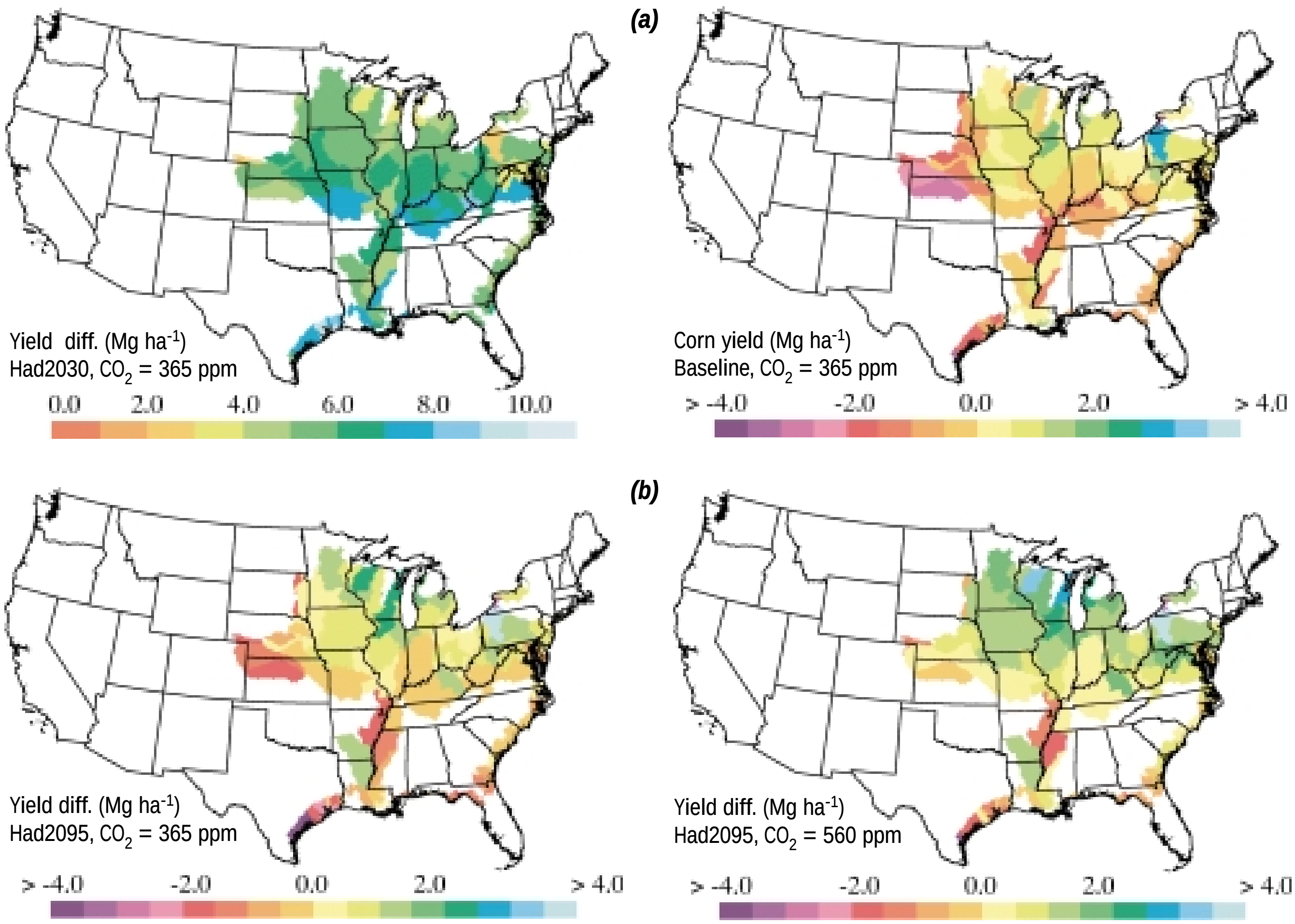

Figure 3.3: Simulated yield changes from baseline for winter wheat grown in (a) 2030 and (b) 2095 under climate scenarios projected with the HadCM2 general circulation model.