Agricultural Adaptation to Climate Change: Issues of Longrun Sustainability. By David Schimmelpfennig, Jan Lewandrowski, John Reilly, Marinos Tsigas, and Ian Parry; with contributions from Roy Darwin, Zhuang Li, Robert Mendelsohn, and Tim Mount. Natural Resources and Environment Division, Economic Research Service, U.S. Department of Agriculture. AER-740.

Abstract

Early evaluations of the effects of climate change on agriculture, which did not account for economic adjustments or consider the broader economic and environmental implications of such changes, overestimated the negative effects of climate change. This report, which highlights ERS research, focuses on economic adaptation and concludes there is considerably more sectoral flexibility and adaptability than found in other analyses. The report frames the discussion of economic adjustments within the context of global agricultural environmental sustainability.

Keywords: global warming, adaptation, longrun sustainability

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Preface

This report summarizes and synthesizes results from several studies on agricultural impacts of climate change conducted within ERS or through cooperative agreements with university collaborators. These included agreements with Cornell University, Yale University, Auburn University, University of California at Berkeley, Purdue University, and Wesleyan University. Principal investigators under these agreements included Duane Chapman, Curtis Jolly, Harry Kaiser, Robert Mendelsohn, Tim Mount, William Nordhaus, and Gary Yohe. These studies were conducted with funding identified as part of the U.S. Global Change Research Program. Published studies conducted or funded, in part, by ERS that are the basis of this report include:

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Contents

Summary

The costs and benefits of climate change cannot be evaluated independently of behavioral, economic, and institutional adjustments engendered by changing climate. There remains scientific controversy about the nature and rate of climate change, but most scenarios suggest gradual change over decades, thus providing the opportunity for farms and other parts of the agricultural system to adapt. In addition, the time scale of 80 to 100 years makes other profound social changes inevitable. Income and population growth, and technological innovation, will accelerate or decelerate, depending on global location, at the same time that adaptation to climate is taking place. While none of these factors can be considered in isolation, recent research shows that the negative effects of climate change on agriculture are likely overestimated by studies that do not account for economic adjustments or consider the broader economic and environmental implications of such changes.

Based on a collection of research efforts at the farm, national, and global levels, we find that there is considerably more sectoral flexibility and adaptation potential than found in other analyses. The report advances the understanding of these economic adjustments by preliminarily considering them within the broader context of global agricultural environmental sustainability. Specifically,

- Farmers, input suppliers, water managers, food processors, and consumers will adapt to climate change and the market signals resulting from changed agricultural production potential.
    - Farm-level declines in yield without the carbon dioxide (CO_2) fertilization effect, for the major cash crops, have been estimated in previous work at between -4 and -76 percent by the time atmospheric CO_2 doubles. Recent studies that allow for a greater range of adaptation show that yields could increase or decrease (-24 percent to 24 percent) under identical climate scenarios and over the same time period (see chapter 2, table 2.1).
    - For the United States, recent studies that allow for stronger adaptation than earlier work, but no CO_2 fertilization effect, show economic impacts of between -\$11.1 and \$33.1 billion annually, while agricultural producers alone in the United States are impacted by -\$5.8 to \$33.1 billion annually. Work based on crop modeling studies estimated aggregate economic impacts of between -\$67 and \$10.8 billion annually, while agricultural producers are impacted by \$6.6 to \$115 billion annually (see chapter 3, table 3.3).
    - At the global level, where international trade allows disruptions in one area to be compensated by improvements in another, world gross domestic product could increase or decrease by one-tenth of 1 percent (rounded) with adaptation and no CO_2 fertilization effect, a range of -\$24.5 to \$25.2 billion by the time atmospheric CO_2 doubles (see chapter 4, table 4.7). These are longrun equilibrium results that do not consider adjustment costs.

  - These results indicate the importance of various assumptions, particularly the level of aggregation used, in the analysis of climate change impacts on agriculture. These results are not a best guess of the effects of climate change on agriculture. A possibly important factor that has been left largely out of the analysis, to facilitate the kinds of comparisons that have been made, is the CO_2 fertilization effect. While there remains scientific controversy concerning this effect, one study estimated CO_2 fertilization to have global benefits of $119 to $197 billion over the same time period as the other results (see "CO_2 Effects on Crop Growth," in Results section of chapter 4, and see figure 1 for the temperature rise and timeframe associated with a doubling of atmospheric CO_2). Other potentially negative offsetting effects could be caused by other greenhouse gases.

- Agriculture must compete with other sectors for land, water, and investments of time and money. If, for example, conditions generally become more arid, competition among agricultural, urban, and industrial users of water would increase. Similarly, shifting of agricultural production to new areas could lead to conversion of grazing, pasture, or forest land to intensive cropland. If such conversions occur, they could contribute to loss of forests and natural ecosystems even as climate change is simultaneously disrupting them.

- Government policies and programs ranging from crop insurance and disaster assistance to acreage reduction programs, tariffs and quotas, and the level of agricultural research will affect the farm sector's response to climate change by affecting the economic incentives for farmers (and others) to adapt and technological options with which they can adapt.

- Climate change is a global phenomenon; the economic impact of climate change on the U.S. farm sector and consumers depends not only on how production potential is affected within the United States, but also on how changes around the world affect export supplies and import demands in other global regions of the United States' current and potential trading partners. The negative effects of climate change on agriculture have probably been overestimated by studies that do not account for economic adjustments that would almost certainly be made. The report summarizes and interprets data and conclusions from previous ERS reports on climate change and agriculture.

Agricultural Adaptation to Climate Change

Issues of Longrun Sustainability

David Schimmelpfennig
Jan Lewandrowski
John Reilly
Marinos Tsigas
Ian Parry

with contributions from Roy Darwin, Zhuang Li,
Robert Mendelsohn, and Tim Mount

Chapter 1. Introduction

World agriculture faces many future challenges, including how potential changes in climate may alter the productivity of farming systems across the world. Most analyses that have examined climate change have looked only at changing climate, and not the broader issues of agricultural sustainability, population growth, and technological innovation. The main results of this report are based on the body of work that considers climate change in isolation from other changes. How agricultural sustainability—the ability to feed a growing world population without degrading the environmental and natural resource base—will change and be affected by climate change is critical. The final chapter of this report analyzes the effects of climate change on agriculture in the context of global agricultural sustainability.

Climate Change Research and Policy—Recent History

The potential for emissions of greenhouse gases to alter Earth's climate has been the subject of concerted Federal research since the late 1970's. The issue became international in the late 1980's with the formation of the Intergovernmental Panel on Climate Change (IPCC) under the auspices of the United Nations Environment Programme (UNEP) and the World Meteorological Organization (WMO). At the same time, the U.S. Government implemented the U.S. Global Change Research Program (USGCRP) to better understand the human causes, scientific underpinnings, and societal consequences of climate change.

The United Nations Framework Convention on Climate Change was signed by 155 countries, including the United States, at the United Nations Conference on Environment and Development (the Rio Earth Summit) in 1992. More than 50 nations, including the United States, ratified the Convention in late 1994, putting the agreement into force. The key provision for agriculture is Article 2: "The ultimate objective of this Convention... is to achieve stabilization of greenhouse gas concentrations in the atmosphere at a level that would prevent dangerous anthropogenic interference with the climate system. Such a level should be achieved within a time-frame sufficient to allow ecosystems to adapt naturally to climate change, to ensure that food production is not threatened and to enable economic development to proceed in a sustainable manner." Implementation of this agreement depends critically on research to better understand whether and how food production is threatened by potential climate change. This work provides part of the basis for political judgments of what constitutes "dangerous anthropogenic interference" in the climate system.

Climate Change and Its Impact on Agriculture

While Federal research on climate change due to greenhouse gases dates to the late 1970's, relatively little attention was given to potential impacts on agriculture until the late 1980's.[1] Early attempts to investigate potential impacts of climate change on agriculture revealed a number of limitations in conventional modeling approaches.

- Farmers, input suppliers, water managers, food processors, and consumers will adapt to climate change and the market signals resulting from shifting patterns of comparative advantage in agricultural production. Adaptation potential has been generally recognized, but conventional approaches likely underestimated the extent to which adaptation would be economically feasible.

- Agriculture must compete with other sectors for land, water, and investments of time and money. If, for example, conditions generally become more arid, competition among agricultural, urban, and industrial users of water would increase. Similarly, shifting of agricultural production to new areas could lead to conversion of range, pasture, or forest land to cropland. Such conversions could contribute to the loss of forests and natural ecosystems even as climate change is simultaneously disrupting them.

- Government policies and programs—ranging from crop insurance and disaster assistance to acreage reduction programs, tariffs, and quotas—will affect the response of the farm sector to climate change by affecting the economic incentives for farmers (and others) to adapt. The level of agricultural research will determine technological options with which they can adapt.

- Climate change is a global phenomenon. The economic impact of climate change on the U.S. farm sector and consumers will depend not only on domestic production potential, but also on how global changes force export and import adjustments of the United States' trading partners.

- Climate change is only one of many forces that will shape the world economy and the supply and demand for agricultural products over the coming decades. Population, economic activity, and technology will be the major driving forces. How these factors change and interact through the responses of producers, consumers, and governments will have important implications for natural resource use and the environment. Resulting changes in resource quality and availability will feed back to affect agricultural production.

Methods for Estimating Climatic Impacts on Agriculture

Climate change presents a challenge for research due to the global scale of likely impacts, the diversity of agricultural systems, and the decades-long time scale. Current climatic, soil, and socioeconomic conditions vary widely across the United States and the world. Each crop and crop variety has specific climatic tolerances and optima. It is not possible to model world agriculture in a way that captures the details of plant response in every location. The availability of data with the necessary geographic detail is the major limitation rather than computational capability or basic understanding of crop responses to climate. As a result, compromises are necessary in developing quantitative analyses. Research reported in subsequent chapters employs several methods. When results from widely different approaches provide comparable estimates, we can place greater confidence in the results. When different approaches provide widely different estimates, a careful comparison can suggest further research that might narrow the differences.

Two basic methods have been used to estimate the effect of climate on crop production: (1) *structural modeling* of crop and farmer response, combining the agronomic response of plants with economic/ management decisions of farmers; and (2) *spatial analogue models* that exploit observed differences in agricultural production and climate among regions. These approaches are complementary. Reconciling differences in results between these methods enables better understanding of agricultural adjustment to climate change. Some uncertainty will necessarily remain because of the nature of climate and agricultural production.

For the first approach, sufficient *structural* detail is needed to represent specific crops and crop varieties whose responses to different conditions are known through detailed experiments, called *crop response models*. Similar detail on farm management allows

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[1] Studies of climate change date back to 1970, but early studies did not consider warming due to greenhouse gases; a major concern of the time was global cooling. For the most part, analysis of impacts was extremely limited (Reilly and Thomas, 1993). An exception was a National Defense University study that considered potential warming and cooling impacts on U.S. agriculture, developing yield impacts using a Delphi approach (Gard, 1980).

direct modeling of the timing of field operations, crop choices, and how these decisions affect costs and revenues. The advantage of this approach is that it provides a detailed understanding of the physical, biological, and economic responses and adjustments. A major disadvantage is that for aggregate studies, heroic inferences must be made from a relatively few sites and crops to large areas and diverse production systems. For example, the most comprehensive assessment of this type for the United States is that of Rosenzweig and Iglesias (1994). It considers only 19 U.S. sites with none located in the major agricultural States of Arkansas, Illinois, Michigan, Minnesota, Missouri, New York, Ohio, Oklahoma, Oregon, and Wisconsin. Additionally, only one site is located in each of the climatically and agronomically diverse States of California and Texas. The study considers only three crops (wheat, maize, and soybeans), representing 42 percent of the value of U.S. crop production.

The *spatial analogue* approach may involve *statistical* estimation using cross-section data, and is basically an elaboration of the case study approach. Using cross-section evidence on current production in warm and cool regions, it attempts to draw implications with regard to how the cool region could adopt the practices of the warm region if climate warmed. Statistical analysis of data across geographic areas allows researchers to separate out factors that explain production differences across regions. The statistical approach provides direct evidence on how commercial farmers have responded to different climatic conditions. Statistical estimation allows for factors that crop response models do not routinely consider, such as land quality, but relies on data being representative and on the ability of statistical analysis to isolate confounding effects.

Mendelsohn and others (1994), for example, relate cross-sectional (that is, U.S. county-level) climate differences to differences in agricultural land values. Their underlying premise is that as the climate warms, farmers will be able to adopt the farming practices, plant varieties, and crops of farmers in warmer regions. A potentially serious limitation of this approach is that large and widespread climate change could cause crop prices to change for prolonged periods all around the world. In this case, the impact of climate change on land values would be estimated incorrectly because it is based on information for incremental change. The degree and direction of error would depend on how prices changed.

Potential Changes in Climate Due to Greenhouse Gases

The impacts of climate change on agriculture will depend on the ultimate form of climate change, particularly the geographic pattern of temperature and precipitation changes. At present, it is impossible to predict such details of future climate with any confidence. The analyses in this report generally rely on climate projections generated by General Circulation Models (GCM's).

Generally, the studies reported here analyze climate scenarios from four equilibrium GCM simulations that show a doubling of carbon dioxide in the atmosphere.[2] The four GCM runs are those of the Goddard Institute for Space Studies (GISS), the Geophysical Fluid Dynamics Laboratory (GFDL), the United Kingdom Meteorological Office (UKMO), and the Oregon State University (OSU) models. In some of the studies reported, other climate scenarios were used. Kaiser and others (1993) constructed a simple, statistically based weather generator. This allows construction of many different weather scenarios that show gradual warming over time consistent with a predetermined final temperature. While this approach is limited to the sites for which it was developed, it provides a way to generate time paths of climate change in the absence of such data from GCM runs.

While equilibrium $2xCO_2$ scenarios have been standard model experiments reported from GCM's, these experiments do not provide direct evidence of when these potential changes may occur. The timing of climate change depends on the specific path of CO_2 concentration increase and climate system interactions with the ocean. In figure 1, we indicate how the global mean temperature change in $2xCO_2$ scenarios compares with the time path presented in IPCC (1996). These scenarios generally represent global temperature increases beyond what is expected by 2100. The exception is the OSU model where the global mean temperature change of 2.8° C is in the middle of range of temperatures expected by 2100.

Regional changes in mean surface temperature and precipitation differ from the global means (table 1.1) and there are large differences in the pattern of change among the different GCM's. ("Regional" will be used throughout the report to refer to a subset of the area under consideration. Here, we are referring to global climate variables, so "regional" means countries or groups of countries located together.)

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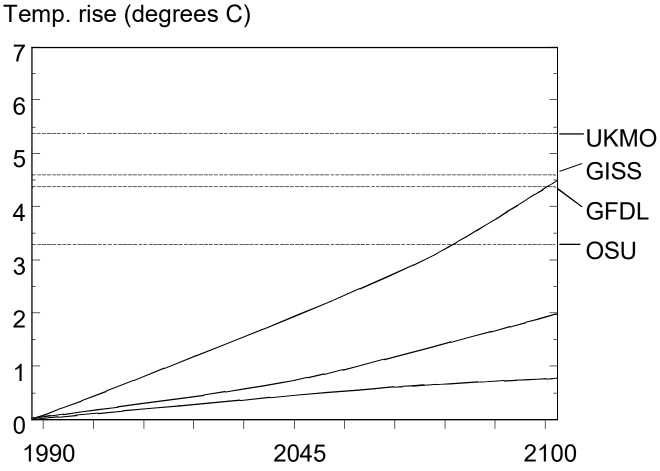
[2] To standardize results, GCM simulations consider a doubled pre-industrial level of CO_2 in the atmosphere ($2xCO_2$).

Figure 1

Global mean temperature rise



Note: Projection of global mean temperature change from 1990 to 2100 for 3 climate sensitivities and a median emissions scenario including uncertainty in future aerosol concentrations, compared with 2xCO$_2$ General Circulation Model results for GISS, GFDL, UKMO, and OSU (see footnote, table 4.1).
Source: Compiled by ERS from IPCC, 1996.

There is general agreement among GCM predictions that higher latitudes will warm more than the global average and will receive disproportionately more precipitation, while midcontinental midlatitude areas may become drier, depending on the effects of aerosols (IPCC, 1996).

The United States, Canada, and former Soviet Union/Mongolia data generally demonstrate these conclusions. For example, the hypothesized U.S. temperature increase is just slightly higher than the global mean and the relatively small increase in precipitation for the United States is likely to result in decreased soil moisture because of increased evaporation that accompanies higher temperatures. In comparison, temperature increases for Canada and the FSU/Mongolia are substantially above the mean, and precipitation increases, except for the OSU model, are much larger than the global land area mean. Tropical regions tend to show temperature increases slightly less than the mean temperature increase over the global land area. While there is some evidence to suggest that midcontinents become drier, precipitation

Table 1.1—Temperature (°C) and precipitation increase (percent) in four GCM's for world regions

Region	GCM							
	OSU		GISS		GFDL		UKMO	
	Temp. increase	Precip.	Temp. increase	Precip.	Temp. increase	Precip.	Temp. increase	Precip.
	° C	*Percent change*	*° C*	*Percent change*	*° C*	*Percent change*	*° C*	*Percent change*
Global	2.8	7	4.2	11	4.0	8	5.2	15
Land[1]	3.0	14	4.3	15	4.1	8	6.0	13
Regions[2]								
U.S.	3.2	5	4.6	6	4.4	5	6.7	14
Canada	3.4	11	4.9	17	5.5	15	7.9	32
EC	2.9	5	3.9	7	4.4	5	6.0	10
Japan	2.8	9	3.1	2	4.0	12	4.9	0
Other East Asia	2.8	23	4.3	19	3.9	12	5.6	16
Southeast Asia	2.1	4	3.7	11	2.4	2	3.4	4
Australia/New Zealand	2.8	23	4.3	19	3.9	1	5.6	16
Rest of the World								
FSU/ Mongolia	3.6	10	4.8	20	5.2	14	7.6	27
Other Europe	3.6	15	4.3	20	5.7	18	6.5	27
Other Asia	3.2	11	3.8	12	3.5	13	5.3	11
Latin America	2.6	23	4.2	15	3.1	5	4.7	6
Africa	2.8	19	4.2	19	3.5	1	5.4	9

[1] Global changes over land area only, excluding Antarctica.
[2] Regions as defined in Darwin and others (1995).
Compiled by ERS and Roy Darwin based on results reported in Darwin and others (1995).

Table 1.2—Temperature and precipitation increase in four GCM's for U.S. agricultural production regions

Region	GCM							
	OSU		GISS		GFDL		UKMO	
	Temp. increase	Precip.	Temp. increase	Precip.	Temp. increase	Precip.	Temp. increase	Precip.
	^{o} C	*Percent change*	*^{o} C*	*Percent change*	*^{o} C*	*Percent change*	*^{o} C*	*Percent change*
United States	3.2	5	4.6	6	4.4	5	6.7	14
Northeast	3.2	11	3.9	0	4.6	-2	7.6	16
Lake States	3.5	4	4.7	6	4.7	12	8.3	11
Corn Belt	3.5	2	4.8	4	4.3	6	7.2	8
Northern Plains	3.2	6	4.8	2	4.4	6	6.7	12
Appalachia	3.5	7	4.2	9	4.0	3	6.6	7
Southeast	3.4	11	3.7	-1	3.7	6	5.5	6
Delta States	3.4	2	4.4	-2	3.9	6	5.8	-1
Southern Plains	3.3	-2	4.4	-6	4.0	-4	5.9	-4
Mountain States	2.7	-1	4.8	11	4.4	-1	6.3	19
Pacific States	2.3	-1	4.6	15	3.9	7	6.2	20
Alaska	3.7	24	4.8	14	5.1	20	7.9	37
Hawaii	2.5	2	3.3	2	2.9	1	3.7	31

Compiled by ERS and Roy Darwin based on results reported in Darwin and others (1995).

changes vary substantially across regions for each GCM. For all regions except the European Community, at least 10 percentage points separate the highest and lowest precipitation change predicted by different GCM's. The OSU and GISS models predict that increased precipitation will fall more than proportionally on land, whereas the UKMO model predicts that proportionally more will fall over the ocean.

By USDA farm production region, temperature changes vary less across regions and scenarios than does precipitation (table 1.2). The Southern Plains region shows a consistent precipitation decrease across GCM scenarios. The Lake States, Corn Belt, and Appalachia show a somewhat consistent precipitation increase of 5-10 percent. For other regions, the range of precipitation change is generally 10 percentage points or more between the largest and smallest increase. Agreement among these four scenarios should not be interpreted as lending a high degree of confidence to these projections because they are only four of an almost infinite number of GCM scenarios, any one of which has a number of limitations as predictions of future climate.

Carbon Dioxide and Its Direct Effect on Plant Growth

Much of the work reported in subsequent chapters does not consider the direct effect of carbon dioxide (CO_2) or other trace gases on plant growth. There is scientific evidence that CO_2 increases plant growth and yields, even under open field conditions (Senft, 1995). For C3 crops (most crops other than corn, sorghum, and sugar cane), the estimated effect is a 30-percent increase in yield if carbon dioxide doubles; for C4 crops (corn, sorghum, and sugar cane), the effect is a 7-percent increase in yield (Kimball, 1983; Cure and Acock, 1986). Increased carbon dioxide levels also increase water use efficiency (Kimball, 1985; Woodward, 1993).[3]

Scientists studying the physiological effects of CO_2 have raised a number of other issues. Plants may

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[3] Our reference scenarios are for an "equivalent-doubling" of carbon dioxide. Although projections of trace gas emissions suggest that carbon dioxide will be dominant, it is not the only contributor to increased upward pressure on temperature caused by the atmosphere (radiative forcing). Carbon dioxide is likely to contribute about 80 percent of the radiative forcing. Thus, we would expect a proportionately smaller yield effect than if CO_2 provided all of the increased radiative forcing because other greenhouse trace gases have not been shown to contribute to plant growth.

adapt to higher CO_2 over succeeding generations and may show a lower response over time. The quality, primarily the protein content, of grain and leaf may decline, meaning that the total food value of the harvest may not increase as much as the yield volume (Bazzaz and Fajer, 1992; Mooney and Koch, 1994). The photosynthetic effect of CO_2 varies with temperature and other environmental conditions and, thus, the observed effect will not be equivalent at all locations (Van de Geijn and others, 1993). Increased CO_2 may also make plants more resilient to some stresses. Finally, the effect is unlikely to be as strong if other nutrients are limited as may be the case in some developing countries, such as those in Sub-Saharan Africa, where fertilizer is often not available. The growth of weeds that compete with crops is also stimulated by CO_2 fertilization.[4]

Issues and Uncertainties in Climate Change Projections

The four GCM scenarios presented above are representative of possible climate changes under a doubled atmospheric CO_2 climate, not predictions of future climate. The expertise to predict exactly a 5-percent chance that the global temperature will rise by more than 4°C by the year 2100 does not yet exist. Reviews of the state of scientific understanding of potential climate change point out several sources of uncertainty (Houghton and others, 1995; Houghton and others, 1992; IPCC, 1996; Schimmelpfennig, 1996). There is broad scientific agreement on many fundamental aspects of how human activities contribute to changes in the Earth's climate. The radiative effect of increased levels of CO_2 is well established. Natural levels of CO_2 and water vapor maintain the mean surface temperature of the Earth at about 15°C; without them, the mean surface temperature would be about -15°C (Albritton, 1992). Gases like chlorofluorocarbons (CFC's), methane, and nitrous oxide alter the radiative balance of the atmosphere (Houghton and others, 1992), and the atmospheric abundance of these gases has been increasing (Boden and others, 1994). Industrial activities that lead to emissions of CO_2 and CFC's are reasonably well measured and largely account for increases that have occurred since the late 1800's. There is also little doubt that, without substantial changes in energy use, CO_2 emissions will continue to increase.

Together, these facts provide a strong case that CO_2 emissions from the use of fossil fuels will contribute to warming. After more than a decade of research, consensus estimates of the increase in mean global surface temperature from doubling the level of CO_2 in the atmosphere have not changed from the 1.5°C to 4.5°C initially reported by the NRC (1983). This is, however, a substantial range. If the mean temperature change is at the lower end of this range, most studies indicate minor or possibly beneficial impacts on agriculture. If, however, the mean temperature change is at the upper end of the range, some studies find more negative impacts on agriculture. Other uncertainties affecting assessment of agricultural impacts include:

The global time path and local rate of global change. GCM results are better at describing a $2xCO_2$ world than the path taken to get there. Studies of climate change in the early 1980's suggested the indicated scenarios might be observed by as early as 2030. This date has shifted as far forward as to 2100 as slower emissions growth and an ocean-thermal lag have been included in the models (fig. 1). Localized changes may be more rapid than the global average because geographic patterns can change while the global mean is changing. Changes in regular storm tracks could, over a few years, lead to greatly reduced rainfall in one area and increased rainfall in a new area. Gradual change spread over several decades would allow far more opportunities for adaptation.

Changes in the daily and seasonal pattern of climate change. Given the magnitude of changes in the global system, there is no reason to believe that the daily, monthly, and seasonal patterns of temperature and precipitation will remain unaffected. Recent history shows an upward trend in nighttime low temperatures in the Northern Hemisphere but little or no change in daytime high temperatures (Kukla and Karl, 1993). Schimmelpfennig and Yohe (1994) estimate an index of crop vulnerability that provides a preliminary understanding of how changes in variability of climate affect production.

Changes in the intensity of weather events. Heavy rain and high winds damage crops and cause soil erosion. Some scientific findings suggest that rainfall could become more intense with warmer temperatures (Pittock and others, 1991). The frequency and strength of regular weather cycles such as ENSO (El Niño Southern Oscillation) and the strength of the jet stream may change and thus change weather patterns. These factors and others leading to hurricanes, tornadoes, and hail and wind storms are not adequately modeled by coarse-resolution GCM simulations. These events have serious consequences

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[4] For a general discussion of the CO_2 fertilization effect, see Reilly (1992).

for agriculture; any increase in their frequency could have important effects not addressed in existing agricultural studies.

Other factors not controlled for by GCM's are: (1) there may be a natural trend in climate over a geologic time scale; (2) solar activity may influence climate trends; (3) stratospheric ozone depletion due to CFC's may provide tropospheric cooling, partly offsetting warming due to greenhouse gases (Ramaswamy and others, 1992); and (4) sulfur emissions from burning coal may also offset warming (IPCC, 1996; Houghton and others, 1995). Sulfur emissions remain in the atmosphere only a few days and CFC's are being phased out under the Montreal Protocol, so the greenhouse effect could be "unmasked" and accelerate warming in the near future.

Unmodeled regional effects include wide-scale irrigation, deforestation, dust from tillage, and urbanization, which affect local temperature, precipitation, and insolation. While the combination of these effects may not have a significant effect on the global change in mean temperature or precipitation, they could make a substantial difference to local areas when combined with longrun climate change.

Climate Scenarios and Agricultural Impacts

Despite the many uncertainties associated with climate forecasts, decisions are being made at the international level that require analysis of global food production. This report provides a synthesis of the best information available to support those decisions, given that many uncertainties exist. The results presented are quantitative, but the numbers merely facilitate the comparison of models to reach qualitative conclusions. The uncertainties associated with climate change impacts, compounded with uncertainty about the future, make it foolhardy to suggest that one set of numbers is right while another set is wrong. Abrupt changes in climate leading to agricultural catastrophes are not considered likely, while a rise in sea level is considered to affect only a small proportion of the world's agricultural land. These factors, therefore, are not discussed here.

Chapter 2. Farm-Level Adjustments to Climate Change

Agricultural adaptation to climate change at the farm level depends on the technological potential (different varieties of crops, irrigation technologies); basic soil, water, and biological response; and the capability of farmers to detect climate change and undertake any necessary actions. As discussed in chapter 1, two approaches have been developed to analyze potential impacts and the ability of farmers to adapt to changing climate. The major advantage of the structural modeling approach is that it provides far more detail on the basic mechanisms of adaptation and provides the ability to integrate more directly scientific understanding of plant responses. Until recently, however, the biophysical detail of crop-response models had not been adequately linked with equally detailed models of the economic-technical options for adapting to climate change.

This chapter draws on a set of structural studies that integrate crop-response models with an economic management model. We focus on results that highlight the ability of individual farmers to adapt and respond to climate change. While it was not possible to consider results for many different farming systems at many different sites, it is possible to compare results with those of crop-response studies that do not fully consider the ability of farmers to adapt. These comparisons suggest considerable underestimation of adaptation potential in previous work. These results are sensitive to the time period over which the climate changes. Gradual climate change allows for a gradual shift in the mix of crops and to alternative farming systems (for example, a gradual trend toward a more arid and warmer climate might see the gradual introduction of a summer fallow period with spring and fall crops of shorter season grains). Gradual climate change could allow time for major infrastructure investments such as water projects and irrigation systems, transportation, and crop processing and storage systems to adapt to smaller or larger levels of production or to a different mix of crops (U.S. Congress (OTA), 1993; CAST, 1992). This chapter will answer the following questions:

- Are technological options available to U.S. farmers for adaptation to climate change? Some of the alternatives considered are adoption of later maturing cultivars, change of crop mix, and a timing shift of field operations to take advantage of longer growing seasons.
- Do studies that incorporate technology adaptations estimate smaller damages from climate change at the farm level in the United States than studies that do not allow for adaptations?

Climatic variability is a feature of current climate in most geographic areas. This variability may make it difficult for farmers to readily detect climate change and respond appropriately. Climate may also become more or less variable, or extreme climatic events may occur with more or less frequency. The second part of this chapter addresses the issue of farmer response to uncertainty.

Yield Changes of Major Crops on the U.S. Farm

Kaiser and others (1993) combine a crop-response model with a detailed structural model of the management and economic decisions farmers must make over a growing season for a site in Minnesota. Monthly temperature, precipitation, and solar radiation data are generated by a stochastic weather generator that is calibrated to produce ending values consistent with the $2xCO_2$ results produced by the GISS GCM. Using the weather data, a crop-response model determines crop yields, grain moisture content, and field-time availability. Field-time availability considers whether fields have dried sufficiently in the spring to allow access of farm equipment. The three outputs from the crop model feed into an economic model that determines the optimal crop mix, scheduling of field operations, and expected net farm income. Farmers decide when to fall plow, spring plow, plant, and harvest based on expectations of four factors that are affected by the stochastic weather—field time availability, crop yields, grain drying costs, and crop prices.

Farmers' expectations are treated explicitly because farmers must make planting and other decisions before they observe the actual weather for the season. Their expectations are conditioned on the previous decade of weather simulated by the stochastic weather generator. Thus, farmers in the model are not ideally adapted to changing climate. Further, in any single year, actual weather may differ significantly from expected weather. Crop prices are determined by assuming that the crop yield on the individual farm is correlated with national crop yields and therefore the national price. Kaiser and others (1995) extend the Minnesota results to six additional regions: Georgia, Illinois, Iowa, Nebraska, North Carolina, and Ohio. Mount and Li (1994) extend Kaiser and others' (1993) integrated agronomic/economic results by developing response surfaces for yield, average production, and net returns using the integrated model for the range of temperatures and amounts of precipitation observed in the Midwest.

Sometimes, differences between research projects are only in the details, and this is the case for studies of climate change impacts on U.S. farms. On the surface, a U.S. EPA study by Rosenzweig and others (1994) is very similar to the work done at Cornell by Mount and Li, and Kaiser and others. Each study determines impacts on yields of maize, soybeans, and winter wheat for similar areas in Nebraska and Iowa. Because the weather data in the Cornell studies were slightly different than the GCM results used by other researchers, Li provided new simulations that give yield changes in his and Mount's response surface model for the same GCM results (GISS, GFDL, and UKMO) used by Rosenzweig and others (1994).[5]

Given the similarity of approaches and the use of identical climate scenarios, the percentage yield changes from Li's report and Rosenzweig and others (1994), presented in table 2.1, are surprisingly different. The only results that are reasonably similar are GFDL maize in both locations and wheat in Iowa. Differences may result from assumptions regarding soil type, crop response characteristics, and the effects of farmer adaptation.

Soil Types

Although the studies consider the same locations, they do not make the same assumption about soil type. Rosenzweig and others use a deep sandy soil with poor water-holding capacity in Nebraska, and a fine loamy mixed mesic soil with excellent water-holding capacity in Iowa. The results of Mount and Li reported here (from a model that is closely related to Kaiser and others, 1995) are based on a deep, clay soil with good water-holding capacity for both sites. Differences in soil characteristics may explain some of the yield difference in Nebraska, but not in Iowa. We would expect the poor water retention of the sandy soil in Rosenzweig and others to make the Nebraska crop more vulnerable to hot and dry weather than in Mount and Li (-31 percent vs. 14 percent for soybeans; -33 percent vs. -4 percent for wheat (UKMO)). However, since the UKMO climate scenario in Nebraska is 30-percent wetter after climate change, this factor cannot explain the pronounced difference between the percentage yield changes in table 2.1.

Crop-Response Models

The results shown in table 2.1 also follow from different crop models. Rosenzweig and others use the CERES-maize, CERES-wheat, and SOYGRO models validated recently by Egli and Bruening (1992) and Jones and Ritchie (1991). The GAPS model used in Kaiser and others (1993) and Mount and Li incorporates the earliest version of SOYGRO (Wilkerson and others, 1983), so any improvements made to SOYGRO are missing. GAPS itself was being refined over this time, which made soybean yields more robust under dry conditions. It is not possible to say whether GAPS or SOYGRO is a better model. The GAPS-maize (Stockle and Campbell, 1985) and the GAPS-wheat models (Stockle and Campbell, 1989) have identical owners. Differences in crop models, then, account for some of the differences between yield results.

The effect of differences in crop models may be demonstrated with Iowa soybeans. Under the GFDL scenario—a scenario that includes an almost 5-degree-Celsius temperature increase and a 36-percent decline in precipitation—Mount and Li show a 17-percent increase in yield for Iowa soybeans, while Rosenzweig and others show a 26-percent decline. In general, the results in Rosenzweig and others are far more negative than in Mount and Li. Even though some differences have been identified in the details of the crop-response models, none of these factors explain the pronounced and consistent difference in results between the studies.

Farmer Adaptation

The results in Rosenzweig and others are consistently more pessimistic than in Mount and Li because their estimated yield changes do not include farmer adaptation. Mount and Li include several adaptation alternatives, such as later maturing cultivars that permit farmers to take advantage of longer growing seasons, earlier planting dates resulting from climate change, and changes in other field operations. Farmers select specific practices to maximize profits given their expectations about future climate. Yield results presented by Rosenzweig and others assume that farmers will continue to plant the regional cultivars being planted now, implying that farmers will be unable to detect changing climate conditions even over a 50- to 80-year period. Another source of adaptation that does not directly affect crop yields, but that does affect profitability, is the mix of the three crops chosen by the farmer. The economic model in Kaiser and others (1993) and Mount and Li

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[5] Chapter 1 discusses these climate models in detail.

Table 2.1—Major cash crops percentage yield change (1xCO_2 to 2xCO_2)[1]

State/crop	Kaiser and others (1995)/Mount & Li (1994)[2]			Rosenzweig and others (1994)		
	GISS[3]	GFDL	UKMO	GISS	GFDL	UKMO
				Percent		
Nebraska:						
Dryland maize	18	-22	19	-22	-17	-57
Dryland soybeans	24	19	14	-12	-18	-31
Dryland winter wheat	11	-3	-4	-18	-36	-33
Iowa:						
Dryland maize	22	-24	3	-21	-27	-42
Dryland soybeans	15	17	-1	-7	-26	-76
Dryland winter wheat	0	-6	-5	-4	-12	-15

[1] Results without CO_2 fertilization effect.

[2] To obtain results as comparable as possible to Rosenzweig and others (1994), a special report was generated by Li that runs the same GCM results used by Rosenzweig and others (1994) through Kaiser and others (1993) and Mount and Li's (1994) models. The results from this special report appear in this column. We are grateful to Li for generating the report and helping us to isolate the reasons for differences between the results of the studies.

[3] The acronyms in this row refer to general circulation climate model (GCM) results; Goddard Institute for Space Studies (GISS), Geophysical Fluid Dynamics Laboratory (GFDL), and United Kingdom Meteorological Office (UKMO).

Compiled by Economic Research Service, USDA.

Table 2.2—Percentage yield change from 1xCO_2 to 2xCO_2 - dryland maize

	Kaiser and others (1995)		Rosenzweig and others (1994)		
	Warm/wet (2.5, 10)	Hot/dry (4.2, -20)	GISS	GFDL	UKMO
			Percent		
Sigourney, IA/Des Moines, IA	-12	-24	-21 (2.2, 10)	-27 (4.7, -36)	-42 (7.3, -16)
Urbana, IL/Columbia, MO	-10	-20	-28 (3.7,50)	-90 (3.8, -35)	-28 (4.8,12)
Lincoln, NE/Columbia, MO	0	-5	-28 (3.7, 50)	-90 (3.8, -35)	-28 (4.8,12)
Greenville, OH/Indianapolis, IN	-8	-16	-7 (2.2, 10)	-59 (3.8, -35)	-20 (5.5, 6)
Tifton, GA/Tallahassee, FL	-14	-28	-5 (3.1, 2)	-41 (2.8, -36)	-34 (9.2, -37)
Tarboro, NC/Lynchburg, VA	-4	-17	-58 (3, 41)	-61 (5.1, -51)	-21 (6.4, -12)

Numbers in parentheses are the change in temperature (degrees C) separated by a comma from the percent change in precipitation used in determination of percent change in yield. Goddard Institute for Space Studies (GISS), Geophysical Fluid Dynamics Laboratory (GFDL), and United Kingdom Meteorological Office (UKMO) readings are for the crop heading month (July).

Compiled by Economic Research Service from Cooperative Agreements, USDA, ERS and Rosenzweig and others (1994).

allows for this source of adaptation not reflected in the yield figures in table 2.1.

While Rosenzweig and others (1994) do not report adaptation results, local estimates of supply shocks for different crops are developed as a basis for simulating national and global economic impacts of climate change. A set of Rosenzweig and others' (1994) results with adaptation are reported in Reilly and others (1993), but are not available for more than a few locations. Adaptation is able to reduce the yield losses, but the double-digit gains found by Mount and Li for all crops, except Iowa wheat, under at least one scenario, are still not evident. Adaptation offsets the yield losses at the most severely affected sites in Rosenzweig and others (1994), so it is surprising that the same adaptation does not lead to greater yield gains at the less severely affected sites (Reilly, 1994).

Tables 2.2-2.4 compare yield results from Kaiser and others (1995) with Rosenzweig and others (1994) for various sites. The climate scenarios differ and the sites, while generally less than 200 miles apart, are

Table 2.3—Percentage yield change from 1xCO_2 to 2xCO_2 - dryland winter wheat

	Kaiser and others (1995)		Rosenzweig and others (1994)		
	Warm/wet (2.5,10)	Hot/dry (4.2, -20)	GISS	GFDL	UKMO
			Percent		
Sigourney, IA/Des Moines, IA	3	0	-4 (2.6, 12)	-12 (3.6, 17)	-15 (6.2, 30)
Urbana, IL/Columbia, MO	-33	-23	-22 (3.5, 43)	-19 (3.4, 50)	-35 (5.7, 24)
Lincoln, NE/Columbia, MO	15	-9	-22 (3.5, 43)	-19 (3.4, 50)	-35 (5.7, 24)
Greenville, OH/Indianapolis, IN	-2	0	-3 (2.6, 12)	-6 (3.4, 50)	-16 (6, 11)
Tifton, GA/Tallahassee, FL	22	0	-56 (4.1, 4)	-80 (3.3, 42)	-100 (crop failure) (6.4, -15)
Tarboro, NC/Lynchburg, VA	6	10	-6 (4.3, 14)	-2 (3.6, 44)	-25 (6.8, 2)

Numbers in parentheses are the change in temperature (degrees C) separated by a comma from the percent change in precipitation used in determination of percent change in yield. Goddard Institute for Space Studies (GISS), Geophysical Fluid Dynamics Laboratory (GFDL), and United Kingdom Meteorological Office (UKMO) readings are for the crop heading month (May).

Compiled by Economic Research Service, USDA from Cooperative Agreements, USDA, ERS and Rosenzweig and others (1994).

Table 2.4—Percentage yield change from 1xCO_2 to 2xCO_2 - dryland soybeans

	Kaiser and others (1995)		Rosenzweig and others (1994)		
	Warm/wet (2.5, 10)	Hot/dry (4.2, -20)	GISS	GFDL	UKMO
			Percent		
Sigourney, IA/Des Moines, IA	-10	-19	-7 (2.2, 10)	-26 (4.7, -36)	-76 (7.3, -16)
Urbana, IL/Columbia, MO	0	-20	-19 (3.7, 50)	-35 (3.8, -35)	-22 (4.8, 12)
Lincoln, NE/Columbia, MO	0	-24	-31 (4.4, -20)	-36 (4.5, 0)	-40 (4.8, 12)
Greenville, OH/Indianapolis, IN	14	-4	-12 (2.2, 10)	-37 (3.8, -35)	-43 (5.5, 6)
Tifton, GA/Macon, GA	-5	-55	-24 (3, 41)	-61 (4, -39)	-86 (9.2 -37)
Tifton, GA/Tallahassee, FL	-5	-55	-23 (3.1, 2)	-21 (2.8, -36)	-69 (9.2, -37)
Tarboro, NC/Lynchburg, VA	-3	-46	2 (3, 41)	-65 (5.1, -51)	-71 (6.4, -12)

Numbers in parentheses are the change in temperature (degrees C) separated by a comma from the percent change in precipitation used in determination of percent change in yield. Goddard Institute for Space Studies (GISS), Geophysical Fluid Dynamics Laboratory (GFDL), and United Kingdom Meteorological Office (UKMO) readings are for the crop heading month (July).

Compiled by Economic Research Service from Cooperative Agreements, USDA, ERS and Rosenzweig and others (1994).

not identical; thus, the results are not directly comparable. Temperature and precipitation changes are presented in the tables for each GCM model at each location.

Table 2.2 repeats the pattern found in table 2.1, except for the Georgia/Florida location. Yield declines for corn in Rosenzweig and others (1994) are generally more severe than those in Kaiser and others (1995). The pattern continues for wheat and soybeans. For wheat, Illinois/Missouri is the only location showing a larger yield decline in Kaiser and others (1995) than in Rosenzweig and others (table 2.3). The Georgia/Florida location shows a 100-percent yield difference between the studies (from no effect to crop failure) and this may be due to farmer adaptation at high temperatures in the summer or because a chilling requirement (vernalization) is not part of Kaiser and others' (1995) crop model.[6] If the temperature does not fall low enough in the winter, the chilling requirement for winter wheat in the crop model in Rosenzweig and others is not satisfied, and crop failure results. For

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[6] Personal communication with Susan Riha.

About the Studies

Comparison of results in tables 2.1-2.4 involves several technical modeling issues that do not depend on highly uncertain climate change estimates from global circulation models (CGM's). Scenarios are the same for both studies in table 2.1. In tables 2.2-2.4, the reader can control for the scenario by considering the changes in temperature and precipitation used in each study, given the yield changes on those tables. There are other differences in the studies that are harder to control for. The crop models are different and we cannot say which is better. The size of the yield differences that exist must to some extent be caused by differences in adaptation assumptions. As Rozenzweig and others admit, their yield change estimates would be more positive with stronger adaptation assumptions.

soybeans, locations generally show smaller yield declines in Kaiser and others (1995) than in Rosenzweig and others (table 2.4).

Kaiser and others (1995) show more moderate impacts than Rosenzweig and others (1994), with smaller negative and some positive yield changes for all three major crops. Kaiser and others (1995) include adaptation alternatives like later maturing cultivars and alteration of timing of field operations to take advantage of longer growing seasons. Kaiser and others (1993) point out that it is possible to fall plow later under a higher temperature regime, giving the crop more time in the field. Conservation tillage is a farming practice, not considered, that could be used to conserve soil moisture under a drier climate. None of the scenarios predict severe water stress, so optimistic conclusions about the possibilities for the dryland adaptation should be considered dependent on small changes in precipitation. Other adaptations, like irrigation, would become more important with larger rainfall deficits. Changes in crop mix, an adaptation to changing yields accounted for by Kaiser and others, feeds into the economic model and affects farm revenue and profitability.

All of the results presented are without the effect of CO_2 fertilization, so the comparison of results is not confounded by this effect. Although there is no consensus on the size of this effect, the yield changes would be more positive for all studies with this effect.

Additional methods of adaptation are considered in Hansen (1991), who tests whether or not there are significant yield effects associated with minor onfarm production adaptations to climate that are not captured in crop growth models. Using a statistical approach, and regression analysis and field-level data from 10 major corn-producing States, Hansen estimates a corn yield function. The model's regressors include six variables that reflect longrun average July temperature and precipitation levels (these capture longrun average climate effects on yields); six variables that reflect actual July temperatures and precipitation levels (these capture weather pattern effects on yields); and adaptation variables for tillage practice, irrigation, nitrogen use, planting date, seeding rate, soil erodibility, and soil loss tolerance.

Minor farm-level adaptations currently available to farmers are significant at the 99-percent level for all but tillage practice, which is significant at 95 percent. By showing the significance of these adaptations, Hansen highlights the importance of routine farm practices in adjustment to climate change. Assuming climate change takes the form of a 6.5-degree F increase in average July temperatures, Hansen estimates that corn yields would increase 43.8 percent where this variable is now 67.0 degrees F; yields would decrease 5.0, 38.7, and 69.6 percent where average July temperatures are now 70.0, 73.5, and 76.5 degrees F, respectively. A half-inch increase in average July precipitation increases corn yields between 1.1 percent and 10.7 percent, depending on current precipitation levels.

Hansen's results indicate that the Corn Belt could be particularly hard hit by climate change. Since average July temperatures in much of this area are at least 73.5 degrees F, Hansen's results imply that decreases in corn yields of at least 38 percent would be relatively common (that is, assuming a 6.5-degree F increase in average July temperatures). It may be possible in the future to assess the relative efficacy of these minor adaptations on corn and other crops, along with other adaptation alternatives like those considered by Kaiser and others.

Response models have also been used to assess potential impacts of climate change on U.S. livestock production. For summer months, studies tend to agree that in warmer areas, such as the South, climate change would hurt livestock; effects include reductions in animal weight gain, dairy output, and feed conversion efficiency (Hahn and others, 1990; Klinedinst and others, 1993; Baker and others, 1993). In cooler regions, impacts would be mixed; increased forage would improve grazing but capital-intensive operations, like dairy, would be hurt (Klinedinst and others; Baker and others). For fall and winter months, climate change is predicted to benefit livestock in all regions due to reduced feed requirements, increased survival of young, and lower energy costs.

The role of management and the potential for adaptation are also key in assessing the impact of climate change on livestock operations (Hahn and others; Baker and others; Klinedinst and others). The growth of dairy in the South is a testament to the creativity of farmers in finding ways to cool animals in hot climates (for example, shading, wetting, circulating air, and air conditioning). Other adaptations include herd reduction in dry years, shifting to heat-resistant breeds (for example, Brahman cattle), and replacing cattle with sheep.[7]

There are additional crop adaptations that have not been considered, like the development of new seed varieties that profit from longer growing seasons, the development of entire new crops, and other technological adaptations. Reilly (1995) finds that taking advantage of these additional adaptations involves significant time lags and long-term capital investment decisions, but including them could further reduce the negative impacts of climate change on crops.

The Capability To Adapt in Developing Countries

How the United States fares under climate change depends on the production impacts in the United States *relative* to those abroad. The capability of technologically advanced agricultural systems like those in the United States to adapt is thought to outstrip this ability in poorer developing countries. We focus on a single developing country to assess the potential for adaptation to climate change in Africa.

Jolly and others (1995) and Olowolayemo and others (1995) find that agricultural production in Senegal must be well planned and executed to avoid serious shortfalls from subsistence levels under climate change. Two of the country's three agricultural regions are expected to be self-sufficient, with one region producing three crops every year under irrigation, and the economy shifting from cash crops like cotton and peanuts (groundnuts) to maize, with the elimination of food imports. (Senegal presently imports over half of its food requirements, mostly rice.) Any surplus from two of the regions is expected to meet the shortfall in the third, mainly livestock, zone. The margin for error and uncertainty in the analysis is not discussed, but it is clear that few of the adaptation alternatives available to farmers in the Midwest are open to their counterparts in Senegal because of rainfall deficits.

Most production of crops is subsistence-level, with 75 percent of the population living in rural areas that rely on traditional or nonmechanized farming practices as their main source of income. The Government, with the aid of international organizations, has made substantial investments in agriculture over the last 30 years. During that time period, rainfall has declined at all Senegalese reporting stations, as it has across the Sudano-Sahelian region, and per-hectare production of food has fallen to almost half the level of the early 1960's. Over the last 50 years, the population of Senegal has more than doubled, with average per capita food production following per-hectare production. The studies conclude that Senegalese farmers should adapt by shifting from a cash to a staple system, requiring long-term and expensive investments in irrigation.

Uncertainty in Climate Change Impacts

Estimates of the effects of possible climate change on farm yields, much like annual estimates of farm productivity or estimates of the effects of an ongoing drought or flood, are uncertain (Schimmelpfennig, 1996). All farmers have a level of risk aversion, or willingness to bear risk. If climate uncertainty grows and the climate changes, this level of risk aversion may become very important. Yohe (1992), for example, demonstrates that if risk aversion is high, farmers may shift production from corn to sorghum, a more drought-tolerant crop, even though average corn returns are still higher under the new climate. Yohe's analysis highlights that farmers should not be expected to exhibit the same behavior after climate change that they do now. The farming system selects out farmers who are unwilling or unable to adapt to changing conditions by making those who do adapt more profitable. But how will the system respond to climate change?

It is because farmers are exposed to a significant degree of uncertainty in crop prices that hedging strategies, taking advantage of futures markets, have become a standard practice in the United States. The uncertainty of climate change, while not quantified, adds to the uncertainty that farmers and commodity markets routinely internalize. Existing markets for pooling price risk will expand and become even more

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[7] Hahn (1994) reports, for example, that the upper end of the optimal temperature zone for growing ad-lib-fed lambs is 2-3 degrees C higher than that for growing ad-lib-fed feeder calves.

widely used, especially if farm support programs and crop insurance continue to be cut back.

Another way to help farmers adapt to increased risk is to improve the information they receive. Schimmelpfennig and Yohe (1994) have developed an index of crop vulnerability to changes in the distribution of weather variables. With investments in research to expand the locations covered by the index, and education and training through extension services, farmers may use the index to signal appropriate times to switch from usual practices.

The following are incremental risks from a changing climate that farmers and farm markets will need to account for:

- **Extreme event risks**—If the average temperature rises, the climate may foster more extreme weather events, even though the spread or variability of the temperature distribution itself may not increase. Although there is very little evidence whether the variability of temperature will increase or decrease, an increase in temperature variance has the same effect without an increase in the mean. Both together compound the probability of extreme-temperature events.
- **Field-time availability risks**—More extreme precipitation events, both wet and dry, affect the timing of field operations. Extremely wet weather in the spring, as experienced by midwestern farmers in 1995, delays planting, possibly causing corn farmers to switch to soybeans. Dry weather late in the season reduces crop drying costs.
- **Yield risks**—When temperature and precipitation are too high or low, crop yields suffer. For example, 1988 was so dry that 30 percent of the anticipated corn harvest did not materialize, and California recently began to recover from a 7-year drought. It is difficult to forecast these events, but decisions concerning when to employ adaptation alternatives can be supported by the best available information.
- **Interactions between risk factors**—All of these risks are interrelated. Increased climate variability affects field-time availability, which in turn influences yield.

Farm-Level Adjustments Policy Summary

Many options currently available to U.S. farmers would facilitate adaptation to climate change. These include adoption of later maturing cultivars, change of crop mix, and shifting the timing of field operations to take advantage of longer growing seasons. Planning is essential, because significant time lags often accompany the strongest form of these adaptations.

When farm-level adaptations and responses to uncertainty are included in the analysis, the impact of climate change on U.S. producers can be neutral or positive. These impacts are assumed to occur gradually over long periods of time, allowing adaptations in both practices and institutions. Regional effects can be negative, offset by positive effects in other areas. Developing countries are exposed to greater negative impacts than the United States because developing countries have fewer adaptation alternatives available to them, experience larger population growth, and have smaller income growth to fall back on.

It will be important to design policies that encourage adaptation. If farmers implement appropriate adaptations, the impact of climate change on U.S. agriculture can be a matter of reallocating farming resources to different regions. This topic will be discussed again in the next chapter when the U.S. farming system as a whole and farm programs are considered. Policies also need to foster the development of markets that allow farmers to hedge their risks as they respond to climate's inherent uncertainty–uncertainty that may be growing as climate changes.

Chapter 3. National Adjustments to Climate Change

By altering temperature and precipitation conditions on a global scale, climate change threatens to shift national and world patterns of comparative advantage in the production of many crop and livestock products. The response of U.S. agriculture to climate change, then, will depend not only on how domestic farmers adapt to new environmental conditions, but also on a host of other factors that affect national and international commodity markets. In this chapter, we review recent research relating to potential impacts of climate change on U.S. agriculture and, to a lesser extent, the U.S. economy. Our objective is to see how results obtained in these studies can help address four questions of particular importance to national climate change policy.

- Are the aggregate economic impacts of climate change on U.S. agriculture and the U.S. economy likely to be positive or negative? As a related matter, which parts of the farm sector are most vulnerable to climate change?
- To what extent might negative climate change impacts on existing U.S. crop and livestock systems be mitigated or offset by farm-level adaptation and by international trade?
- How might climate change affect the allocation of U.S. land and water resources among competing uses?
- How can farm policy affect agriculture's response to climate change and are there actions the Federal Government might consider taking now?

Research Findings

Recently, Mendelsohn and others (1994), Adams and others (1995), and Darwin and others (1995) have investigated potential economic impacts of climate change on U.S. agriculture.[8] Adams and others develop estimates of climate change impacts on yields for specific crops; they then incorporate these impacts into a detailed analogous-regions model of U.S. agriculture. Mendelsohn and others and Darwin and others bypass explicit consideration of yield effects. These studies develop comprehensive measures of farm sector response to climate change from cross-sectional data on climate, economic activity, and resource endowments. Mendelsohn and others focus on the United States while Darwin and others take a global view.

Adams and others use quadratic programming to assess how climate change might affect the present structure of U.S. agriculture. Their spatial equilibrium model describes production and consumption of 42 primary and processed crop and livestock products. Production is modeled for 63 regions covering the contiguous 48 States; these are aggregated to 10 input supply regions for purposes of modeling agriculture's use of land, labor, and irrigation water. Demand is modeled at the national level and includes both domestic and foreign consumption. World commodity market conditions, however, are not endogenous to the model. Rather, changes in U.S. agricultural exports are keyed to forecasted changes in world food production from Rosenzweig and others (1993).

A base case scenario is obtained by running the model under 1990 climate, economic, and technology conditions. Crop yields, water supplies, and crop water use parameters in each region are then modified to reflect the $2xCO_2$ scenarios of the GISS, GFDL, and UKMO GCM's. Estimates of each scenario's impacts on crop yields are based on crop-response model results for corn, wheat, and soybeans from the U.S. sites reported in Rosenzweig and others (1994) (see chapter 2).

Among the three studies, the primary strength of Adams and others is its level of geographic and commodity detail. By disaggregating U.S. agriculture into 63 production regions and explicitly considering 30 primary crop and livestock commodities, the model indicates how regional producers might alter their output mixes in response to climate change. Viewed in total, these results indicate how climate change might shift national patterns of comparative advantage in the production of many crop and livestock products. A second strength of the study is that it explicitly considers CO_2 fertilization effects.

The main limitation of Adams and others is that its framework is partial equilibrium. Because it does not consider nonfood producing sectors, it assumes that agriculture's response to climate change is independent of the responses of nonagricultural sectors. In input markets, this means that climate change does not affect intersectoral competition for land and water resources. A second limitation is that farm-level adaptation to climate change is limited to choosing the most profitable output mix from a set of exogenously specified alternatives (and making the

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[8] Similar approaches were used in earlier studies by Dudek (1989), Adams and others (1990), and Easterling and others (1992).

Table 3.1—Land class boundaries in Darwin and others (1995)

Land class	Length of growing season	Days with soil temperatures above 5^{o} C	Principal crops and cropping patterns	Sample regions
1	0 to 100	125 or less	Sparse forage for rough grazing	Northern Alaska
2	0 to 100	More than 125	Millets, pulses, sparse forage for rough grazing	Mojave Desert
3	101 to 165	More than 125	Short season grains, forage: one crop per year	Palouse
4	166 to 250	More than 125	Maize: some doublecropping possible	Corn Belt
5	251 to 300	More than 125	Cotton, rice: doublecropping common	Tennessee
6	301 to 365	More than 125	Sugar cane, tropical fruits; double cropping common	Southeast coast

Compiled by Economic Research Service from Darwin and others (1995), USDA.

implied adjustments in land and water use). Hence, many feasible farm-level adaptations have been overlooked.

Mendelsohn and others take a statistical approach and use regression analysis and county-level data for the contiguous 48 States to estimate marginal effects of various climate, economic, and other factors on farmland values. They assume that all land is in its highest valued use so that farmland values reflect all economic opportunities of farmland. Climate variables, reflecting mean monthly temperature and precipitation levels for January, April, July, and October, allow the model to distinguish economic costs and benefits associated with climate change depending on when in the year impacts occur. Warmer temperatures in October, for example, would favor agriculture by extending growing seasons and facilitating harvest operations. Warmer temperatures in July, however, would tend to hurt agriculture by increasing plant stress and irrigation requirements.

Regressions are run weighting each county by the percentage of its area in farmland and by its crop revenue; each regression is estimated using data from 1978 and 1982. The crop revenue weights emphasize irrigated lands, where production is intense with high-value crops (for example, fruits and vegetables). The cropland weights emphasize areas where cool-season grains dominate production.

Climate change is simulated by uniformly increasing mean county temperature and precipitation levels by 5 degrees F and 8 percent. Under this scenario, irrigated lands expand (particularly in the West and South) and cool-season grain production contracts. Reflecting these land-use changes, the value of U.S. farmland falls $119 - $141 billion using the cropland-weighted model and increases $20 - $35 billion using the crop revenue-weighted model. Mendelsohn and others conclude that the revenue model gives the better economic measure of climate change impacts on U.S. agriculture because it more fully reflects the value of farm-level adaptations to new environmental conditions. The cropland model, however, shows how focusing on major grain producing areas can bias assessments of climate change impacts on U.S. agriculture.

Aside from valuing seasonal effects of climate change, the major strength of Mendelsohn and others' framework is that it captures effects of farm-level adaptation without having to enumerate specific actions. Climate-induced changes in farmland values assume that farmers adapt to new environmental conditions by altering input choices, production technologies, and crop mixes. Hence, farm-level adaptation is both implicit and endogenous in the model. Additionally, the set of adaptations available to farmers is by definition everything currently done in U.S. agriculture. The framework also implicitly allows nonagricultural sectors to compete for farmland because if the value of land goes too high or too low, it will exit agriculture.[9]

Mendelsohn and others' model has two limitations. First, because it only considers farmland values, it cannot assess how climate change impacts might be distributed among agents (for example, producers and

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[9] The model does not, however, let new land enter agricultural production.

Table 3.2—Current U.S. land and water endowments and percentage changes in endowments by climate change scenario

Resource	Present endowment	Percent change by scenario			
		GISS	GFDL	UKMO	OSU
	Million hectares	*Percent*			
Land class 1	120.45	-51.77	-54.84	-67.28	-43.57
Land class 2	300.97	-9.97	1.89	8.40	9.42
Land class 3	116.21	45.83	105.41	42.85	48.42
Land class 4	198.80	-14.84	-25.42	-27.96	-29.98
Land class 5	68.96	36.61	63.11	101.64	16.81
Land class 6	111.26	38.96	-49.54	-7.68	14.25
	Cubic kilometers				
Renewable water	2,478.00	-6.73	7.51	4.22	0.53
Water supply	467.00	-3.16	3.52	1.98	0.25

Climate change scenarios generated by the general circulation models of the Goddard Institute for Space Studies (GISS), the Geophysical Fluid Dynamics Laboratory (GFDL), the United Kingdom Meteorological Office (UKMO), and Oregon State University (OSU).

Compiled by Economic Research Service from Darwin and others (1995), USDA.

consumers). The underlying assumption that prices do not change means that consumers are not affected and that the net affect on global production is zero. Regionally, some producers gain what others lose. Second, being a partial equilibrium analysis, interactions between sectors and regions are not accounted for. It is assumed, for example, that climate change will not affect output prices, nonland input prices, or world trade flows. While climate change can affect the price of a given tract of land, the price of land with a given set of characteristics is fixed. The analysis also abstracts from adjustment costs associated with changing structural features related to agriculture (for example, irrigation systems). Hence, differences between model simulations reflect movements between points of longrun equilibrium.

Darwin and others combine a computable general equilibrium (CGE) model and a geographic information system (GIS) to analyze potential climate change impacts on U.S. agriculture, taking account of interactions with nonagricultural sectors and other global regions. Their model has 8 global regions, each with an 11-sector economy that produces 13 commodities. Agricultural sectors include crops and livestock; agricultural commodities include wheat, other grains, nongrains, and livestock. All regions consume, produce, and trade all 13 commodities. General equilibrium refers to the fact that prices clear all input and output markets simultaneously.

The GIS describes regional land areas in terms of endowments of up to six heterogeneous land classes. Land classes are differentiated by length of growing season, which is computed from mean monthly temperature and precipitation data (table 3.1). The GIS also describes regional water resources and helps to define unique production structures (that is, technologies, input and output mixes) for crops, livestock, and forestry for each region/land-class combination. The production structures are developed from cross-sectional data on current land cover, land use, and production. In this way, the production possibilities associated with a region's agricultural resources depend directly on its land class and water endowments.

Climate change scenarios are imposed in the GIS by adjusting global temperature and precipitation data to reflect the 2xCO_2 simulations of the GISS, GFDL, UKMO, and OSU GCM's. By altering regional land class and water endowments, these scenarios shift the production possibilities facing regional crop and livestock producers. Table 3.2 shows how each scenario would affect U.S. land and water resources. Percent changes in regional land class and water endowments associated with each scenario are then entered into the CGE model as factor endowment

Table 3.3—Estimated annual economic impacts of climate change on the U.S. economy

Scenario[4]	Adams and others[1]			Darwin and others[2]		Mendelsohn[3]	
	with CO_2 and trade effects	no CO_2 or trade effects	CO_2 effects but no trade effects	Land use restricted	Land use unrestricted	Cropland weights	Crop revenue weights
				Billion dollars			
A. Aggregate U.S. economic impacts:[5]							
GISS	10.82	-11.33	10.21	5.9	5.8	- 9.2	16.4
GFDL	4.37	-19.09	4.57	-11.1	- 4.8	-35.6	33.1
UKMO	9.03	-67.01	-17.58	- 1.2	1.1	-36.6	8.9
OSU	NA	NA	NA	- 6.6	- 3.9	-28.1	- 5.8
B: Impacts on U.S. agricultural producers:							
GISS	12.56	10.79	12.74	2.8	-1.5	- 9.2	16.4
GFDL	6.61	16.84	7.22	8.3	-1.5	-35.6	33.1
UKMO	44.44	114.97	41.52	8.2	-1.7	-36.6	8.9
OSU	NA	NA	NA	5.9	0.4	-28.1	- 5.8

[1] Part A reflects changes in total surplus. Part B reflects changes in producer surplus. In 1990 dollars, the base scenario total (producer) surplus was $1,124 billion ($21 billion).

[2] Part A reflects changes in 1990 Gross Domestic Product (GDP). Part B reflects changes in returns to agricultural land, capital, labor, and water resources.

[3] Reflects changes in the annual stream of returns to farmland due to climate change.

[4] Climate change scenarios generated by the general circulation models of the Goddard Institute for Space Studies (GISS), the Geophysical Fluid Dynamics Laboratory (GFDL), the United Kingdom Meteorological Office (UKMO), and Oregon State University (OSU).

[5] For comparison purposes, base scenario (Darwin and others) U.S. GDP was $5,497 billion (in 1990 dollars), and the annualized 1982 implicit return to agricultural land in 1990 dollars was $31.1 billion.

Compiled by Economic Research Service, USDA.

shocks. Given these shocks, the CGE model computes regional and world responses in commodity production, consumption, and trade.

The primary strength of Darwin and others is that the framework directly links land and water resources to climate conditions and economic activity on a global scale. Hence, estimates of climate change impacts on U.S. agriculture account for the full range of interactions with nonagricultural sectors and other global regions. As in Mendelsohn and others, farm-level adaptation to new environmental conditions is implicit and endogenous. When climate change forces a given tract of land into a new land class, that land assumes the production possibilities associated with its new region/land-class designation. Darwin and others also describe intersectoral competition for land and water resources explicitly. In model simulations, then, all input and output market impacts are internally consistent. Finally, Darwin and others do not consider adjustment costs and so, like Mendelsohn and others, their results also refer to points of longrun equilibrium.

Results of Studies

Part A of table 3.3 presents estimates of aggregate economic impacts of climate change on the U.S. economy as reported in Adams and others, Darwin and others, and Mendelsohn.[10] Because of the different methods used in these studies, direct comparisons of results must be qualified. Still, the studies agree that the economic impact of climate change on the U.S. economy is likely to be small. Whether this impact will be positive or negative, however, is uncertain.

For the GISS, GFDL, and UKMO climate change scenarios, Adams and others estimate total economic gains for the United States of $4.4-$10.8 billion (see "with CO_2 and trade effects" case). In this and each subsequent case, these are the figures reported in the executive summary and are considered to be generated by the appropriate statistical technique for

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[10] Mendelsohn has redone the analysis in Mendelsohn and others using the GISS, GFDL, UKMO, and OSU scenarios. For Part B of table 3.3, Darwin redid the impacts in Darwin and others for U.S. agricultural producers only. The discussion here refers to these updated impacts.

analyzing overall impacts on the U.S. economy. For the same scenarios and the OSU scenario, Darwin and others estimate total U.S. economic impacts ranging from -$4.8 billion to $5.8 billion (see "land-use unrestricted" case). Results in both studies are reported in 1990 dollars, implying a net climate change impact somewhere between -0.2 and 0.2 percent of U.S. gross domestic product. Impacts in Mendelsohn tend to be larger, ranging from -$5.8 billion to $33.1 billion for the four scenarios (see “crop revenue weights” case). Additionally, the three studies generally agree with respect to the direction of impact associated with each of the change scenarios. The exception is the GFDL scenario, where the aggregate effect is negative in Darwin and others and positive in Adams and others and Mendelsohn and others.[11]

The effects of climate change on agricultural producers will be marginally negative at worst, and moderately to very beneficial at best (table 3.3, part B). Results from Adams and others reflect changes in producer surplus associated with climate change. Focusing again on the “with CO_2 and trade effects” case, producer surplus increases $6.6-$44.4 billion across the three scenarios analyzed. These gains reflect increases in baseline (1990) producer surplus of between 31.4 and 200.1 percent (baseline producer surplus was $21 billion).[12] Additionally, the increases in producer surplus exceed the gains in total surplus in each scenario, implying negative impacts for U.S. consumers.

Results from the other studies are generally less favorable for U.S. agriculture than those in Adams and others.[13] With respect to Mendelsohn, 1982 gross U.S. farm income in 1990 dollars was $191 billion. Hence, the results imply climate change impacts on annual farm income of -3.0 to 17.1 percent. Results from Darwin and others reflect changes in annual returns to agricultural land. Income from agricultural land in their base case is $25.4 billion; the results then, imply climate change impacts on returns to agricultural land of between -7.8 and 5.8 percent.

Besides indicating potential magnitudes and directions of climate change impacts on the U.S. economy and U.S. agriculture, two additional points should be highlighted from table 3.3. First, among the three studies, only Adams and others consider CO_2 fertilization effects. In their results, accounting for CO_2 fertilization positively affects estimates of climate change impacts on the U.S. economy by $20-$40 billion per year (see columns 2 and 3 of part A); Part B shows that these gains generally accrue to producers. This suggests that the results reported by Mendelsohn, and Darwin and others would almost certainly be more optimistic if CO_2 fertilization had been accounted for.

The other point to highlight from table 3.3 is the potential bias inherent in using a partial, as opposed to a general equilibrium, framework for analyzing economic impacts associated with climate change. Of the three studies, only Darwin and others explicitly account for interaction effects between sectors and between regions; Mendelsohn abstracts from interregion effects and Adams abstracts from intersector effects. With respect to magnitude, the Mendelsohn, and Adams and others results are always larger than those in Darwin and others. Additionally, interaction effects can capture important differences in the distribution of costs and benefits. For example, in three of four scenarios, Darwin and others find that the United States is better off when all global land is allowed to change land use in response to climate change than when it is restricted to its present use (part A, columns 4 and 5). U.S. agriculture, however, is always better off when land use is restricted (part B, columns 4 and 5). This is because much of the land that enters agricultural production under climate change is outside the United States and trade allows

Table 3.4—Changes in U.S. agricultural land rents under various constraints, by climate change scenario[1]

Scenario	Farm-level adaptations only[2]	Price changes occur: Land use fixed	Price changes occur: No land-use restrictions
		Percent change	
GISS	4.1	0.8	-7.8
GFDL	-16.1	21.9	4.3
UKMO	-4.4	12.6	-5.4
OSU	-10.0	11.5	5.8

Compiled by Economic Research Service, USDA.

[1] Agricultural land is composed of cropland and pasture land.

[2] No price changes.

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[11] Adams and others do not consider the OSU scenario.

[12] Personal communication with R. Adams.

[13] Results in Parts A and B for Mendelsohn are identical because fixing output prices restricts impacts to agricultural producers.

Table 3.5—Base values and percentage changes in U.S. commodity production by climate change scenario

Commodity	Base value (1990)[1]	GISS		GFDL		UKMO		OSU	
		Rest.	Unrest.	Rest.	Unrest.	Rest.	Unrest.	Rest.	Unrest.
		Percent							
Wheat	74,475	8.191	5.986	14.761	12.392	10.518	9.374	6.087	1.479
Other grains	238,352	-5.177	-5.854	-10.638	-6.479	-9.804	-7.071	-9.298	-7.349
Nongrain crops	194,389	7.655	2.768	-3.454	-3.947	9.549	0.643	1.550	-0.317
Livestock	170,647	-0.464	-0.691	-1.476	-0.462	-1.512	-0.582	-1.819	-1.274
Forest products	498,000	0.566	0.713	-2.028	-0.818	-1.435	-0.470	-0.296	-0.253
Coal/oil/gas	215,073	-0.173	-0.010	-0.228	-0.063	-0.343	-0.042	-0.279	-0.166
Other minerals	24,786	-0.293	0.047	-0.050	0.136	-0.454	0.094	-0.284	-0.118
Fish/meat/milk	121,363	-0.081	-0.155	-0.837	-0.156	-0.736	-0.102	-0.987	-0.588
Other processed foods	292,850	0.380	0.130	-0.584	-0.372	0.072	-0.165	-0.327	-0.321
Text./cloth./footwear	155,999	0.091	0.091	0.021	-0.046	0.278	0.180	-0.082	-0.126
Other nonmetal. manuf.	1,067,890	0.048	0.099	-0.224	-0.027	-0.122	0.052	-0.207	-0.127
Other manuf.	1,266,520	-0.183	0.156	0.070	0.218	-0.213	0.258	-0.091	0.076
Services	6,103,870	0.050	0.077	-0.190	-0.075	-0.087	0.002	-0.156	-0.100

[1] For wheat, other grains, and nongrains, values are in 1,000 metric tons. For livestock, values are in 1,000 head. Forest products values are in 1,000 cubic meters. For all other commodities, values reflect total value of production (in million $U.S.).

Climate scenarios generated by the General Circulation Models of the Goddard Institute for Spaces Studies (GISS), the Geophysical Fluid Dynamics Laboratory (GFDL), the United Kingdom Meteorological Office (UKMO), and Oregon State University (OSU).

Rest. = cropland, pasture, forest, and land in other uses restricted to 1990 locations and quantities; Unrest. = all land can move between cropland, pasture, and other uses.

Compiled by Economic Research Service from Darwin and others (1995), USDA.

other regions to take advantage of this shift in comparative advantage.

An experiment undertaken for this report simulated the Mendelsohn and others approach using the Future Agricultural Resources Model (FARM). Table 3.4 shows percentage changes in agricultural land rents in the general equilibrium FARM when prices are assumed fixed. This is a closer direct comparison (than the one in table 3.3) of FARM and Mendelsohn's study that implicitly assumes that prices do not change. Comparing the first column of results in table 3.4 with columns 6 and 7 in table 3.3 indicates that FARM produces results closer to the crop revenue-weighted results than the cropland weights by Mendelsohn. When the fixed price assumption is relaxed in columns 2 and 3 of table 3.4 the results are more positive and somewhat similar to the crop revenue results obtained by Mendelsohn in table 3.3.

Table 3.5 shows climate change impacts on U.S. commodity production from Darwin and others. Focusing again on the "land-use unrestricted" case, impacts are small to moderate across commodities. These results also make clear that, regardless of the aggregate impact, climate change will likely have both positive and negative impacts within agriculture. In all scenarios, wheat production increases (the range is 1.5 to 12.4 percent), while output of other grains and livestock decline (the ranges are 5.9 to 7.3 percent and 0.5 to 1.3 percent). The drop in other grains is primarily due to reduced maize production in the Corn Belt under warmer and drier growing seasons, supporting results discussed in chapter 2. For nongrains, production increases or decreases depending on the scenario; the range is -3.9 to 2.8 percent. In food processing sectors, output generally declines; fish, meat, and milk decrease in all scenarios while other processed foods decrease in three scenarios.

Adaptation

The conclusion in Adams and others, Mendelsohn and others, and Darwin and others that climate change will not seriously threaten U.S. agriculture assumes that farmers will adapt their choices of inputs, production practices, and outputs to best suit their environments. The potential for farm-level adaptation to mitigate any negative impacts of climate change is highlighted by a series of simulations from Darwin and others (table 3.6). For each of the scenarios, Darwin and others estimate the impact on U.S. cereals (wheat and other grains) supply and production.

Table 3.6—Percentage changes in U.S. supply and production[1] of cereals under various constraints by climate change scenario

Scenario	Supply[2]		Production	
	No adaptation	With adaptation	Land use fixed	No restrictions
	Percent			
GISS	-21.5	-8.7	-2.0	-3.0
GFDL	-37.8	-22.3	-4.6	-2.0
UKMO	-34.1	-19.4	-3.2	-5.0
OSU	-31.9	-20.9	-5.6	-5.2

[1] Changes in supply show the additional quantities (positive or negative) that firms would be willing to sell at 1990 prices under the alternative climate. Changes in production show changes in quantities that firms would be willing to sell and consumers would be willing to buy at new market prices under the alternative climate.

[2] Land use is fixed in both supply cases, i.e., cropland cannot increase.

Compiled by Economic Research Service from Darwin and others (1995), USDA.

Supply effects represent changes in quantities (positive or negative) that producers would be willing to sell at 1990 prices under the alternative climates; production effects take into account changes in trade and consumer demand; that is, they show changes in what producers are willing to sell and consumers are willing to buy.

The "no adaptation" case in table 3.6 assumes that given new climate conditions, farmers do exactly what they are now doing. This case, then, shows how the four GCM's would impact current U.S. cereals production. Across scenarios, U.S. cereals supply decreases between 21.5 and 37.8 percent. The "adaptation" case allows farmers to alter mixes of inputs and outputs, but only on land currently in production and still holding prices fixed at 1990 levels. U.S. cereals supply now decreases between 8.7 and 22.3 percent. By adapting input and output choices on existing cropland then, cereals producers offset 35-60 percent of the initial climate-induced supply shock.

The "land-use fixed" case shows climate change impacts on current cereals production allowing for onfarm adaptation and changes in trade flows and consumer demand; total cropland, however, is still fixed at 1990 levels. Under these conditions, U.S. cereals production decreases between 2.0 and 5.6 percent. This implies that when all market-induced responses are accounted for, 82-91 percent of the initial climate change shock to U.S. cereals production is offset.

Finally, the “no restrictions” case allows global cropland to expand. Relative to the "land-use fixed" case, there are marginal reductions in the climate change shock on U.S. cereals producers in the GFDL and OSU scenarios. In the GISS and UKMO scenarios, however, the magnitude of the shock increases. This suggests that the global competitiveness of U.S. grain producers may depend on world agriculture’s ability to expand in areas where cold temperatures now limit crop production.

Land Use Changes and Regional Shifts in Production

By altering temperature and precipitation patterns, climate change will shift the production possibilities associated with land and water resources in much of the United States. These shifts, combined with changing economic conditions, will alter the nature of competition for land and water resources. Resulting land-use changes are likely to alter domestic patterns of commodity production, particularly in land-intensive crops, livestock, and forest products. Results in Mendelsohn and others and Darwin and others provide a number of insights into which economic activities and which areas of the United States stand to be most affected by climate change.[14]

In Mendelsohn and others, the cropland-weighted model emphasizes counties where grains are important. Grains tend to favor cooler temperatures. Assuming land now in grain production is in its highest valued use, generally warmer climates would hurt many grain producing areas. The crop revenue-weighted model, on the other hand, emphasizes irrigated lands in the West and South. In Mendelsohn and others, these lands expand under uniformly warmer temperatures. Hence, the climate change scenarios favor agriculture in much of the South and West.

In Darwin and others, imposing climate change scenarios causes between 38.9 and 55.3 percent of all U.S. land to shift to a new land class. Table 3.2 shows the percentage changes in each land class by scenario; percentage changes in land use, by scenario, are presented in table 3.7. Across scenarios, land in crop production increases (the range is 1.6 to 9.7 percent), while in three scenarios, land in pasture also expands. From a national perspective then, these

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[14] Adams and others discuss regional welfare effects but not regional production effects.

Table 3.7—Percentage of all U.S. land changing land use and net percentage changes in U.S. cropland, permanent pasture, forest land, and land in other uses, by climate change scenario

Climate change scenario	Percent of all U.S. land changing land use	Net percentage change in U.S.			
		Cropland	Pasture	Forest	Other Land
			Percent		
GISS	8.3	9.7	-0.1	2.9	-13.9
GFDL	14.1	3.9	0.7	2.3	-8.4
UKMO	15.1	4.9	7.0	0.6	-14.6
OSU	11.6	1.6	7.4	-0.8	-9.7

Compiled by Economic Research Service from Darwin and others (1995), USDA.

results suggest that climate change would increase the total amount of U.S. land in agricultural production.

At the same time, Darwin and others estimate that between 8.6 and 19.1 percent of existing U.S. cropland would leave production (table 3.8). Hence, some farm communities and agricultural industries are likely to be severely disrupted by climate change. The decreases in land class 4 (see table 3.1) in all scenarios in the Corn Belt and land class 6 (two scenarios) in the Southeast suggest negative impacts on existing agricultural systems. As for agricultural industries, results in Darwin and others suggest that climate change favors wheat production and restricts the output of other grains and livestock; effects on nongrain are uncertain (see table 3.5).

Uncertainty

Given all that is unknown about climate change, analysts and policymakers must accept uncertainty as given. Aside from the ultimate form of climate change, the impacts of several climate change events are much disputed; these include magnitudes of CO_2 fertilization effects, pest distribution effects, and the ability of agriculture to expand in the northern latitudes given warmer average temperatures. Finally, even if the aggregate national impact of climate change is small, sector and region impacts are uncertain and these could have more policy relevance than national effects. Economic analysis can help policymakers deal with climate change uncertainties in two important ways.

Table 3.8—New and abandoned U.S. cropland by climate change scenario

Climate change scenario	New cropland		Abandoned cropland	
	Million hectares	*Percent*	*Million hectares*	*Percent*
GISS	34.8	18.3	16.2	8.6
GFDL	43.8	23.1	36.4	19.1
UKMO	42.4	22.3	33.2	17.5
OSU	32.2	17.0	29.1	15.3

Compiled by Economic Research Service, USDA.

First, economic analysis can assess and compare impacts of different climate change scenarios as well as different policy responses. The quality of these analyses, however, depends on how well the economic models can reflect what is known about climate change or allow what is not known to be subjected to sensitivity testing. While economic models of U.S. agriculture under climate change have improved greatly in recent years, some capacities still need to be developed. Most important are developing the capacities to analyze climate change impacts: (1) among developing regions (since it appears that the most dramatic effects will be in these countries), and (2) in a dynamic framework (since climate change will evolve gradually over the next several decades).

The second way economic analysis can help climate change policy address uncertainty is by identifying those areas where uncertainty matters most; that is, areas where having the wrong information or understanding can most bias economic assessments of climate change. This allows resources to be targeted to areas where the payoff to reducing uncertainty is highest. One such area is improving our understanding of potential climate change impacts on regional water resources. The conclusion that climate change will not seriously threaten U.S. agriculture typically hinges on optimistic assumptions concerning the impact of climate change on water resources. The large increase in irrigated acreage obtained in Adams and others, for example, assumes agriculture has a first-right to water resources. Similarly, the expansion of irrigation implicit in Mendelsohn (see table 3.3) assumes that if an area becomes more arid, farmers will have to pay what they now pay in arid places for water. It is possible that under a generally drier climate, the prices of alternative water supplies could also be bid up.

In Darwin and others, the allocation of water (among regional crops, livestock, and services sectors) and its price are market-determined. Regional water markets, however, embody several important simplifications. First, water resources can be transported anywhere within a region at zero marginal cost. Also, snowpack is not considered and too much water does not hurt production. Given these simplifications, Darwin and others find that water scarcity decreases for the United States under the GISS, GFDL, and UKMO scenarios (that is, the price of U.S. water falls between 1.52 and 3.22 percent). In the OSU scenario, the U.S. water price rises 8.97 percent, reflecting an increase in scarcity. Further, when land is restricted to its present use (that is, cropland, pasture, forest, and other), water scarcity increases for the United States in all four scenarios; associated price increases are between 4.05 and 11.73 percent.

Another area where uncertainty can be reduced in analyses of climate change and U.S. agriculture is improving our understanding of world agriculture's potential for expanding into areas where cold temperatures now limit production (mainly in northern latitudes). Some argue that this potential is small due to the prevalence of poor soils and other limiting factors in these areas (Ward and others, 1989), but the prevailing view is that a significant potential exists.

Darwin and others show impacts on the U.S. economy under the assumptions that all global land can and cannot shift into new uses (columns 4 and 5 of table 3.3, part A). Within the United States, the land-use restricted case implies that fewer adaptations are available to farmers and that consumers have less ability to offset negative impacts in world commodity markets. As a result, aggregate costs to the U.S. economy are higher for all but the GISS scenario; the magnitude of the cost increase is about double that in the unrestricted case. For the GISS scenario, aggregate U.S. costs are about the same when land use is and is not restricted.

For U.S. agriculture, however, the net effect of restricting land use is generally positive. Imposing climate change and restricting land to its present use insulates U.S. farmers from losses in comparative advantage in agricultural production relative to the case where land can freely shift into new uses worldwide. The primary effects of restricting land use are favorable shifts in domestic patterns of commodity production (see table 3.6). In all scenarios, for example, wheat production increases but the increases are larger when land use is restricted.[15] Similarly, production of other grains and livestock decreases in all scenarios but, in all but the GISS scenario, the decreases are larger when land use is restricted. Output of nongrains increases or decreases depending on scenario, but the effects are always more optimistic (that is, more positive or less negative) when land use is restricted. These results suggest the worldwide expansion of agriculturally suitable lands under climate change hurts U.S. agriculture (tables 3.3 and 3.6).

Government Farm Programs

The view that agriculture could offset many negative impacts associated with climate change assumes that the Government will not create *disincentives* for farmers to adapt to new climate conditions. Lewandrowski and Brazee (1993) analyze how farm price and income support programs affect U.S. agriculture's response to climate change.

Using a simple portfolio model, Lewandrowski and Brazee develop three decision rules regarding a farmer's crop mix. More resources are allocated to producing crop *i* when: (1) the expected returns to crop *i* increase relative to other investments, (2) the risks associated with crop *i* decrease relative to other investments, and (3) the covariance, or the amount that returns to crop *i* and the returns to other assets move together, decreases. These rules are used to consider how farmers would respond to three climate change scenarios with and without the present set of farm programs in place. The scenarios are: (1) an increase in atmospheric CO_2, (2) higher atmospheric CO_2 and an increase in average temperature and precipitation levels, and (3) higher atmospheric CO_2 and increases in both the means and variances of current temperature and precipitation levels.

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[15] When land use is not restricted, large quantities of newly available cropland enter production in Canada and the former Soviet Union. This land is well-suited to growing wheat, so comparative advantage for wheat deteriorates for the United States and improves for Canada and the former Soviet Union relative to the case when land use is restricted.

Lewandrowski and Brazee conclude that farm price and income support programs discourage many obvious farm sector adaptations to climate change. Target prices and deficiency payments, nonrecourse loans, and multiyear penalties for reducing program acreage all dissuade farmers from switching crops. Disaster payments and subsidized crop insurance reduce consideration of crop failures in production decisions. In much of the West, Federal irrigation subsidies have discouraged investments in water-conserving technologies.

In the past, farm program costs have tended to be highest following very good harvests. This is because the Government must purchase (at above market prices) and store large quantities of output. Low prices also increase deficiency payments for some crops. Very poor harvests can also be costly. Federal disaster assistance to farmers following the 1988 drought totaled more than $3.1 billion. If climate change increases the occurrence of very good or very poor harvests, society could pay a high price for programs that discourage farmers from adapting to new environmental conditions.

A farm program adjustment to consider is how to encourage water conservation. Examples include removing institutional barriers to water markets in the West and promoting adoption of water-efficient irrigation technologies in general. Developing water markets and allowing water from Federal projects to move in those markets would facilitate the flow of water to its highest valued use. These markets, coupled with reform of water laws, would give farmers the resources and incentive to invest in more water-efficient irrigation systems. At present, the high cost of such systems makes their adoption unlikely by farmers who have access to adequate water supplies.

Aside from urban areas in the West, there may be other regions where promoting water conservation in agriculture is economically rational (for example, the Ogallala Aquifer in the Southern Plains and the Edwards Aquifer in Texas). Where irrigation is subsidized, where withdrawals exceed replacement, or where water has alternative uses, the social benefits of reducing agricultural water use may justify government programs to help farmers acquire more water-efficient irrigation systems. Farmers then, would also be in a better position to adapt to hotter and/or drier growing seasons.

Finally, disaster assistance payments could be tied to a moving average of yields over the past few years. Past disaster payments have been based on various measures of "average" production (for example, average county yields or average program area planted). In computing these averages, however, years with very low harvests have generally been omitted. The Disaster Assistance Acts of 1988 and 1989, for example, use similar definitions of "normal" production but the measures used in the 1989 Act do not include poor 1988 harvests. The effect then, is to bias upward the measure of "normal" production. Although aggregate agricultural impacts of gradual climate warming may be slightly positive, in any given area, growing conditions for the present mix of crops are likely to deteriorate slowly. We may perceive a series of crop failures before recognizing that the climate has changed. This modification provides a check against making a series of disaster payments when, in fact, yields are average given the new environmental conditions. Also, implementing the change would be inexpensive and would have no effect if the climate remained constant.

Along with the above changes in commodity programs, the Federal Government could help prepare the U.S. farm sector for possible climate change by promoting research aimed at maintaining agricultural productivity under possible future temperature and precipitation conditions. There is, at present, little economic incentive for private agents to undertake such research because its benefits typically will not be realized for several decades (if ever). Fuglie and others (1995) have estimated the average (historical) and marginal rates of return to public investments in agricultural research to be at least 35 percent. To date, this effort has focused largely on increasing yields.[16] Potentially large returns to research aimed at extending the temperature tolerances and/or reducing the water requirements of crops and livestock are indicated by the expansion of wheat production in the United States (particularly hard red winter wheat) and dryland corn production in Canada over the last 75 years (U.S. Congress, OTA, 1993).

Reilly and others (1996) provide a thorough review of these and other technological and socioeconomic factors that have been identified in the climate change literature as potentially important for adaptation to climate change. Chapter 2 discussed changing crop seasons and planting dates, developing new crops and

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[16] Between June 1, 1984, and June 1, 1989, for example, USDA released 599 new plant varieties and germplasms; of these, 80 percent had improved disease resistance, 30 percent had better insect resistance, and 10 percent were more resistant to nematodes (Senft and McNeil, 1995).

crop varieties, and improving farm management practices. Other areas where public agricultural R&D could help prepare U.S. agriculture for possible climate change include developing new irrigation and tillage systems, improving short-term climate prediction, implementing training and education programs, and improving transportation and market integration systems.

Conclusions

This chapter has discussed recent evidence relating to the potential roles of farm-level adaptation, international trade, intersectoral competition for land and water resources, and government farm programs in shaping the response of U.S. agriculture to climate change. In response to the questions posed at the beginning of the chapter, five broad results have emerged from this work.

- Climate change is not likely to seriously disrupt the U.S. economy—most estimates suggest aggregate economic impacts of between -0.2 and 0.2 percent of gross domestic product. It is also unlikely that the ability of U.S. agriculture to meet domestic food needs will be threatened.

- Throughout the United States, climate change will alter the production possibilities associated with land and water resources. Farm-level adaptation (that is, adjusting input choices, technologies, and output mixes) will enable U.S. agriculture to mitigate most negative impacts that climate change might have on current production practices.

- Shifting production possibilities and changing economic conditions will alter the nature of competition for land and water resources among economic sectors. Resulting land-use changes will alter domestic patterns of crop and livestock production. While net impacts on U.S. agriculture are likely to be small, some regional impacts could be very disruptive.

- Major areas of uncertainty regarding U.S. agriculture and climate change include the form of climate change, potential impacts on water supplies, and the ability of global agriculture to expand into areas where production is now limited by cold temperatures.

- Government farm price and income support programs largely discourage farm sector adaptation to climate change, but water and disaster assistance programs and agricultural R&D could facilitate adaptation to climate change.

Chapter 4. Global Adjustments to Climate Change

Agriculture's response to climate change will depend not only on the new climatic conditions facing farmers and agriculture's interactions with other domestic sectors, but also on the responses of producers and consumers around the world as signaled through prices determined in global markets. International trade in agricultural and food products has been steadily increasing over the last several decades and now averages about $335 billion per year (FAO, 1994). This amount is still small relative to agricultural production (about 15 percent of world production), but a well-functioning international trading system gives price signals to agriculturalists to help meet increasing demands for food with more efficient allocation of production across countries. As demonstrated in early studies of the global impacts of climate change (for example, Kane and others, 1991), how international prices and production change as a result of climate change can easily be more important to a national or local economy than the initial impact of climate change on the agricultural sector of the economy. Thus, even if one's principal interest is in the effect of climate change on a single country such as the United States, it is essential to consider the impact of climate change on that country's current and potential export markets and export competitors' markets.

Several studies have examined various aspects of global climate change impacts on world agricultural production and trade. A number of these analyses used the supply shocks reported by Rosenzweig and others (1993) and Rosenzweig and Parry (1994) that were developed from an extensive set of crop-response modeling studies (Rosenzweig and Iglesias, 1994). As a result, this group of analyses do not provide fully independent estimates of potential climate change impacts. Differences between results reflect differences in the economic models used to evaluate supply changes. As demonstrated in previous chapters, different methods for estimating the initial effects of climate change (before producers and consumers respond to changing prices) can give widely varying results. Thus, we focus our comparison of the results of global studies on the group of studies that rely on the crop-response modeling studies of Rosenzweig and Parry (1994) and Darwin and others (1995), which use completely independent approaches for estimating the initial impact of climate change on crop production. In addition, the impacts and potential to adapt may affect developing countries differently. We consider a unique study investigating how climate change might affect developing countries with different 'archetype' agricultural economies (Winters and others, 1994).

The principal objectives of this chapter are to consider answers to the following questions.

- Is global food production likely to be seriously threatened by climate change?
- What is the potential for adaptation to climate change in the global agricultural economy?
- How might the effects of climate change differ regionally and can we identify potential winners and losers from climate change?
- What effects might agricultural adjustment have on patterns of land use, particularly in areas currently devoted to forests and other unmanaged or less intensively managed ecosystems?

Climate Change in Economic Models of Global Agriculture

The most important issue in assessing the economic impact of climate change on global agriculture is the modeling of climate change itself. Factors generating differences in results are (1) the climate change scenario considered, (2) the method used to estimate the initial climate change impact, (3) whether the direct effect of CO_2 on plant growth is considered, and (4) the extent to which farm-level adaptations are considered (table 4.1).

Climate Change Scenarios. General Circulation Models (GCM's) provide the most detailed projections of Earth's climate under elevated atmospheric CO_2 levels. Four GCM scenarios have been popular in assessing the economic impacts of climate change on world agriculture. These scenarios are the $2xCO_2$ simulations of the models at the Goddard Institute for Space Studies (GISS), the General Fluid Dynamics Laboratory (GFDL), the United Kingdom Meteorological Office (UKMO), and Oregon State University (OSU).[17]

Climate Change Impact Methods. Two approaches have been used to incorporate climate change impacts into economic models of world agriculture. Most authors select a GCM scenario and then use *crop-response models* to estimate impacts of climate

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[17] Chapter 1 discusses GCM's in more detail, as well as methods for estimating climate change impacts.

Table 4.1--Selected studies estimating the impact of climate change on global agriculture: modeling climate change

	Study					
	Kane and others, 1991	**Reilly and others, 1994**	**Winters and others, 1994**	**Tsigas and others, 1996**	**Rosenzweig and others, 1993**	**Darwin and others, 1995**
Climate change scenarios	*Moderate impacts* scenario from IPCC, Working Group II on Impacts	General circulation models: GISS, GFDL, UKMO.	General circulation models: GISS, GFDL, UKMO	General circulation model: GISS	General circulation models: GISS, GFDL, UKMO.	General circulation models: GISS, GFDL, UKMO, OSU
Modeling of climate change	Exogenous changes in crop yields based on a literature survey of crop yield changes and sensitivity analysis linked to stylized potential regional climate impacts.	Exogenous changes in crop yields based on Rosenzweig and others, 1993.	Exogenous changes in crop yields based on Rosenzweig and others, 1993.	Exogenous changes in crop yields based on Rosenzweig and others, 1993.	Exogenous changes in crop yields from crop response models for wheat, rice, maize, and soybeans. Yields of other crop commodities were also changed (based on review of the literature).	Climate change affects productivity of land resources, and water availability
Direct effect of CO_2 on crop growth	Not considered	Simulations without and with CO_2	Simulations with CO_2	Simulations without and with CO_2	Simulations without and with CO_2	Not considered
Farm-level adaptations	Not specifically evaluated	Adaptations reflecting small shift in planting date, increased irrigation for irrigated crops, change in crop variety.	Adaptations reflecting small shift in planting date, increased irrigation for irrigated crops, change in crop variety.	Not considered	Two levels of adaptation: *Level 1*: small shift in planting date, increased irrigation for irrigated crops, change in crop variety; and *Level 2*: large shift in planting date, increased use of fertilizer, installation of irrigation systems, development of new crop varieties	Endogenous adaptations within limits of existing agricultural and silvicultural systems in a region

Climate change scenarios generated by the general circulation models of the Goddard Institute for Space Studies (GISS), the Geophysical Fluid Dynamics Laboratory (GFDL), the United Kingdom Meteorological Office (UKMO), and Oregon State University (OSU).
Compiled by Economic Research Service from studies listed above.

change on field-level crop yields. Typically, a set of yield impacts are estimated that embody various adaptations on the part of farmers to new climatic conditions (for example, shifting planting dates and switching crops or cultivars). The field-level results are then used to estimate national and regional yield impacts, which are plugged directly into economic models as changes in crop productivity.

The most comprehensive use of crop-response models to assess the impacts of climate change on crop yields is reported in Rosenzweig and Iglesias (1994). For 112 sites in 18 countries, crop-response models are run for wheat, maize, rice, and soybeans assuming climate conditions reflecting the GISS, GFDL and UKMO 2xCO_2 scenarios. Other crop-response model results are used to provide information on other crops. These studies are the basis of national and regional climate change impact shocks as developed by Rosenzweig and Parry (1994). Except for Darwin and others (1995), all studies reviewed here borrow climate change impacts on crop yields from Rosenzweig and Parry (1994) and thus are based on the Rosenzweig and Iglesias crop-response studies (table 4.1). Tsigas and others (1996) provide a useful point of comparison. This study uses the yield shocks of Rosenzweig and Parry (1994) with the same basic economic data base and general equilibrium modeling structure as that used by Darwin and others (1995). Thus, the main difference between Tsigas and others (1996) and Darwin and others (1995) is how the initial climate shock affects regional agricultural production potential.

Darwin and others (1995) apply the *spatial analogues* (IPCC, 1994) approach to incorporate climate change impacts into the Future Agricultural Resources Model (FARM) of world agriculture. The spatial analogues approach assumes that the geographic distribution of crops is primarily a function of temperature and precipitation conditions. By matching current crop production patterns with current climate conditions, one can project how current production patterns will change under alternative temperature and precipitation conditions. Darwin and others (1995) extend the spatial analogues approach by allowing all input and output markets to fully adjust to production possibilities associated with new climate conditions.

Direct Effect of Atmospheric CO_2 on Crop Growth. Numerous studies have shown that elevated levels of atmospheric CO_2 boost crop and forest growth rates, and water use efficiency under managed experimental conditions (see chapter 1). Rosenzweig and others (1993); Reilly, Hohmann, and Kane (1994); and Tsigas, Frisvold, and Kuhn (1996) examine the sensitivity of world agriculture to CO_2 fertilization. All of these studies rely on the crop-response modeling simulations conducted by Rosenzweig and Iglesias (1994). The importance of the CO_2 fertilization effect in these analyses (see table 4.1) in terms of crop yields is demonstrated for the GISS scenario shown in table 4.2. Part A shows that when only changes in regional temperature and precipitation levels are considered, the impact of climate change on crop yields is negative across regions. For the world as a whole, yields fall 16 to 26 percent, depending on the crop. Regional yield effects may vary. In Mexico and the ASEAN region, for example, average rice yields drop by more than 43 and 35 percent. At the other extreme are Canada and the European Union, where decreases in crop yields are never more than 12 percent.

When CO_2 fertilization is accounted for, impacts of climate change on agriculture are far less adverse and in most cases beneficial. With the exception of Mexico and the ASEAN region, the adverse consequences of climate change are largely offset if not reversed (table 4.2, part B).

Farm-Level Adaptations. Increased atmospheric CO_2 levels not only affect global temperature and precipitation patterns, but also cause other changes like shifts in the geographic distributions of agricultural pests. All of these changes taken together are likely to affect the production possibilities associated with agricultural resources in much of the world. Over time, farmers in these areas can be expected to adjust their input/output mix and production technologies to best suit their new climate and economic conditions, as discussed in chapter 2.

Most studies reviewed here allow for some adaptation on the part of farmers to climate change. Rosenzweig and others (1993) incorporate adaptation by exogenously specifying sets of actions that farmers can use to respond to new environmental conditions. Rosenzweig and others (1993) is the most detailed study in this respect because it considers two levels of adaptation. *Minor* (or *level 1*) adaptations reflect actions that today's farmers could easily take and include shifting planting dates 1 month, increasing irrigation water on existing irrigated land, and switching to new, but existing, crop varieties. *Major* (or *level 2*) adaptations include shifting planting dates in excess of 1 month, increasing fertilizer use, expanding irrigation systems, and developing new crop varieties. Reilly and others (1994) and Winters

Table 4.2—Regional crop yield changes for GISS scenario[1] as estimated by Rosenzweig and Parry

	Canada	United States	Mexico	EU	China	ASEAN	Australia	ROW	World
					Percent change				
A. Impacts without the direct effect of CO_2 on crop growth									
Rice	0	-18	-43	0	-24	-35	-13	-26	-26
Wheat	-12	-21	-53	-12	-5	0	-18	-22	-16
Other grains	-5	-20	-43	-8	-21	-40	-16	-16	-18
B. Impacts with the direct effect of CO_2 on crop growth									
Rice	0	1	-24	0	-3	-8	-12	-8	-7
Wheat	27	-2	-31	8	16	0	8	5	6
Other grains	15	-16	-35	1	-14	-33	5	-3	-9

[1] Climate change scenario generated by General Circulation Model of the Goddard Institute for Space Studies (GISS).

Notes: EU denotes the European Union-12. The ASEAN (Association of South East Asian Nations) region consists of Indonesia, Malaysia, the Philippines, Singapore, and Thailand.

Compiled by Economic Research Service from Tsigas and others (1996).

and others (1994) use the yield and supply shocks generated by Rosenzweig and others (1993) and hence they consider the same set of adaptations. These studies have used only the minor (level 1) adaptation scenarios on the assumption that the major (level 2) adaptations would occur only if prices rise sufficiently to justify the additional cost, and adaptations arising from price changes are already reflected in the modeled response of supply to price changes in the economic models used in these studies.

Another method is to make adaptations to climate change endogenous in the economic model. This is the approach taken by Darwin and others. In the FARM model, each region/land-class combination is associated with a unique set of production characteristics—at least with respect to crops, livestock, and forestry. These characteristics reflect differences in land-use patterns as they are determined by land productivity (that is, relative suitability for crops, livestock, and forestry production); crop mixes (for example, wheat-intensive vs. other grains-intensive); and input mixes. Climate change can cause a given tract of land to assume production characteristics that embody all adaptations on the part of crop, livestock, and forestry producers to the new climate conditions.

Specification of Economic Models

The choices of economic framework, region and commodity specification, and frame of reference can all affect model simulation results. However, these differences appear less important in the final result than how the initial climate impacts were estimated. Structural differences in modeling approaches reflect different degrees of regional and crop detail and varying attention to agricultural sector interactions with the rest of the economy or with competing land and water using sectors (table 4.3). As a result, different models have comparative strengths for different purposes. For example, the model of Darwin and others (1995) is unique in that it has a more complete and detailed specification of climate impacts on nonagricultural sectors that compete for agricultural resources such as land and water. Land resources provide the link between economic markets and changes in climate conditions. The Basic Linked System (BLS) model used by Rosenzweig and others (1993) is able to represent dynamic economic response over time. Winters and others (1994) concentrate on modeling interactions of the agricultural and nonagricultural sectors of developing countries and how such economies interact with world markets that are not well captured in global models. The SWOPSIM model used by Kane and others (1991) and Reilly and others (1994) has considerable detail on commodities, including interaction of crop and livestock sectors, while the other models generally treat agricultural sector interactions with the rest of the economy but have less commodity detail.

Results

Climate change may cause significant declines in the productivity of existing agricultural systems in some regions of the world (table 4.2). Results from the six studies reviewed here, however, suggest that the economic impacts of these declines will be largely

Table 4.3--Selected studies estimating the impact of climate change on global agriculture: specification of economic models

	Kane and others, 1991	Reilly and others, 1994	Winters and others, 1994	Tsigas and others, 1996	Rosenzweig and others, 1993	Darwin and others, 1995
Economic model	Static World Policy Simulation (SWOPSIM) Model: comparative statics, multi-product, multi-region, partial equilibrium	Static World Policy Simulation (SWOPSIM) Model: comparative statics, multi-product, multi-region, partial equilibrium	3 archetype, comparative statics, general equilibrium models	Global Trade Analysis Project (GTAP) Model: comparative statics, multi-region, general equilibrium	Basic Linked System (BLS): multi-region, general equilibrium, sequenced through time to obtain series of temporary equilibria	Future Agricultural Resources Model (FARM): comparative statics, multi-region, general equilibrium
Benchmark	1986	1989	2050	1992	2060	1990
Regions	13 regions: USA, Canada, European Union-12, N. Europe, Japan, Australia, China, Former Soviet Union, Brazil, Argentina, Pakistan, Thailand, Rest-of-World	33 regions: USA, Canada, European Union, Other W. Europe, Japan, Australia, N. Zealand, S. Africa, E. Europe, Former Soviet Union, China, Mexico, C. America & Caribbean, Brazil, Argentina, Venezuela, Other Lat. America, Nigeria, Other Sub-Saharan Africa, Egypt, Middle East & N. Africa-Oil, Other Middle East & N. Africa, India, Other S. Asia, Indonesia, Thailand, Malaysia, Philippines, Other SE Asia, S. Korea, Taiwan, Other E. Asia, Rest-of-World	representative of low income, cereal importing countries in Africa, Asia, and Latin America	8 regions: Canada, USA, Mexico, European Union-12, China, Association of South East Asian Nations (ASEAN), Australia, Rest-of-World	34 regions: USA, Canada, European Union-12, E. Europe & Former Soviet Union, Japan, Australia, China, India, Brazil, Argentina, Pakistan, Thailand, Kenya, Mexico, Nigeria, Austria, N. Zealand, Egypt, Turkey, Indonesia, 5 Regions for Africa, 3 Regions for Other Latin America, 5 Regions for Other Asia, and Rest-of-World	8 regions: USA, Australia & New Zealand, Canada, Japan, Other East Asia, Southeast Asia, European Union-12, Rest-of-World
Commodities	22 farm & food commodities: cotton, sugar, tobacco and livestock, cereals, and oil crops commodities	22 farm & food commodities: cotton, sugar, tobacco and livestock, cereals, and oil crops commodities	8 commodities for Africa and Asia: cash crops, food crops, other agriculture, agricultural processing, energy, manufactures, construction & services, government services. 7 commodities for Latin America: cash crops, other agriculture, oil & minerals, other energy, manufactures, construction & services, government services	8 commodities: rice, wheat, other grains, other crops, livestock, processed agriculture, manufactures, services	10 commodities: wheat, rice, coarse grains, protein feeds, red meats, dairy products, other animal products, other food, non-food agriculture, non-agriculture	13 commodities: wheat, other grains, non-grain crops, livestock, forestry, energy mining, other minerals, fish-meat-milk, other proc. foods, textiles etc, other non-metallic manufactures, other manufactures, services

Compiled by Economic Research Service from studies listed above.

Table 4.4—Kane and others study: regional welfare impacts

Country/region	Welfare impact	
	Million 1986 $US	*Percent GDP*
United States	194	0.005
Canada	-167	0.047
European Union-12	-673	0.019
Northern Europe	-51	0.010
Japan	-1,209	0.062
Australia	66	0.038
China	2,882	1.280
Former Soviet Union	658	0.032
Brazil	-47	0.017
Argentina	95	0.120
Pakistan	-50	0.153
Thailand	-33	0.081
Rest of world	-67	0.002
World total	1,509	0.010

Compiled by Economic Research Service from Kane and others (1991).

offset through farm-level adaptations, international trade, and CO_2 fertilization. We first review the aggregate impacts of climate change on world welfare and world agriculture; we then consider some regional results. Next, we discuss some environmental impacts that would be consistent with study results. Finally, we consider the potential roles that CO_2 fertilization and adaptation might play in mitigating any negative impacts climate change might have on existing agricultural systems.

Global Impacts. Tables 4.4 - 4.7 detail aggregate regional and world economic impacts associated with various climate change scenarios. These results suggest that the impact of climate change on world agriculture and welfare will likely be small; whether these impacts are positive or negative, however, depends on the scenario considered and the underlying assumptions concerning CO_2 fertilization, and farm-level adaptation.

For their moderate-impacts climate change scenario, Kane and others (1991) find that world gross domestic product (GDP) increases by 0.01 percent (US$ 1.5 billion in 1986) (table 4.4). Effects on global GDP in Tsigas and others (1996) and Darwin and others (1995) are of similar magnitude. For the GISS climate change scenario and allowing for CO_2 fertilization, Tsigas and others estimate that global GDP would increase 0.007 percent (US$ 1.5 billion in 1992) (table 4.6, part B). Darwin and others find that under the GISS, GFDL, UKMO, and OSU scenarios, impacts on 1990 world GDP are 0.01, -0.01, -0.12, and 0.12 percent (table 4.7, part A).

The most pronounced climate change impacts on the world economy are reported by Reilly and others

Table 4.5—Reilly and others study: welfare impacts for selected regions by climate change scenario

Country/region	No CO_2, no adaptation			With CO_2, no adaptation			With CO_2 and adaptation		
	GISS	GFDL	UKMO	GISS	GFDL	UKMO	GISS	GFDL	UKMO
					Million 1989 US$				
United States	7,048	6,228	5,413	-775	1,374	-4,586	253	-667	-788
Canada	1,696	3,836	2,073	-9	848	896	-56	390	593
European Union-12	-11,051	-16,384	-11,476	2,228	-1,487	-6,051	3,381	628	-2,890
Japan	-12,827	-19,809	-29,082	1,290	-2,016	-7,839	2,170	-501	-4,686
Australia	4,450	7,868	18,585	-47	887	3,768	-116	378	2,206
China	-34,549	-43,603	-66,708	1,039	80	-275	2,535	2,199	3,183
Former Soviet Union	-8,866	-21,292	-49,166	1,367	-1,502	-10,403	1,859	-293	-5,020
Brazil	-2,666	672	-374	-319	19	-150	-486	-194	-908
Argentina	3,242	3,775	11,419	-373	151	3,782	-579	-107	2,039
Thailand	116	2,190	1,312	215	655	463	141	398	281
Rest of world	-62,064	-72,121	-130,120	-4,742	-13,289	-40,830	-2,099	-8,366	-31,633
World total	-115,471	-148,640	-248,124	-126	-17,028	-61,225	7,003	-6,135	-37,623

[1] Climate change scenarios generated by General Circulation Models of the Goddard Institute for Space Studies (GISS), the Geophysical Fluid Dynamics Laboratory (GFDL), and the United Kingdom Meteorological Office (UKMO).

Note: figures for rest-of-the-world calculated from data in Reilly and others (1994).

Compiled by Economic Research Service from Reilly and others (1994).

Table 4.6—Tsigas and others study: regional welfare impacts and change in consumer prices for GISS scenario

Impact	Canada	United States	Mexico	EU	China	ASEAN	Australia	ROW	World
A. With yield impacts which do not account for direct effect of CO_2 on crop growth									
					Percent change				
Consumer prices	1.57	1.14	7.58	1.46	13.29	8.68	2.19	3.16	na
Welfare change	-0.02	-0.56	-6.70	-1.02	-7.23	-7.59	-0.21	-2.48	-1.75
					$				
Welfare change	-93	-29,499	-20,356	-60,323	-33,596	-28,149	-533	-180,957	-353,505
B. With yield impacts which account for direct effect of CO_2 on crop growth									
					Percent change				
Consumer prices	0.16	0.01	2.35	-0.01	-0.20	0.84	0.04	0.07	na
Welfare change	0.50	0.04	-2.78	0.29	0.54	-1.73	0.26	-0.12	0.007
					$				
Welfare change	2,629	2,026	-8,273	17,253	2,397	-6,216	681	-8,958	1,539

Notes: Welfare change in dollars is in millions of 1990 US dollars and as a percent of 1990 GDP.A consumer price index was not calculated for the world as whole. EU denotes the European Union-12.The ASEAN (Association of South East Asian Nations) region consists of Indonesia, Malaysia, the Philippines, Singapore, and Thailand.

Compiled by Economic Research Service from Tsigas and others (1996).

Table 4.7—Darwin and others study: regional welfare impacts by climate change scenario

Scenario[1]	United States	Canada	EU	Japan	OEA	SEA	ANZ	ROW	World
				Billion 1990 $US (Percentage of 1990 GDP)					
A. Simulations with unrestricted land use									
GISS	5.7 (0.1)	11.3 (1.9)	-56.5 (-0.9)	23.1 (0.8)	3.0 (0.4)	-2.7 (-0.9)	.3 (0.1)	17.9 (0.4)	2.2 (0.01)
GFDL	-4.8 (-0.1)	13.6 (2.3)	-42.1 (-0.7)	17.2 (0.6)	3.1 (0.4)	-3.9 (-0.6)	-.9 (-0.2)	13.1 (0.3)	-2.6 (-0.01)
UKMO	1.2 (0.0)	16.5 (2.8)	-63.2 (-1.1)	10.0 (0.3)	3.1 (0.4)	-3.9 (-1.3)	-1.6 (-0.4)	13.4 (0.3)	-24.5 (-0.1)
OSU	-3.9 (-0.1)	11.0 (1.9)	-20.5 (-0.3)	21.6 (0.7)	1.6 (0.2)	-.5 (-0.2)	3.0 (0.8)	12.9 (0.3)	25.2 (0.1)
B. Simulations with restricted land use									
GISS	5.9 (0.1)	10.4 (1.7)	-68.0 (-1.1)	18.1 (0.6)	1.5 (0.2)	-4.6 (-1.6)	.7 (0.2)	9.6 (0.2)	-26.3 (-0.1)
GFDL	-11.1 (-0.2)	11.6 (2.0)	-52.3 (-0.9)	8.7 (0.3)	.2 (0.0)	4.0 (-1.3)	-.4 (-0.1)	4.7 (0.1)	-42.6 (-0.3)
UKMO	-1.2 (-0.0)	14.1 (2.4)	-77.4 (-1.3)	1.3 (0.0)	-1.4 (-0.2)	-7.8 (-2.6)	-.7 (-0.2)	-1.2 (-0.0)	-74.3 (-0.3)
OSU	-6.6 (-0.1)	9.6 (1.6)	-27.0 (-0.5)	15.5 (0.5)	-.3 (-0.0)	-1.9 (-0.6)	3.5 (1.0)	6.3 (0.1)	-.7 (-0.0)

[1] Climate change scenarios generated by General Circulation Models of the Goddard Institute for Space Studies (GISS), the Geophysical Fluid Dynamics Laboratory (GFDL), the United Kingdom Meteorological Office (UKMO), and Oregon State University (OSU).

Notes: EU denotes the European Union-12; OEA denotes Other East Asia; SEA denotes South East Asia; and ANZ denotes the aggregate of Australia and New Zealand.

Compiled by Economic Research Service from Darwin and others (1995).

Table 4.8—Reilly and others study: percentage change in world prices for agricultural and food commodities by climate change scenario[1]

	With CO_2, no adaptation			With CO_2 and adaptation		
Commodity	GISS	GFDL	UKMO	GISS	GFDL	UKMO
			Percent change			
Beef	0.74	2.19	4.82	-0.39	0.98	2.68
Pork	1.38	6.62	16.33	-1.76	2.79	9.27
Lamb	-0.14	0.14	0.41	-0.51	-0.02	-0.33
Poultry meat	1.84	6.88	16.43	-1.52	2.95	9.22
Poultry eggs	1.00	5.58	13.96	-1.60	2.33	7.86
Butter	-0.56	-1.94	-3.79	-0.05	-0.97	-2.72
Cheese	0.04	0.28	0.75	-0.15	0.10	0.36
Milk powder	0.40	1.55	3.28	-0.17	0.72	2.06
Wheat	-17.83	20.41	88.20	-21.84	2.18	49.70
Maize	24.35	43.80	91.66	1.30	19.59	44.21
Sorghum	1.02	27.19	74.10	-6.72	12.79	42.35
Rice	34.01	41.17	109.12	24.15	22.84	78.09
Soybeans	-17.14	-3.66	63.42	-20.26	-7.15	28.31
Soybean meal	0.45	10.22	37.22	-5.51	3.49	19.14
Soybean oil	-19.04	-11.21	27.76	-18.57	-10.50	12.92
Groundnuts	-21.38	-8.90	36.19	-22.76	-11.96	23.48
Groundnut meal	-2.71	6.80	30.15	-7.27	1.05	17.44
Groundnut oil	-12.22	-6.19	14.31	-12.43	-6.97	9.51
Cotton	-21.32	-12.09	42.47	-22.22	-14.23	26.61
Sugar	16.30	25.99	87.29	14.48	20.10	78.15
Tobacco	-26.43	-13.90	28.11	-42.02	-32.89	-5.39

[1] Climate change scenarios generated by General Circulation Models of the Goddard Institute for Space Studies (GISS), the Geophysical Fluid Dynamics Laboratory (GFDL), the United Kingdom Meteorological Office (UKMO), and Oregon State University (OSU).

Compiled by Economic Research Service from Reilly and others (1994).

(1994) and are based on the crop response impacts of Rosenzweig and Parry (1994). Given world agriculture as it existed in 1989 and allowing for both CO_2 fertilization and minor farm-level adaptations, these authors estimate that world GDP would increase US$ 7 billion under the GISS scenario; they also find that world GDP would decrease US$ 6.1 billion and US$ 37.6 billion under the GFDL and UKMO scenarios (table 4.5, column 3). While the magnitudes of these impacts are larger than those reported in the other studies, they are still less than 0.2 percent of 1989 world GDP.

Tables 4.8 - 4.10 present climate change impacts on world commodity markets. These results, along with results in Kane and others (1991) and Rosenzweig and others (1993), suggest that climate change is unlikely to severely disrupt global food production. For their moderate-impacts scenario, Kane and others find that world crop prices decline an average of 4 percent (see table 6 in Kane and others). Two important exceptions, however, are maize and soybeans; world prices for these crops increase 9.2 and 10.2 percent. Because maize and soybeans are important feed crops, world prices for livestock commodities rise between 0.1 and 0.6 percent. Given the inelastic nature of aggregate food demand, Kane and others conclude that the price changes obtained in their climate change simulation would have relatively little effect on global consumption and production of agricultural commodities. This result is obtained by all studies reviewed here.

As with the net global economic impacts discussed above, global commodity market effects in Reilly and others (1994) are more pronounced than those in Kane and others. While the two studies use similar economic models, their results are not directly

Table 4.9—Tsigas and others study: world production and price impacts for GISS scenario[1]

Impact	Rice	Wheat	Other grains	Other crops	Livestock	Processed agriculture	Manufact.	Services
	Percent change							
A. With yield impacts which do not account for direct effect of CO_2 on crop growth								
World production	-4.69	-4.37	-3.03	-2.02	-2.31	-3.33	-0.85	-0.84
World price	59.31	30.98	36.99	39.78	8.98	8.26	0.20	0.08
B. With yield impacts which account for direct effect of CO_2 on crop growth								
World production	-0.35	-0.54	1.85	-0.33	0.07	-0.15	0.01	0.02
World price	10.18	-7.31	14.59	-6.50	1.02	0.30	0.03	0.05

[1] Climate change scenario generated by General Circulation Model of the Goddard Institute for Space Studies (GISS).

Notes: EU denotes the European Union-12. The ASEAN (Association of South East Asian Nations) region consists of Indonesia, Malaysia, the Philippines, Singapore, and Thailand.

Compiled by Economic Research Service from Tsigas and others (1996).

comparable, because Reilly and others analyze GCM, not generic, scenarios; and they allow for CO_2 fertilization effects and minor farm-level adaptation. With these allowances, Reilly and others find that world crop prices generally move in the same direction under the GISS and GFDL scenarios (table 4.8). Specifically, prices for soybeans, cotton, groundnuts, and tobacco fall, while prices for rice, sugar, and maize rise (table 4.8). Price movements of 10 to 24 percent are common. Prices for wheat and sorghum (allowing for adaptation) fall in the GISS scenario and rise in the GFDL scenario. Under the UKMO scenario, prices for all crops increase and these increases are always larger in magnitude than under the GISS and GFDL scenarios (5 of 9 crop commodities have price increases over 40 percent). For livestock commodities, Reilly and others obtain similar results with the GFDL and UKMO scenarios. For these scenarios, prices rise for most livestock commodities, though the magnitude of the price changes are generally less than 3 percent. Again, the magnitudes of the price effects are always larger in the UKMO scenario. In the GISS scenario, all livestock commodity prices decrease. Rosenzweig and others (1993) find similar results using the same yield impacts, focusing their analysis of global impacts on how climate change might affect the world market for cereals. In simulations that account for CO_2 fertilization and minor farm-level adaptation, world cereals prices increase by 10, 24, and 100 percent under the GISS, GFDL, and UKMO scenarios. The respective declines in world cereals production, however, are much less: 0.0, 1.5, and 5.0 percent.

World crop commodity impacts reported in Tsigas and others (1996) are qualitatively consistent with the GISS results in Reilly and others (1994). For this scenario and allowing for CO_2 fertilization, Tsigas and others find that the world price of wheat declines by 7.3 percent while the prices of rice and other grains increase 10.2 and 14.6 percent (table 4.9, part B). For livestock and processed food commodities, Tsigas and others find that world prices increase 1.0 and 0.3 percent. These results are not significantly different from the results of Reilly and others (1994), who find that world prices for processed livestock and food commodities increase under the GISS scenario that does not allow for adaptation (table 4.8). Tsigas and others (1996) is a useful comparison between crop-response estimates and Darwin and others' (1995) spatial analogue approach because both studies use the Global Trade Analysis Project (GTAP) economic database and modeling framework (Hertel, 1996). Thus, differences in the results represent primarily differences in how climate change impacts are estimated.

Darwin and others (1995) find that climate change is not likely to imperil global food production (table 4.10, part A). Across the four GCM scenarios analyzed, production of wheat and livestock increase (the respective ranges are 0.47 to 3.3 percent, and 0.72 to 0.90 percent), while production of nongrains decreases (between 0.17 and 1.25 percent). Production of other grains increases for three scenarios (the range is from 0.29 to 0.41 percent) but decreases for the OSU scenario by 0.12 percent. Finally, production in both processed food sectors

Table 4.10—Darwin and others study: percentage changes in world production and prices by climate change scenario

	Scenario[1]							
	GISS		GFDL		UKMO		OSU	
Commodity	Quantity	Price	Quantity	Price	Quantity	Price	Quantity	Price
A. Simulations with unrestricted land use								
Wheat	1.920	-2.481	0.471	-7.771	3.293	-9.704	0.781	-4.586
Other grains	0.409	-3.468	0.287	-4.309	0.320	-6.426	-0.115	-1.022
Nongrains	-0.505	0.540	-0.432	2.949	-1.252	4.407	-0.170	0.217
Livestock	0.858	-1.855	0.744	-1.928	.0.899	-2.735	0.723	-1.169
Forestry	0.274	-1.658	0.007	-0.093	-0.014	-1.022	0.144	-0.413
Coal/oil/gas .	0.182	-0.087	0.097	-0.071	0.101	-0.138	0.145	-0.022
Other minerals	-0.409	0.157	-0.280	0.108	-0.439	0.109	-0.089	0.091
Fish/meat/milk	0.371	-0.387	0.273	-0.489	0.310	-0.677	0.294	-0.224
Other processed food	0.382	-0.824	0.161	-0.758	0.225	-1.032	0.260	-0.616
Textiles/clothing/footwear	0.120	-0.049	0.049	0.104	-0.022	0.100	0.190	-0.016
Other nonmetal manufacturing	0.098	-0.047	0.062	-0.004	-0.006	-0.046	0.162	-0.005
Other manufacturing	0.114	0.036	0.060	0.042	0.001	0.046	0.156	0.043
Services	0.023	0.044	-0.003	0.013	-0.107	0.022	0.122	0.020
B. Simulations with restricted land use								
Wheat	0.625	7.554	-0.971	0.584	1.171	3.751	-0.395	0.512
Other grains	0.006	-0.593	-0.434	1.528	-0.811	0.480	-0.532	2.399
Nongrains	-1.250	2.871	-0.596	5.711	-2.633	8.565	-0.417	2.316
Livestock	0.589	-0.851	0.340	-0.369	0.383	-0.871	0.786	-0.529
Forestry	0.117	-1.794	-0.190	0.594	-0.342	-0.986	0.027	-0.474
Coal/oil/gas	0.001	-0.090	-0.155	-0.086	-0.223	-0.162	-0.004	-0.026
Other minerals	-0.467	0.085	-0.432	0.064	-0.596	0.018	-0.186	0.066
Fish/meat/milk	-0.013	0.537	-0.207	0.763	-0.349	0.927	-0.002	0.524
Other processed food	-0.140	0.299	-0.406	0.780	-0.580	0.863	-0.070	0.330
Textiles/clothing/footwear	-0.171	0.073	-0.332	0.306	-0.509	0.324	-0.049	0.107
Other nonmetal manufacturing	-0.107	-0.021	-0.208	0.042	-0.346	0.011	-0.002	0.018
Other manufacturing	0.011	0.000	-0.095	-0.015	-0.179	-0.014	0.066	0.012
Services	-0.068	0.035	-0.147	-0.022	-0.271	0.007	0.032	0.010

[1] Climate change scenarios generated by General Circulation Models of the Goddard Institute for Space Studies (GISS), the Geophysical Fluid Dynamics Laboratory (GFDL), the United Kingdom Meteorological Office (UKMO), and Oregon State University (OSU).

Compiled by Economic Research Service from Darwin and others (1995).

increase across scenarios (the range is from 0.16 to 0.38 percent).

Regional Impacts. While climate change may have only marginally detrimental impacts on world agriculture, from a policy perspective, it is regional impacts that will shape strategies to address climate change. The studies examined here suggest that regional impacts will be more pronounced than global impacts. All studies find that climate change will hurt Southeast Asia and will benefit Japan and China. For most regions, however, the magnitude and direction of the economic impact of climate change vary from study to study and thus depend on assumptions made by the authors.

In any particular region, the economic impacts of climate change will depend on the direct effects of climate change on crop yields, the ability of producers to adjust to new climatic conditions, and trade relationships with other regions. The importance of world commodity markets in promoting interregional adjustments in production and consumption can be illustrated by comparing results in Kane and others (1991) with findings in studies that consider impacts of climate change on one country. Adams and others (1988), for example, examine the economic effects of climate change on U.S. agriculture assuming no other regions or economic sectors are affected. For the GISS and GFDL scenarios, Adams and others conclude that the United States loses about $7 billion and $34 billion. Under their moderate-impacts scenario, which was based in large part on the GISS and GFDL scenarios, Kane and others find that the United States would gain about $0.2 billion.

A relatively common result across studies is that developing regions, as a group, will be hurt by climate change. Reilly and others (1994) show that even under the GISS scenario with CO_2 fertilization and adaptation (where the global welfare impact is positive), developing countries as a group suffer economic losses. Individual developing countries, however, may experience economic impacts that differ from those indicated by the aggregate results (table 4.5). Argentina, which is a net exporter of crops, gains under all three scenarios not accounting for CO_2 fertilization and adaptation; but Argentina loses under the mildest scenario (GISS) when CO_2 fertilization and adaptation are taken into account (table 4.5). This perverse result comes about under more severe climate change scenarios because other regions are unable to supply grains, world prices rise, and Argentina is a world grain exporter. When other regions are able to supply grains, world prices are depressed and Argentina experiences an economic loss. The opposite is true for the former Soviet Union.

Winters and others (1994) find that the GISS, GFDL, and UKMO scenarios induce GDP losses for low-income, cereal-importing countries in Africa, Latin America, and Asia. These losses are largest in Africa, ranging between 6.5 and 9.5 percent. For Latin America and Asia, the reductions in GDP range from 2.1 to 6.4 percent, and from 0.2 to 3.1 percent. The relatively large economic impact for Africa reflects the authors' assumptions regarding economic conditions in 2050: (1) with no prospects for growth, the agricultural sector generates a large portion (about 38 percent) of GDP, even in the year 2050; (2) world prices of competing cash crops are projected to decline due to global climate change; (3) agricultural production in Africa has small supply response; and (4) consumers in Africa cannot take advantage of relatively cheaper food imports due to a low elasticity of substitution between imported and domestic foods.

The Asian countries suffer less than Latin American countries, even though the Asian agricultural sector is projected to remain important in the year 2050 (accounting for 18 percent of GDP), whereas in Latin America it accounts for 7.6 percent. These results suggest that the degree of dependence of an economy on agriculture is a relevant consideration, but it is equally important that an economy have the capacity to substitute for more expensive domestic foods with less expensive imported foods.

Results in Tsigas and others (1996) suggest that consumers in most regions will have to pay higher prices, with consumers in Mexico and the ASEAN region paying 2.3 and 0.8 percent more (table 4.6 part B). Consumer prices in China are projected to decline by 0.2 percent. Overall, welfare in Mexico and the ASEAN region is estimated to decline by 2.7 and 1.7 percent. All other regions will experience a relatively small increase in welfare, measured as a change in real income, ranging from 0.04 percent for the United States to 0.54 percent for China. Welfare in the Rest-of-the-World region will decline by 0.12 percent. The two extreme cases in Tsigas and others are Canada and Mexico. Canada is a net exporter of agricultural commodities and it gains the most in crops productivity due to climate change (see table 4.2, part B). Mexico, on the other hand, is a net importer of agricultural commodities and it loses the most in productivity. In Canada, agricultural production increases, and the nonfood part of the economy shrinks. Consumer prices increase because nonfood prices increase, but gains in producer surplus offset loses in consumer surplus and welfare increases by about $US 2.6 billion. In Mexico, agricultural production declines, but the nonfood part of the economy shrinks too. Consumer prices increase because food prices increase; both producers and consumers lose and welfare declines by $US 8.3 billion.

Finally, Darwin and others (1995) find that there are significant differences in regional welfare impacts. Canada, Japan, Other East Asia, and the Rest-of-the-World are projected to benefit from climate change under all scenarios (table 4.7, part A). The European Union and Southeast Asia are projected to lose from 0.3 to 1.1 percent, and from 0.2 to 1.3 percent of GDP. The direction of welfare impacts for the U.S. and the aggregate region of Australia and New Zealand varies from scenario to scenario, but welfare impacts are no more than 0.1 percent of GDP for the United States, and no more than 0.8 percent of GDP for Australia and New Zealand.

Agriculture and the Environment. Aside from exogenously specified shifts in global temperature and precipitation patterns, the six studies reviewed here do not explicitly consider any other environmental implications of climate change. Land-use results in Darwin and others (1995), however, do provide some insights. Globally, Darwin and others identify 43 unique region/land-class combinations, some of which match up reasonably well with broad ecosystem types. For example, an area of about 2.27 billion hectares is assigned to land class 1, which mainly represents arctic and alpine areas where cold temperatures limit growing seasons to a maximum of 100 days.[18] For the four climate change scenarios analyzed by Darwin and others, the global endowment of land class 1 is projected to decline by 32.57 to 62.45 percent (see table 13 in Darwin and others). Hence, this result suggests that climate change may severely stress many arctic and alpine ecosystems.

Darwin and others (1995) assign an area of about 2 billion hectares to land class 6 in the Rest-of-World region, which mainly represents tropical moist forest systems. Across scenarios, this region/land-class combination declines by 18.4 to 51.0 percent. Hence, it appears that climate change may stress many tropical forest ecosystems. Furthermore, when Darwin and others investigate changes in land-use patterns in the Tropics, they find that increased competition from agriculture could aggravate any climate-induced losses of tropical moist forests (see Darwin and others, page 31).

With respect to agricultural resources, Darwin and others find that more land and water will be devoted to agricultural production due to climate change. Depending on the scenario considered, global cropland increases by 7.1 to 14.8 percent and global pasture increases by 1.5 to 4.7 percent. Changes in total crop and livestock production, however, range from -0.3 to zero percent and from 0.7 to 0.9 percent. These results suggest that while climate change may increase the global area of land suitable for agriculture, this land may be less productive (that is, lower average yields per hectare). As for water, Darwin and others find that global supplies (which depend on runoff and regional storage capacities) increase by 6.4 to 12.4 percent across scenarios. Furthermore, of 32 scenario-region combinations analyzed (4 GCM scenarios and 8 regions), there are only 5 cases where a region's water supply decreases (see table 16 in Darwin and others).

CO_2 Effects on Crop Growth. There is considerable uncertainty regarding the direct impact of a $2xCO_2$ climate on existing agricultural systems. However, it is generally believed that the direct effect of CO_2 on crop growth positively affects world agriculture (Reilly and others (1994), Rosenzweig and others (1993), and Tsigas and others (1996)). Inclusion of the CO_2 fertilization effect reduces losses $115-$190 billion in Reilly and Hohmann (1993). Gains from CO_2 fertilization amount to $355 billion for the world as a whole in Tsigas and others for the GISS scenario (table 4.6, part A+part B). However, there remains scientific debate about the CO_2 effect. Issues include the extent to which the full effect will be realized in a commercial agriculture setting; how it may affect different regions and crops depending, for example, on nutrient availability, farm management, crop species, and competing weed varieties; and the broader effects of elevated CO_2 on, for example, water use and yield quality. Resolving these issues will be important for resolving how climate change as caused by elevated atmospheric CO_2 will affect agriculture.

Adjustments and Adaptations. Results in Tsigas and others (1996) and Darwin and others (1995) provide estimates of the impacts of different assumptions concerning the degree of adaptation and adjustment in modeling climate change. Tsigas and others examine the GISS scenario, which does not incorporate the direct effects of CO_2 on crop growth, and they find that global welfare declines by $353 billion (1990 $US) (table 4.6, part A). The model in Darwin and others allows land-intensive sectors a greater degree of adjustment in response to climate change. For the GISS scenario, Darwin and others find that global welfare increases by $2.2 billion (1990 $US) (table 4.7). These results suggest that longrun adjustments in global agriculture have the potential to significantly offset direct climatic effects. The long run refers generally to the time to CO_2 doubling (see fig. 1). Tsigas and others do not consider farm-level adaptation either. These results can also be contrasted with those of Reilly and others (1994) who compare scenarios with and without farm-level adaptation (level 1 as specified by Rosenzweig and Parry, 1994) in both cases with the direct effect of CO_2 on crop growth. They find that these farm-level adaptations reduce global losses by $7-$25 billion (1989 $US).

For some regions, the difference in results is more pronounced than for the world as a whole: Southeast Asia loses only 0.9 percent of 1990 GDP in Darwin and others (table 4.7, part A), but it loses 7.59 percent

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[18] Darwin and others do not consider Antarctica in their study.

in Tsigas and others; Canada gains 1.9 percent in Darwin and others, but it loses 0.02 percent in Tsigas and others. On the other hand, the European Union loses 0.9 percent in Darwin and others and 1.02 percent in Tsigas and others.

Darwin and others (1995) specifically address the potential for changes in land use, whereas this is not explicit in the other studies. They find that the world, as a whole, suffers greater losses due to climate change when land-use patterns are constrained (table 4.7, part B) as would be expected, but the magnitude of the additional loss is not large: for example, for the UKMO scenario, the global welfare loss increases from 0.12 percent to 0.35 percent of 1990 GDP. Regional welfare impacts do not seem to be influenced a great deal by the assumption of unrestricted land use. The importance of this consideration is that detailed global data on soil quality is not available. An ongoing concern of researchers doing agricultural impact studies is that while climatic zones may shift northward, the soils in northern regions such as Canada and Russia may not be highly productive or that land-use change would not be possible because of the desire to maintain the status quo of currently uncropped areas. Darwin and others (1995) estimate impacts constraining agricultural production to current cropland area as an upper-bound estimate of losses if no expansion onto new land is possible. Their unconstrained case is a lower-bound estimate of losses (upper-bound estimate of gains) if expansion is possible and soil quality in newly cropped areas allows a sustainable level of productivity.

The studies reviewed here suggest that climate change may adversely affect agriculture, or at least important components of agriculture, in some regions of the world. Thus, it is plausible that some agricultural interest groups may pursue government intervention rather than switching to alternative input/output mixes and production technologies. From a policy perspective, it is important to determine the impacts of climate change on agriculture under alternative trade policy regimes.

Rosenzweig and others (1993) examine the impacts of climate change under freer trade policies. They establish an alternative baseline scenario where, in addition to population and economic growth, they considered *full* agricultural trade liberalization. They find that the negative impact of climate change on global cereals production is slightly reduced by trade liberalization.

Summary and Conclusions

This chapter has reviewed six studies that assess the economic impact of climate change on agriculture taking into consideration international trade. All studies are based on projections of Earth's climate under an atmospheric CO_2 level that is twice current levels. The climate scenarios are derived from popular General Circulation Models (GCM's). Most authors use crop-response models to estimate impacts of climate change on crop yields; they also estimate crop yield impacts that embody adaptations on the part of farmers to new climatic conditions. One study assumes that the geographic distribution of crops is primarily a function of temperature and precipitation conditions. Hence, by matching current crop production patterns with current climate conditions, the authors project how current production patterns would change under alternative climate conditions. The major findings of these studies may be summarized as follows:

- Some declines in the productivity of regional agricultural systems can be expected, but these declines will be offset by productivity gains in other regions. Thus, the global economic impact of climate change on world agriculture will likely be small.
- Regional economic impacts of climate change will likely be more pronounced than global impacts and it is almost certain that some regions will lose relative to others. For example, studies suggest that Southeast Asia will be hurt by climate change while China and Japan will benefit. For most regions, however, the magnitude and direction of the economic impact of climate change vary from study to study. Because negative economic impacts are likely to generate pressure on governments to protect domestic producers and/or consumers with domestic and border policies, policymakers should know what conditions suggest negative impacts for their region.
- Climate change will likely stress several natural ecosystems because it will alter temperature and precipitation patterns, and lead to changes in land-use patterns. Tropical and arctic ecosystems appear to be particularly vulnerable.
- Most recent studies have addressed adaptation. The most recent study investigating the longrun potential to adapt suggests that economically viable adaptation is able to offset most losses due to climate change even without considering the beneficial effect of CO_2. The longrun equilibrium nature of the study does not allow the investigation of adjustment

costs. Now that studies have been conducted with minimal adaptation and with longrun adaptation, it is possible to bracket the potential contribution of adaptation to mitigating the negative impacts of climate change or enhancing the positive effects.

- Estimates of the economic impacts of climate change on world agriculture are subject to several uncertainties. In particular, there is much debate regarding the magnitude of any CO_2 fertilization effect on crop productivity. If this effect approximates what has been used in economic models to date, climate change will positively affect world agriculture on average. Another important uncertainty is the amount of land that warmer climates might make suitable for agricultural production (primarily in the northern latitudes). Finally, there are no good estimates of the transient effects of climate change. All studies reviewed are based on a doubled CO_2 climate, which is not likely to occur until near or after 2100.

Chapter 5. Climate Change and Longrun Agricultural Production

Climate change is only one of several factors that may affect global food production in the future. Rough estimates suggest that over the next 50 years or so, climate change may be a less serious threat to meeting global food needs than other constraints on agricultural systems. However, climate change could well aggravate regional agricultural problems related to these other constraints. Various authors have considered and debated how regional resource limits might constrain world agriculture from meeting the food needs of a growing population in specific regions (Bongaarts, 1994; Islam, 1995; McCalla, 1994; Norse, 1994).

Specifically, population, income, and economic growth could all affect the severity of climate change impacts in terms of food security, hunger, and nutritional adequacy. If climate change adversely affects agriculture, human effects are likely to be more severe in a poorer world with more people near hunger. In a prosperous economic environment, consumers may suffer a greater economic loss but be less likely to suffer the chronic effects of hunger.

Climate change is also likely to affect other resource problems. Weeds, insects, and other agricultural pests are likely to be redistributed, with some studies showing possible poleward expansion of pest ranges. If this occurs, there may be a greater demand for chemical pesticides unless equally effective and less environmentally risky alternatives are found. Warmer temperatures will also increase water demands for crop growth. In areas where increased water demand is not offset by additional rainfall or irrigation water supplies, climate change may further intensify the competition between growing urban, industrial, recreational, environmental, and agricultural users of water.

Finally, fostering the ability to adapt to changing climate will involve improving the ability of agricultural systems to respond to generally changing and uncertain conditions largely through existing policy instruments such as support for agricultural research, trade policy, water management, and commodity program and pricing. Few if any climate change policies will be distinct from broader issues improving agricultural productivity while minimizing environmental disruption. So-called “no-regrets” improvements in the agricultural system may be made possible when current market signals can be corrected to provide a more accurate reflection of resource scarcity and changing comparative advantage among regions and countries.

This final chapter begins by discussing interactions between economic, demographic, and environmental factors affecting future food security. The next section examines whether global food scarcity, and hence the potential costs of climate change, might be more severe several decades from now. The key issue is whether increases in agricultural supply, which will be determined both by productivity growth and the availability of inputs, can keep pace with rising demand, as appears to have been the case in the past. Existing studies are generally optimistic concerning the development and adoption of yield-enhancing techniques, and increasing quantities of agricultural inputs, to meet agricultural demand over the next 70 years. However, such projections are subject to very large standard errors. For example, projections are highly sensitive to assumptions about the average annual rate of agricultural productivity increase over the period, and there is much scientific uncertainty over potential environmental feedbacks. Moreover, a substantial expansion of infrastructure and irrigation in rural areas of the developing world will be required.

Even though they offset each other in aggregate, there are potentially significant winners and losers from climate change. Today’s poor countries are likely to be the biggest losers, due to the substantial share of agriculture in their gross domestic product, their location in the hotter, drier climates, and limited ability to adjust their farming practices and locations (see chapter 2). These considerations raise questions about whether it is appropriate to aggregate impacts over different regions, and about possible compensation measures. Moreover, climate change threatens to exacerbate problems of hunger and malnutrition, since these are concentrated in developing countries. However, the proportion of the world’s population suffering from such problems could be lower by the middle of next century, even under modest scenarios for real income growth. Much will depend on whether countries pursue policies that are conducive to innovation and investment throughout the economy, and whether they are rich enough to substitute imported food commodities for losses in domestic production caused by climate change. By far, the region of greatest concern is Sub-Saharan Africa, where real income growth is predicted to be sluggish, and rapid population growth threatens to compound problems of hunger and malnutrition.

Factors Affecting the Future World Food Situation

Some commentators (Erlich and Erlich, 1990) worry that rising demand for food over the next century, due to population and real income growth, will lead to increasing global food scarcity, and a worsening of hunger, malnutrition, and associated problems in developing countries. It is argued that most arable land is already under cultivation, and only a small amount of less fertile land remains to meet additional future needs.

The crucial issue is whether agricultural supply can keep pace with increases in future demand. This depends both on the scope for raising agricultural productivity (including reducing waste during distribution) and on the future availability of inputs used in the agricultural sector (land, labor, machinery, water resources, fertilizers, etc.). In the past, growth in supply has more than offset growth in demand, leading to declining global food scarcity and falling real prices for food commodities (although there has been substantial short-term variability in prices). For example, an index of food commodity prices by the World Bank (1992) shows an overall decline of 78 percent between 1950 and 1992. This trend showed no sign of faltering during the 1980's, when grain production increased by 2.1 percent per year, while population grew by 1.7 percent. However, these figures may in part reflect the spread of agricultural protection policies, that is, the underlying trend in food prices may not be declining so markedly. Moreover, the aggregate figures may mask a seriously deteriorating situation in some regions–even if global food scarcity is declining, malnutrition and the threat of famine may still be increasing in particular countries. Finally, just because global food scarcity appears to have fallen in the past does not mean it will continue to do so.

Table 5.1—Projections of real income

Region	GDP growth 1980-2000	GDP growth 1980-2060
	Percent	
World	2.9	1.8
Developed	2.6	1.6
Developing	4.3	2.4
Africa	4.6	3.0
Latin America	3.9	2.1
South East Asia	4.7	2.4
West Asia	4.4	2.8
	Per capita GDP	
	1990	2030
	1990 US$	
Sub-Saharan Africa	340	500
Asia and the Pacific	490	2,000
Latin America	2,180	5,500
Middle East and N. Africa	1,800	4,000

Source: Compiled by Economic Research Service from Fischer and others (1994) and World Bank (1992).

Future Population and Income Growth Scenarios

Most models used to project future population levels take the current population–with its age and sex composition, and age-specific fertility and mortality rates–as given. These models tend to yield reasonably accurate forecasts for up to three decades, since birth and death rates change slowly over time. However, projections further into the future require speculative assumptions about age-specific fertility and mortality rates, subjecting projections to a large degree of uncertainty. There is a general consensus among forecasters that world population will be 8-9 billion by 2025 (see McCalla, 1994). Based on extensions to projections by the United Nations (UN, 1994), Parikh (1994) estimates world population will be 10.3-12.8 billion by 2050, while studies projecting the impacts of climate change around the middle of the next century (Fischer and others, 1994; Rosenzweig and Parry, 1994; Chen and Kates, 1994) have assumed world population levels of approximately 10 billion. Nearly all of the predicted population increase (95 percent) is in the developing world, and the rate of growth is greatest in Africa, where population is projected to increase three- to five-fold over the 1990 level.

Over 1980-2060, real income growth is expected to be higher in the developing countries (2.4 percent per year) than in the developed world (1.6 percent) (table 5.1). However, in per capita terms, the picture is less optimistic in the developing world. The World Bank (1992) predicts that real per capita income will only increase by $160 in Sub-Saharan Africa to $500 in 2030 (table 5.1).

Predictions of Food Commodity Demands

Estimating future food demand is difficult in a number of respects. For example, as income increases, the share of the budget spent on different food items changes significantly.[19] Also, the amount

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[19] That is, the income elasticity of demand varies substantially across commodities. For example, potatoes are thought to have a negative income elasticity in developed countries, while that for quality meats is greater than unity.

of food an individual can consume has physical limits; therefore, assuming food demand is as linear as income is inappropriate. Parikh (1994) predicts caloric demands to increase 150-300 percent by 2050 over 2000 levels. The projected demands for cereals in Fischer and others (1994) are consistent with these estimates (table 5.2). Even though predictions become subject to much uncertainty several decades from now, there is broad consensus on the types of models used for such forecasting (McCalla, 1994). The bulk of the increase in demand comes from the developing world. In developed countries, the average person is already well fed, so an increase in income will not add much to the demand for basic food commodities.

The Potential for Agricultural Supply to Satisfy Demand

Parikh (1994) projects food demands in developed countries (U.S., Canada, Europe, Japan, Australia and New Zealand) to increase modestly above their current levels. Mitchell and Ingco (1994) predict that net grain exports of the developed countries will increase from their current level of 117 million tons to 194 million tons in 2010.

Table 5.3 shows estimates from a Food and Agriculture Organization (FAO) study by Higgins and others (1982) of the maximum population that could be supported by the available quantity of land and other resources in developing countries (except China). If a high level of inputs is devoted to agriculture, then these countries could, on average, support 5.11 people per hectare, which, given the total land availability of 6.495 billion hectares, implies a total population of 33.2 billion! The projected demands in Parikh (1994) imply a 50-percent higher calorie intake than in the FAO study and, adjusting for this, the population carrying-capacity of developing countries is still 22.1 billion. Therefore, in theory, the production potential for meeting projected agricultural demands does exist. However, the key questions are what might be the constraints to developing more agricultural land, to what extent can the need for this expansion be reduced by the invention and adoption of productivity-enhancing technologies, and what are the environmental costs and losses of biodiversity.

Land Resources

As emphasized by Crosson and Anderson (1994), a potentially important constraint on increasing the supply of cropland is that, compared with currently cultivated land, much of the uncultivated land is in areas that are poorly connected to existing domestic and foreign markets (for example, the tropical rainforest areas of Latin America). Therefore, a willingness to invest in infrastructure may be necessary before these areas become commercially viable.

Table 5.2—Projected demands for agricultural products

Year	Cereals		Dairy	Sugar
	Parikh (1994)	Fischer and others (1994)	Parikh (1994)	Parikh (1994)
	Million tons			
2000	2,082	1,992	642	286
2020	2,306-2,763	2,510	641-781	219
2040		2,950		
2050	3,262		856-1,347	324-523
2060		3,285		

Compiled by Economic Research Service from the studies listed above.

There are also a number of important environmental constraints and feedbacks that might reduce the future productivity of agricultural land. Unfortunately, data on the importance of soil erosion (which is primarily due to water and wind erosion) on agricultural yields in developing countries are very poor. When regional soil erosion losses are expressed in terms of billions of tons per year, they imply great risk to food production. Per hectare, the losses might be modest and correctable by improved farming techniques, soil conservation, and productivity improvements. For example, one study for the United States by Crosson (1992) suggests that over the long run, these losses are typically small relative to the gains from technological progress. However, these findings should be interpreted very carefully. Soils in tropical areas are in general more vulnerable to erosion than those in temperate regions, and a given amount of erosion is likely to induce a greater decline in soil productivity. Moreover, farming practices that continuously deplete soils are ultimately unsustainable. Thus, although it would be wrong to suggest that soil erosion will inevitably become worse and exacerbate food production problems caused by climate change, complacency is also unwarranted.

Another potential threat is salinization of soils and water. This is mainly a problem for irrigated areas, but also occurs in hot, dry climates where evaporation can increase salt concentration in soils. In irrigated areas, salinization is usually the result of poor

Table 5.3—Developing country population-supporting capacities

Location	Total land area	Population in 2000	Persons per hectare in 2000	Potential population-supporting capacity in 2000	
				Low inputs	High inputs
	Million hectares	*Millions*		*Persons per hectare*	
Total	6,495	3,590	0.55	0.86	5.11
Africa	2,878	780	0.27	0.44	4.47
SW Asia	677	265	0.39	0.27	0.48
S. America	1,770	393	0.22	0.78	6.99
C. America[1]	272	215	0.79	1.07	4.76
SE Asia	898	1,937	2.16	2.74	7.06

[1] Includes Mexico.

Compiled by Economic Research Service from Parikh (1994).

construction or inadequate maintenance of canals, or excessive use of water (primarily because of inappropriate pricing). The end result is waterlogging, salinization, reduced crop yields, and ultimately the permanent loss of agricultural land. The UN (1992) estimated that 11.5 million hectares per year are lost because of this process, with another 30 million hectares at risk.

Desertification in dry areas threatens Africa and Asia, as well as some areas in Europe and North and South America (table 5.4). Of the 3,569 million hectares that have been degraded in dryland areas of the world, 29 percent is in Africa and 37 percent in Asia. Recently, a scientific consensus (Nelson, 1988; Bie, 1990) shifted toward the view that the incidence of desertification is a lot less than originally thought, and that the contribution of desert margins to food production is small. For example, low rainfall areas accounted for only 12 percent of domestic cereal production in Sub-Saharan Africa and 1 percent in Asia in the early 1980’s (Norse, 1994).

Can the quantity of cultivated land be increased in an environmentally sustainable way? Sustainable agricultural production has often been difficult to achieve on nutrient-poor soils. For example, in Brazil’s Amazon region, government policies in the 1980’s encouraged the conversion of tropical forests to crop and livestock production. Much of this land has since been abandoned (Binswanger, 1989; Mahar, 1989; Repetto, 1988). Reducing the threat of abandonment requires careful study of the local ecosystem prior to conversion.

Finally, the environmental costs from land clearance, particularly the threat to biodiversity in tropical rainforests, are of concern to developed countries. Although efforts to persuade governments in tropical areas to slow deforestation have so far had limited success, outside pressure backed up with financial incentives might be an increasingly important constraint on the future development of potential agricultural land.

Expansion of Irrigation

Expanding irrigation will require both increasing the efficiency of existing systems and the building of new systems. There is much potential for increasing efficiency. Repetto (1986) has documented the enormous waste in existing public irrigation systems in both the developed and developing world, caused by policies that price water well below the costs of supply, and the resulting sparse investment to reduce seepage from canals.

Table 5.4—Extent of desertification and dryland degradation

Region	Total dryland area used in agriculture	Area degraded	Percentage of dryland area degraded
	Million hectares		*Percent*
Africa	1,430	1,050	73
Asia	1,880	1,310	70
Australia	700	380	54
Europe	146	94	65
N. America	578	429	74
S. America	420	306	73
Total	5,154	3,569	69

Compiled by Economic Research Service from Norse (1994).

A difficulty to expanding irrigation in developing countries is the pervasiveness of small-scale farms, for which investment in irrigation and drainage capacity is often not economical. One approach is to encourage cooperation among farmers to share investments in irrigation. However, the most promising longrun solution is steady economic growth, which will lead to a migration of workers from agriculture into other sectors of the economy and enable consolidation into larger scale farms.

At present, not much is known about how climate change might affect water supplies and irrigated agriculture. However, changes in precipitation and snowpack storage could cause droughts or floods that may render some irrigation systems ineffective, while overwhelming others.

Technological Innovation in Agriculture

The invention and diffusion of yield-enhancing technologies and farm practices has been a more important factor in raising global agricultural output over the last 50 years than the expansion in quantities of land and water (Crosson and Anderson, 1994). Biotechnology offers hope for continued development of new crop varieties that raise productivity by increasing resistance to pests, drought, and heat, and by increasing responsiveness to nutrients and moisture (Parikh, 1994). Presently available high-yield varieties often suffer from inefficient applications of chemicals and water, but new information technologies can promote more precise applications of inputs (Ruttan, 1992) and reduce the buildup of undesirable chemical residues in soils. Thus, Parikh (1994) concludes that there are few constraints, from the viewpoint of scientific knowledge, to prevent a steady increase in the rate of agricultural productivity. However, climate change may reduce biodiversity, and with it, the availability of germplasm, and the ability to generate new biotechnology.

Technological Adoption in Agriculture

Even if progress continues to be made on developing better crops and farming techniques, individual farmers may be slow to adopt them for a variety of reasons. Reilly (1995) identifies a range of adoption times for different adaptation measures. Variety adoption, conversion of land to agriculture, and transportation system adaptations can take place quickest, in as little as 3 years, while dams and irrigation projects take the longest time to implement, from 50 to 100 years. In underdeveloped rural areas, people may lack the information or education necessary to take advantage of improved agricultural methods. They also often have inadequate farm equipment to relieve labor shortages and allow timely field operations; face erratic supplies of complementary inputs like seed, chemicals and water; and confront an inadequate transportation infrastructure (Feder and others, 1985). Rural property rights are often poorly defined, and laborers may lack incentives to care about the future productivity of land they farm (Lee and Stewart, 1983). Thus, government has a potentially important role in providing information programs; developing new agricultural technologies, seed varieties, and crops; and extending property rights (Reilly and others, 1994; Repetto, 1988).

On the other hand, government policies for diffusion of technologies and techniques should be designed to work in harmony with other government policies. For example, taxes on investment income, even if only formally levied on wealthy households, reduce the supply of savings and make it more difficult for farmers to borrow in order to purchase new capital goods. In centrally planned and less developed economies, the capital market may barely function, which can effectively rule out big investments for small-scale farmers (Feder and others, 1985).

The scope for increasing farm output and reducing waste in the former Soviet Union and Eastern European countries, in particular, is thought to be substantial. Since 1980, agricultural production in this area has stagnated under political and economic uncertainties. Reforms that decentralize agriculture, increase private ownership of land, allow importation of new technologies, and promote the sale of farm products in world markets are likely to increase efficiency and production dramatically. Thus, for example, Mitchell and Ingco (1994) predict that Eastern Europe and the former Soviet Union will change from a net importer of grains in 1990 (of 27 million tons) to a net exporter (of 16 million tons by 2010).

Predictions of Agricultural Outputs in 2060

In the absence of climate change, most models do not project a substantial increase in food scarcity at the global level over the next few decades. For example, by 2060 Fischer and others (1994) predict that food commodity quantities will have increased by two to three times over their 1980 levels.[20] Despite a 240-percent increase in world population, global food

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[20] Their model uses a general equilibrium framework in which various country/region models are linked by trade, world market prices, and financial flows (known as the Basic Linked System, BLS).

scarcity in 2060 is slightly less than in 1980, reflected by a slight downward trend in real food prices.

However, these long-range predictions are subject to great uncertainty; in particular, results from such models are usually very sensitive to assumed rates of agricultural productivity increase, real income growth, and population growth. Hence, results should be regarded with a good deal of caution until the completion of further sensitivity analysis.

Studies of Climate Change in Future Scenarios

Fischer and others (1994) examine impacts of climate change (from a doubling of atmospheric CO_2) on world agricultural production in 2060, using the GISS, GFDL, and UKMO scenarios discussed in the previous chapters.[21] Assuming no adjustment at the farm level or change in market prices, a 22 to 34-percent reduction in global cereal yields is predicted when there is no CO_2 fertilization effect.[22] These results are broadly consistent with those in Darwin and others (1995), which estimates that current global cereal supplies would fall by 19-29 percent under comparable conditions. Allowing for full economic and farm-level adjustment, global cereal output changes by -6 to 1 percent in the Fischer and others (1994) model, while in Darwin and others (1995) it changes by 0.2-1.2 percent. The preliminary conclusion from Fischer and others (1994) is that the proportionate effects of climate change on agricultural output several decades from now will not be substantially different from the effects had climate change been imposed on today's world.

Moreover, given the 70-year timeframe, a supply gap of even 10 percent is not that large, and could be closed by relatively minor changes in the assumed rate of technological progress. For example, the base case in Fischer and others (1994) assumes that world cereal yields increase by 0.8 percent annually, whereas the rate for 1960-90 was around 1.5 percent. If instead Fischer and others (1994) had assumed a rate of 1 percent, then the whole of a 10-percent supply gap in 2060 would be offset.

Table 5.5—Projected global production of food commodities in 2060

Commodity	1980	2000	2020	2040	2060
			Million tons[1]		
Wheat	441	603	742	861	958
Rice	249	367	480	586	659
Coarse grains	741	1,022	1,289	1,506	1,669
Bovine and ovine meat	65	83	105	123	136
Dairy	470	613	750	877	997
Other animal products	17	25	33	41	48
Protein feed	36	52	64	76	85
Other food	225	326	433	538	629
Non-food	26	34	41	47	52
Agriculture	310	438	572	700	810

[1] Wheat, rice, and coarse grain in million tons; bovine and ovine meat in million tons carcass weight; dairy products in million tons whole milk equivalent; other animal products, and protein feed in million tons protein equivalent; other food in billion 1970 U.S. dollars.

Compiled by Economic Research Service from Fischer and others (1994)

Climate Change and Agricultural Sustainability

Recent debate over the sustainability of agricultural practices has been confused by at least three different notions of sustainability (Ruttan, 1994):

- One definition is the ability to meet increasing demand for agricultural products over the long run. On this basis, the tentative conclusion from the above discussion is that world agriculture probably will be sustainable over the next few decades, despite the threat of climate change.
- A more narrow definition is that an agricultural system is only sustainable if it does not deplete the stock of environmental resources passed on to future generations. To the extent that new agricultural land is developed (rather than through productivity improvements) to meet expanding future demand, then this definition of sustainability will be compromised, and compounded by the threat of climate change.
- An even more stringent definition emphasizes sustaining not only the stock of tangible resources, but also a broad range of community values. Proponents of this view regard the break- up of rural communities caused by consolidation into larger, more mechanized farms as reducing the inheritance of future generations in some aesthetic sense.

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[21] The results in Fischer and others (1994) are the same, though somewhat more detailed, as in Rosenzweig and Parry (1994), since both studies use essentially the same model and climate change scenarios.

[22] Cereals are the most critical crops for people threatened by food security problems, and therefore tend to be studied more often than other crops.

Agricultural and natural resource economists usually have in mind the first definition. The other two definitions are problematic because they rule out any investment that depletes the natural environment (or rural community), even though the costs to future generations may be far less than the benefits from inheriting a larger agricultural base.

Some Distributional Implications of Climate Change

Although the aggregate impact of climate change on world agriculture may not be that large, there could be sizable distributional effects. Indeed, it is the poorer countries, where the problems of hunger and malnutrition are concentrated, that are likely to lose most. However, since these problems primarily result from low income, rather than from constraints on agricultural production, they could be much less acute in 60 years, even under modest scenarios for per capita income growth.

Reasons Why Developing Countries are the Most Vulnerable to Climate Change

- **The level of economic development**

As per capita income rises, agriculture's share of gross domestic product declines, because as people have more income they spend a smaller proportion of it on food. Thus, an across-the-board percentage reduction in agricultural income caused by climate change would be regressive, in the sense that the proportionate income loss for a poorer country is greater. Therefore, given that food expenditure in the United States is around 15 percent of the household budget and around 70 percent in many African countries, agricultural losses from climate change threaten to increase global inequalities in income.

However, this could change dramatically in several decades when climate changes are predicted to become significant, depending on the economic growth of the world's poorest countries. Real income is expected to grow rapidly in Asia, modestly in Latin America, and slowly in Africa (table 5.1). Population growth and agricultural technology diffusion will affect how income growth affects vulnerability to climate change impacts, but the relative importance of agriculture in these regions has declined as they grew during 1965-90 (table 5.6).

Higher personal income reduces vulnerability to climate change in many respects. For example, since food expenditure is a smaller share of the household budget, in periods of high food prices people are better able to cut back on other goods to maintain food consumption. Also, a higher level of income reduces dependency on regional food production. Thus, if a particular community suffers food production losses, people are better able to purchase food from other regions in the country. Similarly, people are able to afford more imported goods. In a more developed economy, imports can be paid for by shifting resources away from domestic food production into, say, manufactured exports.

Table 5.6—Agricultural income as a percentage of GDP

Region	1965	1990
Sub-Saharan Africa	40	32
East Asia	37	21
South Asia	44	33
Latin America and the Caribbean	16	10

Compiled by Economic Research Service from Norse (1994).

- **The sensitivity of agricultural production to local climate**

The sensitivity of agriculture to climate change depends on its direction and magnitude. Higher latitude countries such as Canada are predicted to benefit from a warmer climate, since this could open regions that are currently too cold to farm. Conversely, tropical countries are likely to be losers in a warmer, drier climate.[23] Again, this threatens to compound global income inequalities, since countries located in the Tropics tend to be poor, while richer countries are generally in more temperate climates.

The potential scale of the impacts depends on:

(a) How healthy the agricultural land is. Areas where the soil is fragile, because of intensive farming, salinization, waterlogging, and wind erosion, will typically be much more sensitive to climate change than soils that have been protected and allowed to replenish. The soils in substantial parts of many developing countries have marginal physical characteristics. Further, tenant farmers may have little incentive to care for the land (farmed through share-cropping arrangements), and property rights may be poorly defined.

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[23] In a sense this is a perverse result, since the amount of warming is expected to be lower in the Tropics than the polar regions.

Table 5.7—The effects of climate change on welfare

Region	With CO_2 and adaptation	With CO_2 and no adaptation	No CO_2 and no adaptation
		$ million (1989)	
< $500 per capita	-210 to -14,588	-2,070 to -19,827	-56,692 to -121,063
$500 - $2,000	-429 to -10,669	-1,797 to -15,010	-26,171 to -48,095
$2,000 but still developing country	-603 to -1,021	-328 to -878	-3,870 to -6,661
E. Europe/former USSR	2,423 to -4,875	1,885 to -10,959	-12,494 to -57,471
OECD[1]	5,822 to -6,470	2,674 to -15,101	-13,453 to -21,485
Total	7,003 to -37,623	-126 to -61,225	-115,471 to -248,124

[1] Includes United States.
Source: Reilly and others (1994).

(b) The ability to adapt to a changing climate. Regional adaptability depends on how easy it is to shift agricultural activities to other parts of the country. Typically, populations are more mobile in wealthier countries since infrastructure is more developed and household conveniences reduce the personal reluctance to relocate. At the farm level, changing planting and harvesting dates, crop varieties, and irrigation supplies in response to local climate changes is easier on more technologically advanced farms (see chapter 2).

Again, these would be important considerations if climate change were imposed on today's global economy. However, over the next century, real income growth and the development and adoption of new technologies may reduce the sensitivity of agricultural production to climate change in many developing countries. For example, if workers migrate out of agriculture and into other sectors, some marginal lands that are currently vulnerable to environmental degradation and climate change may go out of crop production, and the consolidation into larger and more capital-intensive farms can make it easier to invest in technologies that reduce the sensitivity of production to the local climate (Feder and others, 1985).

- **The ratio of population to available arable land**

A country with a higher population density may be more at risk from climate change because more people are dependent on given agricultural resources. Since many of today's poor countries also suffer from overcrowding, the impacts from climate change may exacerbate income inequalities. However, higher population densities can spur economic growth by exploiting economies of scale. For example, a larger labor force allows for more specialization of labor, that is, overall productivity increases when people specialize in what they are most efficient at. High population densities did not prevent the development of Western Europe and Japan. Thus, although population growth can lower per capita income and hence regional food security, the link is more ambiguous, depending on the particular stage of economic development indicated by the level of per capita income. Unfortunately, Africa, which has small prospects for aggregate income growth, also has large population growth, which could combine to provide a severe constraint to increasing per capita food consumption (Parikh, 1994).

Some Evidence on Differential Distributional Impacts

Empirical analysis suggests that developing countries are likely to lose most from climate change. Empirical studies use broadly defined country groups, since region-specific climate changes cannot be reliably predicted at this stage. Table 5.7 shows Reilly and others' (1994) estimates for changes in producer and consumer surplus resulting from climate change scenarios imposed on today's world, where the developing countries are grouped into three categories defined by per capita income. In all climate change scenarios, and regardless of the amount of farm-level adjustment or whether the CO_2 fertilization effect is included, the developing countries lose, and by far more than any losses in the OECD countries. For example, when the CO_2 fertilization effect and adaptation are included, economic welfare in the OECD countries changes between -$6.5 and $5.8 billion, while that in countries

Table 5.8—Recent estimates of hunger

Dimension of hunger/food security	Population	Affected
	Millions	*Percent*
Famine (population at risk), 1992	15-35	0.3-0.7
Undernutrition (chronic and seasonal)		
Food poverty, 1980	477	9
Food poverty, 1990-92	786	20
Child malnutrition, 1990	184	34
Micronutrient deficiencies, 1980's		
Iron deficiency (women 15-49)	370	42
Iodine deficiency	211	5.6
Vitamin A deficiency (children < 5)	14	2.8
Nutrient-depleting illness, 1990		
Diarrhea, measles, malaria (deaths of children < 5)	6.5	0.8
Parasites (affected population), 1980's		
Giant roundworm	785-1,300	15-25
Hookworm	700-900	13-17
Whipworm	500-750	10-14

Compiled by Economic Research Service from Chen and Kates (1994).

with less than $2,000 per capita income falls by $0.2-$14.6 billion.

The Implications for World Hunger and Malnutrition–Measuring Hunger

Chen and Kates (1994) use the following four measurements of hunger (table 5.8):

(1) *Famine*. Famine can occur when there is a food shortage, or when the food supply is disrupted by war. The number of people affected by famine is small relative to those affected by less acute forms of hunger. For example, Chen and Kates estimate that no more than 15-35 million people have been at risk of death due to famine in any given year over the past three decades. Indeed, the overall trend in famine has been downwards. For example, the total population of countries affected by famine has fallen from 700 million in 1950-56 to less than 200 million in 1985-91 (Chen and Kates, 1994). This reflects a shift in the incidence of famine away from Asia to Africa, which has a lower population density.

(2) *Undernutrition*. One way to measure undernutrition is to estimate the number of people living in households whose access to food (defined by income or food expenditures) is not adequate to meet dietary requirements for reasonable health and physical development. A UN study suggests that 786 million people were in this category in 1990. An alternative approach is to take surveys on physical characteristics. For example, in 1990, 184 million children under the age of 5 were estimated to weigh less than adequate nutrition would dictate (Chen and Kates, 1994).

(3) *Micronutrient deficiency*. Even if total caloric intake is adequate, people may still suffer from serious deficiencies in certain micronutrients. For example, iodine deficiency can lead to mental retardation and lethargy, and to very damaging effects during pregnancy. Iron deficiency can cause anemia, reduce resistance to disease, and increase risk of death for women during childbirth.

(4) *Nutrient-depleting illness*. Even if the total food intake is adequate, nutrient deficiency can still occur because absorption in the body is reduced by illnesses, such as diarrhea; measles and malaria; or intestinal parasites such as giant roundworm, hookworm, and whipworm. Table 5.8 shows some estimates of the number currently suffering from such diseases.

Predicting the Effects of Climate Change on Future World Hunger

In the absence of climate change, Fischer and others (1994) predict that the number of undernourished people will fall from 23 percent of the developing world population in 1980 to 9 percent in 2060 (table

Table 5.9—Projected number of people at risk of hunger

Region	1980	2000	2020	2040	2060
			Million		
Developing	501 (23)	596 (17)	717 (14)	696 (11)	641 (9)
Africa	120 (26)	185 (22)	292 (21)	367 (19)	415 (18)
Latin America	36 (10)	40 (8)	39 (6)	33 (4)	24 (3)
S and SE Asia	321 (25)	330 (17)	330 (13)	232 (8)	130 (4)
West Asia	27 (18)	41 (16)	55 (14)	64 (12)	72 (11)

*Numbers in parentheses show percentages of population.
Compiled by Economic Research Service from Fischer and others (1994).

5.9), although population growth is sufficient to increase the absolute numbers from 501 million to 641 million.[24] In Latin America and South and Southeast Asia, the absolute numbers affected by undernutrition decline, but they increase in Africa despite a fall in the proportion. This reflects the rapid increase in Africa's population projected over the next several decades. Allowing for the CO_2 fertilization effect and economic and farm-level adjustment, climate change increases the number of undernourished people by up to 119 million, or by 19 percent, in the Fischer and others (1994) model. These figures look much bleaker when farm-level adjustment is hindered, in which case climate change increases hunger by anything up to 60 percent. In addition, global warming may increase the frequency of droughts and floods, which are a major cause of famines.

The region most at risk from problems of food security is Sub-Saharan Africa. It is more sensitive to reduced rainfall, rainfall variability, and evaporation than other regions. Only around 2 percent of its cropland is irrigated, 50 percent is in arid or semi-arid areas, and much of its soil is very fragile (Norse, 1994). It also has the bleakest prospects for real income growth per capita. In Asia, problems could arise because of dependency on irrigation. Climate change may increase aridity and evaporation rates in areas already at risk from salinization, so more irrigated land could be degraded. Conversely, global warming-induced increases in precipitation could increase soil erosion, leading to lower crop yields and faster siltation of irrigation dams and canals. However, the poor state of knowledge on the impacts of soil erosion on crop yields makes these problems difficult to assess.

Summary

This chapter has described some projections for the world demand and supply of agricultural commodities around the middle of the next century, by which time noticeable changes in climate may have occurred. Most of the existing studies predict that increases in supply will approximately keep pace with increases in demand, and therefore the costs of climate change are not substantially different from those in studies that impose climate change scenarios on today's global economy.

Although these predictions may be the best available at present, they are subject to great uncertainty. In particular, the results are sensitive to assumed rates of productivity increase in agriculture, and real income and population growth. Moreover, achieving predicted increases in agricultural supply will require substantial diffusion of agricultural technologies, development of infrastructure, and improvements in irrigation. Predictions assume that environmental feedback effects (soil erosion, salinization, and desertification) will not be important obstacles to expansion. Much will depend on whether future government policies promote investment and increasing efficiency in agriculture. For example, the potential for increasing food production in the former Soviet Union and Eastern European countries is thought to be substantial, if waste during distribution is reduced, property rights are extended, farms are decentralized, and restrictions on food exports and the import of technologies are removed.

Lying behind the agricultural impact figures are potentially sizable increases in global income inequalities. Poor countries are most vulnerable to climate change because of the importance of agriculture in their gross domestic product; their location in the hotter, drier climates; and the difficulties in making farm- and regional-level adjustments. Moreover, climate change threatens to increase the incidence of hunger, malnutrition, and associated problems, which are concentrated in the developing world. However, to the extent that these problems are due to low income, rather than to constraints on agricultural supply, they may be much less severe by the middle of the next century, even under modest scenarios for real income growth. The potential exception is Sub-Saharan Africa, where poor incentives for farmers, slow income growth, and population growth rates of possibly 3 percent are predicted to compound the problems associated with food shortages.

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[24] Since it is primarily an economic model, the BLS makes no projections about famine, micronutrient deficiencies, or nutrient-depleting illnesses.

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