A review of **impacts** to U.S. agricultural **resources**

Prepared for the Pew Center on Global Climate Change

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Contents

Foreword *Eileen Claussen, Executive Director, Pew Center on Global Climate Change*

In order to intelligently respond to climate change, we must first understand the likely consequences on our environment and health. This report, the first in a series of environmental impact reports, will explore anticipated effects of climate change on U.S. agriculture. Other reports in this series will assess what is known about the impact of climate change on weather and include analyses of its impact on water resources, coastal areas, human health, ecosystems, and forests. In evaluating the current state of scientific knowledge regarding the anticipated effects of climate change on U.S. agriculture, this report yields several key observations:

AGRICULTURAL SHIFTS ARE LIKELY. Climate change will result in agricultural shifts and changes across the United States. Given the requisite time and resources to adapt, the United States is likely to continue to be able to feed itself; however, there will clearly be regional winners and losers.

CURRENT PROJECTIONS COULD UNDERSTATE LONG-RANGE IMPACTS. If the rate of greenhouse gas emissions exceeds projected levels or if unanticipated or more frequent extreme events accompany this change, the outlook for the United States would likely worsen. The projections in this report, for example, are based on a doubling of carbon dioxide (CO_2) in the atmosphere which could understate the severity of climate change impacts over the long-term.

GLOBAL IMPACTS COULD BE MORE PROFOUND. Some countries will experience more negative effects on agriculture associated with climate change. The situation will be particularly acute in developing nations that do not have the same resources as the United States to respond to the agricultural changes projected.

This report broadly outlines projected effects on U.S. agricultural regions. The complexity of the climate system itself and its relationship to agricultural resources make it difficult to project specific effects on individual states or communities. More research is needed to better understand this complex system and to incorporate relevant factors into future climate models and assessments. The report does, however, provide an objective foundation upon which to build and clearly demonstrates the impact climate change will have, both direct and indirect, on U.S. agricultural systems.

In addition to reporting on the environmental impacts of climate change, the Pew Center undertakes analyses on domestic and international policy matters and economics. The Center was established in 1998 by the Pew Charitable Trusts to bring a new, cooperative approach and critical scientific, economic and technological expertise to the global climate change debate.

A number of major corporations have taken a bold and historic step in joining the Pew Center on Global Climate Change's Business Environmental Leadership Council. In doing so, they have accepted "the views of most scientists that enough is known about the science and environmental impacts of climate change for us to take actions to address its consequences." Understanding the potential environmental impacts of climate change, as this report illustrates, is an important step toward promoting informed action.

Executive Summary

This paper analyzes the current state of knowledge about the effects of climate change on U.S. food production and agricultural resources. The paper also considers regional changes in agricultural production, including distributional impacts.

The linkages between agriculture and climate are pronounced, often complex, and not always well understood. Temperature increases can have both positive and negative effects on crop yields, with the difference depending in part on location and on the magnitude of the increase. Crop yields in the northern United States and Canada may increase, but yields in the already warm, low-latitude regions of the southern United States are likely to decline. Evidence also suggests positive crop yield effects for mild to moderate temperature increases such as 2ºC to 3ºC (3.6ºF to 5.4ºF). However, once average global temperatures rise beyond about 4°C (7.2ºF), yields begin to fall. Increases in precipitation level, timing, and variability may benefit semi-arid and other water-short areas by increasing soil moisture, but could aggravate problems in regions with excess water. Although most climate models predict precipitation increases, some regions will experience decreased precipitation, which could exacerbate water shortages and droughts. Higher carbon dioxide (CO_2) levels in controlled experiments increase crop growth and decrease water use. However, these experiments often have demonstrated a more positive response than observed under actual field conditions.

Agricultural systems are most sensitive to extreme climatic events such as floods, wind storms, and droughts, and to seasonal variability such as periods of frost, cold temperatures, and changing rainfall patterns. Climate change could alter the frequency and magnitude of extreme events and could change seasonal patterns in both favorable and unfavorable ways, depending on regional conditions. Increases in rainfall intensity pose a threat to agriculture and the environment because heavy rainfall is primarily responsible for soil erosion, leaching of agricultural chemicals, and runoff that carries livestock waste and nutrients into water bodies. Currently available climate forecasts cannot resolve how extreme events and variability will change; however, both are potential risks to agriculture. The rate of change is also uncertain. Adjustment costs are likely to be higher with greater rates of change.

Agricultural systems are managed. Farmers have a number of adaptation options open to them, such as changing planting and harvest dates, rotating crops, selecting crops and crop varieties for cultivation, consuming water for irrigation, using fertilizers, and choosing tillage practices. These adaptation strategies can lessen potential yield losses from climate change and improve yields in regions where climate change has beneficial effects. At the market level, price and other changes can signal further opportunities to adapt as farmers make decisions about land use and which crops to grow. Thus, patterns of food production respond not only to biophysical changes in crop and livestock productivity brought about by climate change or technological change, but also to changes in agricultural management practices, crop and livestock prices, the cost and availability of inputs, and government policies. In the longer term, adaptations include the development and use of new crop varieties that offer advantages under changed climates, or investments in new irrigation infrastructure as insurance against potentially less reliable rainfall. The extent to which opportunities for adaptation are realized depends upon a variety of factors such as information flow, access to capital, and the flexibility of government programs and policies.

Climate change can also have a number of negative indirect effects on agro-environmental systems—effects that have been largely ignored in climate change assessments. These indirect effects include changes in the incidence and distribution of pests and pathogens, increased rates of soil erosion and degradation, and increased tropospheric ozone levels from rising temperatures. Regional shifts in crop production and expansion of irrigated acreage may stress environmental and natural resources, including water quantity and quality, wetlands, soil, fish, and wildlife.

The focus of this paper is on the impacts of climate change on agriculture. However, agriculture is also a potential source of greenhouse gas (GHG) emissions, and it can play an important role in mitigating these emissions. Methane from rice paddies and livestock, nitrous oxide (N_2O) from cultivated soils and feedlots, and CO_2 from the cultivation of virgin agricultural lands and intensive production methods contribute to global warming. Changes in management can reduce emissions from these sources. Agriculture can reduce atmospheric CO_2 through tree-planting and similar programs that sequester significant amounts of carbon and through increased planting of biofuel crops that could replace fossil fuels.

The following describes the current understanding regarding the potential impacts of climate change on U.S. agriculture:

1 CROPS AND LIVESTOCK ARE SENSITIVE TO CLIMATE CHANGES IN BOTH POSITIVE AND NEGATIVE WAYS. Understanding the direct biophysical and economic responses to these changes is complicated and requires more research. In addition, indirect effects—such as changes in pests and water quality and changes in extreme climate events—are not well understood.

2 THE EMERGING CONSENSUS FROM MODELING STUDIES IS THAT THE NET EFFECTS ON U.S. AGRICULTURE ASSOCIATED WITH A DOUBLING OF CO_2 MAY BE SMALL; HOWEVER, REGIONAL CHANGES MAY BE SIGNIFICANT (I.E., THERE WILL BE SOME REGIONS THAT GAIN AND OTHERS THAT LOSE). Beyond a doubling of CO_2, the negative effects are more pronounced both in the United States and globally.

3 THE IMPACT OF CLIMATE CHANGE ON U.S. AGRICULTURE IS MIXED. Climate change is not expected to threaten the ability of the United States to produce enough food to feed itself through the next century; however, regional patterns of production are likely to change. Regions such as the Northern Great Plains and Great Lakes may have increased productivity while the Southern Plains, Delta states, and possibly the Southeast and portions of the Corn Belt could see agricultural productivity fall. However, the form and pattern of change are uncertain because changes in regional climate cannot be predicted with a high degree of confidence.

4 CONSIDERATION OF ADAPTATION AND HUMAN RESPONSE IS CRITICAL TO THE ACCURATE AND CREDIBLE ASSESSMENT OF CLIMATE CHANGE IMPACTS. However, because of the long time horizons involved in climate change assessments and uncertainties concerning the rate at which climate will change, it is difficult to predict accurately what adaptations people will make. This is particularly challenging since adaptations are influenced by many factors, including government policy, prices, technology research and development, and agricultural extension services.

5 BETTER CLIMATE CHANGE FORECASTS ARE KEY TO IMPROVED ASSESSMENTS OF THE IMPACTS OF CLIMATE CHANGE. In the meantime, farmers and the agricultural community must consider strategies that are economically and environmentally viable in the face of uncertainty about the course of climate change.

6 AGRICULTURE IS A SECTOR THAT CAN ADAPT, BUT THERE ARE SOME FACTORS NOT INCLUDED IN ASSESSMENTS THAT COULD CHANGE THIS CONCLUSION. Changes in the incidence and severity of agricultural pests, diseases, soil erosion, and tropospheric ozone levels, as well as changes in extreme events such as droughts and floods, are largely unmeasured or uncertain and have not been incorporated into estimates of impacts. These omitted effects could result in a very different assessment of the true impacts of climate change on agriculture. If the rate or magnitude of climate change is much greater than anticipated, adaptation could be more difficult and impacts could be greater than currently expected.

Overall, the consensus of economic assessments is that global climate change of the magnitudes currently being discussed by the Intergovernmental Panel on Climate Change (IPCC) and other organizations (i.e., +0.8ºC to +4.5ºC or +1.4ºF to +8.1ºF) could result in some lowering of global production but will have only a small overall effect on U.S. agriculture and its ability to provide sufficient food and fiber to both domestic and global customers over the next 100 years. However, distributional effects within the United States can be significant because consumers, producers, and local economies will gain in some regions and lose in others.

Warming beyond that reflected in current studies (i.e., associated with a continued rise in CO_2 beyond the doubling that has been commonly investigated) is expected to impose greater costs, decreasing agricultural production in most areas of the United States and substantially limiting global production. This reinforces the need to determine the magnitude and rate of warming that may accompany the CO_2 and greenhouse gas build-up currently underway in the atmosphere.

I. Introduction

Food and fiber are essential for sustaining and enhancing human welfare; hence, agriculture has been a primary focus in the recent and ongoing debates about the effects of climate change. In fact, the United Nations Framework Convention on Climate Change (FCCC) views the sustainability of food production as paramount in the objectives for stabilizing greenhouse gas (GHG) emissions, stating that emissions should be stabilized at a level that "ensures that food production is not threatened."

This paper examines the most recent research on possible climate change effects on food production and agricultural resources, distills from this research a range of possible effects that are associated with plausible changes in climate, and draws some conclusions about the current state of understanding regarding the threats to U.S. food production under climate change scenarios. In addition to addressing the question of the sufficiency of food production under climate change, this paper also considers distributional effects such as who benefits, who loses, and regional changes in agricultural production. The paper builds on several recent summaries (Easterling, 1996; IPCC, 1996a; Schimmelpfennig et al., 1996; Adams et al., 1998; and Reilly and Fuglie, 1998).

The linkages between agriculture and climate are quite pronounced, often complex, and not always well understood. Crops need nutrients, water, and heat to drive the photosynthetic process and produce edible products. Clearly, water and heat are factors affected by climate, but so are nutrients. Increased atmospheric carbon dioxide (CO_2) concentrations can be beneficial to crop productivity; but changes in temperature and precipitation can have mixed results. Crops are also sensitive to changes in climate variability such as extreme events like floods, wind storms, and droughts, and seasonal factors such as periods of frost and cold temperatures and rainfall patterns. Climate change may alter the types, frequencies, and intensities of crop and livestock pests and diseases, the availability and timing of irrigation water supplies, and the severity of soil erosion.

Another important set of linkages relates to human and market influences. Most agricultural systems throughout the world are managed; that is, there is active human influence in contrast to natural or unmanaged systems. As such, patterns of food production respond not only to biophysical changes in crop and livestock productivity brought about by climate change or technological change, but also to changes in agricultural management practices, crop and livestock prices, the cost and availability of inputs, and government policies. All of these are dynamic and changing within the global economy, even if climate remains constant, and make the assessment of the effects of climate change on production and food supply complex and challenging.

Major uncertainties remain, even though much has been learned about the magnitude of this threat. The major contributing factor to these uncertainties is the lack of precise forecasts of climate change at geographic and time scales relevant to agricultural decision makers. Thus, numerical estimates presented here should be interpreted only as illustrative of the possible consequences of climate change.

The focus of this paper is on the impacts of climate change. However, we do note that there is an important role for agriculture in the mitigation of GHGs. Agriculture is an important source of GHG emissions, such as methane from rice paddies and livestock, nitrous oxide (N_2O) from cultivated soils and feedlots, and CO_2 from the cultivation of virgin agricultural lands and intensive production methods. Changes in management can reduce emissions from these sources. Agriculture can be even more important in other ways, through tree-planting programs that could sequester significant amounts of carbon and through increased planting of biofuel crops that could replace fossil fuels.[1]

II. Dimensions and Trends of U.S. Agriculture

A. Technological Impact on Agricultural Yields

Nearly 400 million acres of farm land are cropped each year in the United States, comprising about 20 percent of the country's total land area. Of these, nearly 60 million acres (15 percent) are irrigated, mostly in the arid West and Midwest, using about 40 percent of water withdrawn from rivers and reservoirs. The value of U.S. agricultural commodities (i.e., food and fiber) exceeds $165 billion at the farm level and over $500 billion after processing and marketing (USDA, 1997b). A substantial proportion of U.S. agricultural production enters world markets, where the United States accounts for more than 25 percent of the total trade in wheat, corn, soybeans, and cotton (USDA, 1997a).

Of greater importance perhaps than the sheer magnitude of U.S. agricultural production is the rate of change of output over time. Agricultural output has increased by approximately 2 percent annually since 1945, meaning that today's production of most commodities is more than 2.5 times the levels observed in 1945. What is notable about this increase is that it was accomplished with a decline in acres farmed and labor but with increased use of chemical inputs such as fertilizers and pesticides. Essentially, the agricultural sector has increased its output by making its inputs more productive. This was achieved primarily through major public sector investments in research and development that led to technological change, which, in turn, was rapidly adopted by farmers (Huffman and Everson, 1992).

The effects of these technological developments and their adoption can be seen in crop yield levels. Yields of major U.S. crops such as corn, soybeans, rice, barley, and cotton have increased dramatically during recent decades. For example, annual average U.S. wheat yields were about 18 bushels/acre (1,000 kg/ha) from the first year of record, 1866, until about 1940. Since then, annual average wheat yields have risen in response to improved genetics and cultural practices, reaching 44 bushels per acre in 1998.[2] Some studies suggest that crop yields could continue to rise nationally and globally, although most likely at a slower rate, and could keep pace with growing U.S. and global populations if both growth rates also fall (Reilly and Fuglie, 1998).[3] It is important to note, however, that as yields have increased, sensitivity to climate variability has not decreased. That is, climate fluctuation remains an important factor affecting crop production, leading to substantial harvest variations from year to year.

B. Population Growth Rates and Expansion of Food Supplies

In the future, global population and food demand are expected to grow more slowly compared to previous decades. For example, between 1950 and 1990, the world population grew at an annual rate of 2.25 percent. Through 2025, however, the United Nations projects that global population will grow at an annual rate of 1.13 percent (WRI et al., 1998). Between 2025 and 2050, projections fall to about 0.6 percent per year. In the United States, population is projected to increase by nearly 60 million between 1998 and 2025, an annual rate of 0.7 percent. The rate is then projected to fall to 0.017 percent between 2025 and 2050. If population and related food demand growth slow to these levels, food supply growth could slow by 40 percent to 50 percent from recent decades and still maintain per capita food production levels. For example, if population and food demand growth slow in the United States, then yield growth would not have to be sustained at the levels observed in the United States from 1945 to the present to meet aggregate food demand.

C. Agricultural-based Pollution and Environmental Challenges

An issue of increasing importance to farming is its relationship to the environment and to health and food safety issues. Soil erosion from croplands is a major source of impairment of lakes, rivers, estuaries, and coastal areas. Agriculture is a major source of non-point source pollution. Agricultural chemicals, which contribute to increased yields, are carried with soils into water bodies and are leached into groundwater supplies.

Although significant progress has been made to address agriculturally based environmental concerns in the United States (e.g., reduced soil erosion through programs like the Conservation Reserve and adoption of reduced and minimum tillage systems), concerns remain about adverse effects of certain agricultural practices on health and the environment. Some agricultural activities aimed at reducing GHG emissions, such as tree planting, also generate additional environmental benefits by reducing soil erosion and chemical runoff. In addition, new pests and diseases are frequently introduced into agriculture. Since all pests over time develop resistance to common control methods, maintenance of production requires constant introduction of new crop varieties and production practices. In the future, meeting the challenge of developing environmentally sustainable practices may equal the challenge of increasing yields and improving productivity.

III. Biophysical Effects of Climate Change on Crops and Livestock

Agricultural systems are influenced by many environmental factors, and chief among them are climate and weather (the term climate describes long-run averaged conditions, whereas weather describes short-run conditions and events). Changes in these can, therefore, lead to changes in crop and livestock yields. Understanding the biophysical linkages between climate and crops poses challenges to crop researchers and agronomists. Factors such as precipitation and temperature can act either synergistically or antagonistically with other factors such as soil conditions and organic matter in determining soil moisture conditions and crop yields (Waggoner, 1983). Much research has been directed toward understanding how climate affects crop production, developing new varieties that reduce crop vulnerability to climatic stresses, and expanding the range of conditions under which they are grown.

One of the major problems in applying this knowledge to the issue of climate change is the difficulty in transferring findings about biophysical responses obtained under controlled, experimental conditions to actual commercial settings. Crop productivity under field conditions, therefore, may respond differently to actual climate changes because of factors that were not considered under the controlled experimental conditions.

A further difficulty relates to the ability to forecast climate changes. Computer models of the earth's atmosphere and oceans have been developed to investigate the effects of changes in the composition of greenhouse gases in the atmosphere on climate. Yet, the inherent uncertainties within these models and differences across models have limited the extent of consensus on how climate is most likely to change. For example, although global and most regional temperatures are expected to rise, there is uncertainty concerning the magnitude and pace of such an increase. Even more complicated and less understood are precipitation changes. Complexities related to cloud formation, cloud cover, and other elements affecting precipitation create significant uncertainty in the estimation of precipitation changes. Box 1 describes these models and provides some estimates of average global changes from leading models.

A. Response of Crop Yields to Climate Change

Most studies have used a limited set of climate scenarios in which global temperature increases range from about 2.5°C to 5.2°C (4.5°F to 9.4°F) or have conducted sensitivity analyses. The IPCC predicts a global surface temperature increase ranging from 1°C to 3.5°C (1.8°F to 6.3°F) by 2100. Quantitative estimates of such temperature changes on crop yields are derived from crop simulation models (e.g., Rosenzweig and Parry, 1994). As shown in Box 1, plausible climate change scenarios project both higher temperatures and increased precipitation. Temperature increases can have both positive and negative effects on crop yields. Clearly, the cold northern parts of the country could benefit from longer growing seasons and warmer temperatures, which would allow these areas to grow high-yielding crops and crop varieties consistent with soil resources. In addition, a reduced incidence of killing frosts could benefit southern regions growing heat tolerant crops such as citrus. But high temperatures, particularly during critical crop growth periods, can speed plant development and reduce yields. Increases in precipitation level, timing, and variability may benefit semi-arid and other water-short areas by increasing soil moisture, but could aggravate problems in regions with excess water, whereas a reduction in rainfall could exacerbate water shortages and droughts.

Box 1

General Circulation Models

General circulation models (GCMs) are sets of sophisticated computer programs that simulate the circulation patterns of the earth's atmosphere and oceans. The purpose of these climate models is to describe how major changes in the earth's atmosphere, such as changes in the concentrations of greenhouse gases, affect climatic patterns including temperature, precipitation, cloud cover, sea ice, snow cover, winds, and atmospheric and oceanic currents. The models are not intended to predict weather events, and their resolution is too coarse to account for the effects of local geographic features such as mountains that may influence regional climate. They are, however, useful tools for examining long-term climatic trends, patterns, and responses to significant changes.

GCMs remain simple, however, compared to the complexity of the real climate system. These models continue to evolve as better information on and understanding of physical relationships are developed, and as improvements in computing power are realized. Climate models differ with respect to their assumptions, detailed structure, spatial and temporal resolution, and complexity, and as a result there is significant variation in the projected results of different models. This variation illustrates the degree of uncertainty associated with climate projections but can also provide a sense of reliability to the extent that consistent patterns emerge across different models.[4] Estimated changes in average global temperatures and precipitation of some of the climate models referenced in this paper are shown below.

Characteristics of Selected Climate Models Under a Doubling of CO_2

GCM	Change in Global Mean Temperature (°C)	Change in Global Precipitation (percent)*
GISS	+4.2	+11.0
GFDL-R30	+4.0	+ 8.3
UKMO	+5.2	+15.0
OSU	+2.8	+ 7.8

* Estimates at regional levels vary considerably across seasons and regions and are much less certain. In some cases, estimates show reduced regional precipitation.

Source: U.S. Country Studies Program, 1994.

Greater concentrations of CO_2 generally result in higher net photosynthetic rates (Cure and Acock, 1986; Allen et al., 1987) and may also reduce transpiration losses from plants (i.e., water loss). The photosynthetic rate is enhanced as additional carbon is available for assimilation; thus, productivity and yields generally rise.[5]

The actual response to CO_2 changes differs among crops. Most commercial crops in the United States, including wheat, rice, barley, oats, potatoes, and most vegetable crops, tend to respond favorably to increased CO_2, with the estimated change in yields for a doubling of CO_2 in the range between +15 percent and +20 percent. Tropical or warm-weather crops, including corn, sorghum, sugar cane, and many tropical grasses, are less responsive to CO_2, with a doubling of CO_2 increasing yields only +5 percent. Some researchers, however, are less optimistic and observe that crop productivity is often limited by factors other than CO_2, such as nutrients and water (Wolfe and Erickson, 1993). Modeling studies have not included adjustments for improved water use efficiency that could result from increased CO_2 levels, which might reduce marginal irrigation and soil moisture needs.[6]

The estimated effects of climate change on agricultural yields vary by region and by crop. Table 1 summarizes changes in crop yields estimated in some recent studies in North and Latin America. The studies of U.S. agriculture show a wide

Table 1

Ranges of Estimated Climate Change Effects on Selected Crop Yields in Latin and North America

Location of Study Site	Impact (Crop: Percent Change in Yield)	Climate Change Scenario
North America		
Canada (Alberta, Manitoba, Saskatchewan, Ontario)	Wheat: –40% to +234% (results varied widely by site and scenario)	GISS, GFDL, UKMO, Incremental* with CO_2
United States (average of total based on selected sites)	Wheat: –20% to –2% Corn: –30% to –15% Soybean: –40% to +15%	GISS, GFDL, UKMO with CO_2
Latin America		
Argentina	Corn: –36% to –17%	GISS, GFDL, UKMO, Incremental* with and without CO_2
	Wheat: +3% to +48%	GISS, GFDL, UKMO with CO_2
	Corn: –4% to –18% Sunflower: +14% to +23% Soybean: –3% to –8%	
Brazil	Wheat: –50% to –15% Corn: –25% to –2% Soybean: –61% to –6%	GISS, GFDL, UKMO, Incremental* with CO_2
Mexico	Corn: –61% to –6%	GISS, GFDL, UKMO, Incremental* with CO_2

* Incremental scenarios = +2ºC and +4ºC; +20% precipitation and –20% precipitation

Source: IPCC, 1996b

range of responses (e.g., for soybeans, the response ranges from a possible decline of 40 percent to a possible increase of 15 percent). Impacts are more negative for southern areas of the country and for climate scenarios in which the temperature increases are large (+5.0°C), such as those predicted by the UKMO general circulation model (Wilson and Mitchell, 1987), or for scenarios in which summer dryness increases, as in the GFDL forecasts.

Despite the limitations inherent in applying crop simulation models, available studies do indicate important regional trends. For example, Rosenzweig and Iglesias (1994) note that for up to a 4°C (7.2°F) warming with a CO_2 fertilization effect, yields in middle- and high-latitude countries (e.g., the northern United States and Canada) may increase, but yields in low-latitude countries (e.g., Brazil) may decline. Additionally, Rosenzweig et al. (1995) find evidence for important threshold effects. For example, their results indicate generally positive crop yield responses to temperature increases of 2°C (3.6°F) but indicate yield reductions beyond 4°C (7.2°F) temperature increases. Other studies (cited in IPCC, 1996a; Smith et al., 1996) concur that crop impacts tend to be more negative in lower latitudes than in higher latitudes, particularly with respect to wheat and corn yields. Rice yields are generally less sensitive to projected changes than wheat and corn yields.

Few studies account for changes in variability of climate and extreme events such as droughts and floods. Attempts to incorporate variability have been made (e.g., Kaiser et al., 1993); however, they have considered only a limited range and type of variability as exhibited in the historical record for a given region. Additionally, the studies generally do not assess impacts to a wide variety of crops, especially important heat-thriving crops such as citrus and some vegetables, which may have less vulnerability to climate change than grain crops.

B. Response of Livestock to Climate Change

Livestock, both grazing and fed cattle, are also affected by climate and hence may be vulnerable to climate change. Livestock can be affected by climate change in two ways: by the quality and quantity of forage from grasslands and supplies of other feeds (e.g., corn) and by direct effects from higher temperatures and greater temperature extremes.

If the quality or supply of forage and feedgrains is altered, livestock production may be more affected by the associated changes in pasture and grain prices than by the direct effects of temperature increases. Changes in the prevalence and distribution of livestock pests and the direct effects of changes in temperature and extreme events like storms may also affect livestock production. For example, blizzards and freezing temperatures in the Northern Plains in the winter of 1996–1997 had severe effects on livestock, and recent periods of drought on western rangelands lowered the short-term livestock carrying capacity.

In the few studies that address climate change effects on livestock, warmer summer temperatures are estimated to suppress livestock appetite, which leads to lower weight gain (Adams et al., 1998). Specifically, Adams et al. observed that under a 5°C (9°F) increase in temperature, livestock yields in the United States fell by 10 percent for cow/calf and dairy operations in Appalachia, the Southeast, the Delta states, the Southern Plains, and Texas. For a 1.5°C (2.7°F) warming, yield loss was estimated at 1 percent. Hanson et al. (1993) found that climate change tended to have adverse impacts on livestock production (e.g., low milk production) through both declining forage quality and increased ambient temperature.

C. Indirect Effects of Climate Change

Indirect effects from climate change have been largely ignored in the assessment of climate change effects. Indirect effects may arise from changes in the incidence and distribution of pests and pathogens, which, because of frostline shifts poleward, may have greater range (Sutherst et al., 1995). Also, increased rates of soil erosion and degradation (Brinkman and Sombroek, 1993) and increased tropospheric ozone levels from rising temperatures are very detrimental to crop yields (Adams, 1986).

IV. The Role of Human Response and Adaptation to Climate Change

Over time, agricultural systems and practices have adapted to changing economic and physical conditions. This has been accomplished by adopting new technologies (including investments in genetic improvements) and by changing crop mixes, cultivated acreage, and institutional arrangements. Such flexibility suggests significant human potential to adapt to climate change (CAST, 1992; Smit et al., 1996). For example, farm-level adaptations can be made in planting and harvest dates, crop rotations, selection of crops and crop varieties for cultivation, water consumption for irrigation, use of fertilizers, and tillage practices. These adaptations are the natural consequence of producers' goals of maximizing profits. Each adaptation can lessen potential yield losses from climate change or even potentially improve yields in some regions. At the market level, price and other changes can signal further opportunities to adapt as farmers make decisions about land use and which crops to grow. In the longer term, adaptation might include the development and use of new crop varieties that offer advantages under possible future climate conditions, or investment in new irrigation infrastructure to insure against the possibility of less reliable rainfall. Inclusion of adaptations is thus a requisite feature of assessments of the effects of climate change on managed systems such as agriculture. Economic studies of climate change include varying degrees of adaptation. Procedures for including adaptation are discussed in Box 2.

A. Possibilities for Adaptation to Climate Change

Although agriculture has adjusted to many economic and technological changes, these adjustments have sometimes come with significant pain and dislocation for farmers and farming communities. A fundamental question with regard to climate change is whether agriculture can adapt quickly and autonomously or whether the response will be slow and dependent on structural policies and programs. Change is a constant in U.S. agriculture. Technology, government policies, prices, and input costs often vary from year to year, and crop varieties often improve and change every 5 to 10 years. Failure to

Box 2

Economic Approaches to Measuring Climate Change Effects

Two general approaches have been used to assess the potential economic consequences of climate change on agriculture: the structural approach and the spatial analogue approach (see Schimmelpfennig et al., 1996 or Adams et al., in press). Each approach contains aspects of human response believed to be important in measuring economic effects. However, the approaches differ in terms of data requirements, assumptions, and the dimensions they measure.

Structural methods consider fundamental changes in crop yields and farmer response, and might also be called "decision duplication" methods because the analyst tries to duplicate the decisions of the farmer in choosing what crops to grow and how to grow them. These methods characterize the economic decision making problem for farmers and consumers, identifying alternative ways of attaining objectives within existing resource and institutional constraints. Solutions to the decision problem are obtained by identifying the choices that result in the greatest economic welfare.

Structural methods are popular in climate change research because of their ability to (1) assess the effects of as yet unrealized environmental changes such as additional warming, precipitation, or higher CO_2 levels, (2) include additional characteristics or changes in the structure of the decision problem, and (3) estimate changes in market prices and distributional effects on regional producers and consumers. One challenge to implementing the structural approach is to identify and incorporate adaptations that farmers and consumers might use to respond to climate changes. This becomes particularly difficult in light of the long time horizons associated with climate change. The main criticism of this approach is that if the analyst fails to anticipate correctly, the resulting estimates may be misleading.

The spatial analogue approach, in contrast, looks at how crop production currently varies across regions with different climates, and tries to infer the effects of climate change from these differences. This reduces the challenge of anticipating future adaptations by using information from past farm-level decisions collected from farmers operating across a range of climatic conditions. Using these data, it may be possible to estimate statistically how changes such as temperature might affect production and profits (Mendelsohn et al., 1994). The strength of the spatial analogue approach is that climate changes and farmer responses are implicit in the analysis (reflected in the data on farmer behavior across regions with different climates). An important weakness is that spatial analogue models abstract from the issues and costs of changes in infrastructure characteristics such as irrigation systems that may be necessary to mimic warmer climate practices. The approach also typically ignores likely changes in output and input prices that may result from global changes in production, and which in turn affect farm-level adaptation decisions. Another limitation is that the approach generally cannot include the effects of CO_2 changes.

Each provides useful, often distinct, information. Several recent studies have combined the approaches to gain the advantages of each. For example, the spatial analogue models have been used to improve the adaptation included in structural models (Darwin, 1995; Adams et al., 1998).

account for adaptation responses in climate change models and assessment could overstate the potential negative impacts or understate potential positive gains associated with climate change.

It is important to identify the appropriate scale for evaluating whether adaptation is successful. Some would start at the scale of the individual farmer or farming village. From this perspective, the culture of the village or countryside is rooted in the crops grown and the methods of farming used. For example, California's Napa Valley is noted as a wine region, Switzerland for its picturesque alpine dairy farms, and Japan for rice production—each of which may not be viable under a changing climate. For those who focus on the individual farmer or farming community, successful adaptation often means keeping these local agricultural systems more or less intact.

In contrast, one could look to the global granary to determine if adaptation to climate change has been successful. If wheat and corn production shifts north to Canada and Russia but global production levels are maintained, then markets have facilitated successful adaptation of world food production. If the wine regions of California fail because of changed climates, then the world market can supply Canadian cabernet sauvignon or Finnish chardonnay. And, even where production fails for some crops, cultural tastes can adapt. Under this market-driven view of the world, consumers will substitute lower-priced products whose range of production has expanded for higher-priced products whose production has been reduced. In addition, those who are displaced are expected to seek new uses for their skills; for example, children of wine growers could potentially take up computer programming, or those of fishermen could learn to be winemakers.

An important question is whether these adaptation changes constitute acceptable adaptation or the destruction of culture and livelihoods. The possible gradations of what is or is not acceptable are endless; the most extreme "successful" adaptation could mean that farming disappears completely from a region and individual communities become ghost towns as people seek economic opportunity elsewhere (as happened during the 1930s Dust Bowl). Less severe but perhaps equally unimaginable for people who depend on farming for their livelihood is the possibility that the Corn Belt becomes a wheat belt, or that winter wheat gives way to corn or ranching.

Finally, the role of government should not be overlooked. Although recent trends toward a more market-driven agricultural economy are significant (and are generally assumed in climate impact assessments), government policies remain a driving force in U.S. agriculture. Though the U.S. government is now less active in establishing commodity prices, it continues to affect farm-level decisions through many programs, including extension programs that provide information and education, agricultural technology research and development, crop insurance, conservation programs, water supply, and export policies. The impacts of climate change on U.S. agriculture will depend on how these policies evolve over time. For example, changes in the Bureau of Reclamation policies to develop and supply agriculture with irrigation water could greatly affect how western agriculture adapts to climate change. In addition, government policies established to address global climate change could affect agriculture in significant ways, such as changing fuel and fertilizer costs, encouraging the planting of tree and biofuel crops, and encouraging agricultural methods that conserve and enhance soil (these topics are addressed further in Section VII). Over the long run, government policies can affect not only prices and farmer behavior but also the tools and strategies that farmers use in adapting to climate change.

B. Assessing Biophysical Effects and Human Responses

A number of economic approaches and models are used to measure the farm- and market-level effects of climate change. These approaches embody different assumptions about the nature of the farm and market responses and, not surprisingly, result in different estimates of impacts. No single economic approach is appropriate for all settings; each, however, offers a view that must be assessed within its own limitations. A simple but useful assessment taxonomy has evolved to summarize the primary approaches to modeling economic problems related to climate change. Classification into structural and spatial analogue methods is about overall assessment frameworks rather than unique techniques or methods (see Box 2).

C. Including Adaptation in Climate Change Assessments

Several studies (of both the structural and spatial analogue types discussed in Box 2) describe substantial opportunities for adaptation to offset the negative effects of climate change (e.g., Kaiser et al., 1993; Mendelsohn et al., 1994; Adams et al., 1998), but these opportunities are not without costs. Furthermore, whether or not the adaptations are undertaken depends on many factors, including the detection of climate change at the farm level, the extent and scope of government policy to facilitate detection, the extent of technical assistance, and investments in research and development of agricultural technology. Assumed changes in technology will require investments into research and development, dissemination of information, development of new equipment, and education. Barriers to adaptation that limit responses include availability and access to financial resources and technical assistance and availability of inputs such as water and fertilizer. Uncertainty about the timing and rate of climate change also limits adaptation and, if expectations are incorrect, could contribute to the costs associated with transition and disequilibrium. Finally, adaptations made in response to changes in climate may add stress to local and regional agricultural economies already dealing with long-term economic changes.

While early assessments focused on grain crops, recent assessments have included some warmer season crops (tomatoes, citrus) that should benefit from warming. Additional improvements in modeling include increased possibilities of crop "migration" (shifts in crop-growing regions in response to changes in climate), adjustments in specific crop yields to reflect more on-farm adaptation by farmers, and inclusion of livestock effects. These adjustments capture a wider range of possible adaptations or changes and can help resolve the role of adaptations in the assessment process. Adams et al. (1998) evaluated the effects of including these changes using the Goddard Institute for Space Studies (GISS) GCM and a harsher climate forecast (a 5°C warming and 7 percent increase in precipitation). For these two climate change scenarios, they found that adding these adaptations to previous scenarios resulted in a 20 percent to 25 percent change in the economic estimates (from $10 billion to $12 billion gain in societal welfare, measured in 1990 dollars).

One of the most important sources of uncertainty concerning climate change impacts on agriculture and the ability of the system to adapt is the climate forecasts. Until recently, those who build and run GCM models (see Box 1) tended to estimate climate under a doubling of CO_2 in the atmosphere (typically referred to as $2xCO_2$). This presents a number of problems. One is that the climate associated with $2xCO_2$ will probably not be realized until late in the 21st century or beyond. Thus, the models do not indicate how climate may change in coming decades. A second problem is that these $2xCO_2$ scenarios assume that atmospheric greenhouse gas concentrations have stabilized, resulting in a stable climate. In fact, concentrations are likely to continue rising and climate is likely to continue changing. In examining agriculture impacts, most studies have assumed that climate has stabilized and the agricultural system just needs to "catch up." It is far more likely that climate will continue to change and agriculture will need to continually adapt to it.

Adaptations may involve significant time lags and long-term capital investment decisions that depend critically on the rate and variability of climate change. If climate changes at a rate that requires rapid adaptation, then the available adaptation options are limited and adjustment costs would be relatively high compared with the costs required under a more gradual climate change, which allows time for major infrastructure investments as systems depreciate (OTA, 1993). The magnitude of warming is also important. Studies to date examine changes in warming up to 5°C (9° F) (based primarily on GCM model forecasts assuming an effective doubling of CO_2). Warming beyond this level increases pressure to develop offsetting technologies (Hall, 1997).

Changes in climate variability and extreme events can also affect adaptation strategies. Few studies have considered changes in climate variability. Should the frequency of drought, flood, or severe storms increase, farmers may find adapting more difficult. If climate uncertainty increases as the climate changes, adaptation responses will be affected. For example, if risk aversion is high among farmers in regions where water is limited, farmers may shift production to more drought-tolerant crops, even if expected returns are lower (Pope, 1982; Hurd, 1994).

Because explicit adaptation responses are difficult to project, an assessment of the agricultural effects of climate change cannot account for the full range of adaptation options likely to arise over the next century. Conversely, adaptation options incorporated into recent assessments may not be technically or economically feasible in some cases or in some regions. While U.S. agriculture may have the means to successfully adapt, the capacity for adaptation in developing countries is limited as a result of limited access to markets for crop inputs or outputs, and limited infrastructure development (Reilly and Hohmann, 1993).

Implementing adaptation often requires local access to financial and physical capital, technical assistance, and other inputs such as water and fertilizer. Infrastructure costs (e.g., for irrigation, reservoirs, and distribution systems) are also important. To the extent that climate change results in significant geographic shifts in production, costs to move or add infrastructure capacity could be substantial.

V. Impacts of Climate Change on Agricultural Production, Prices, and Welfare

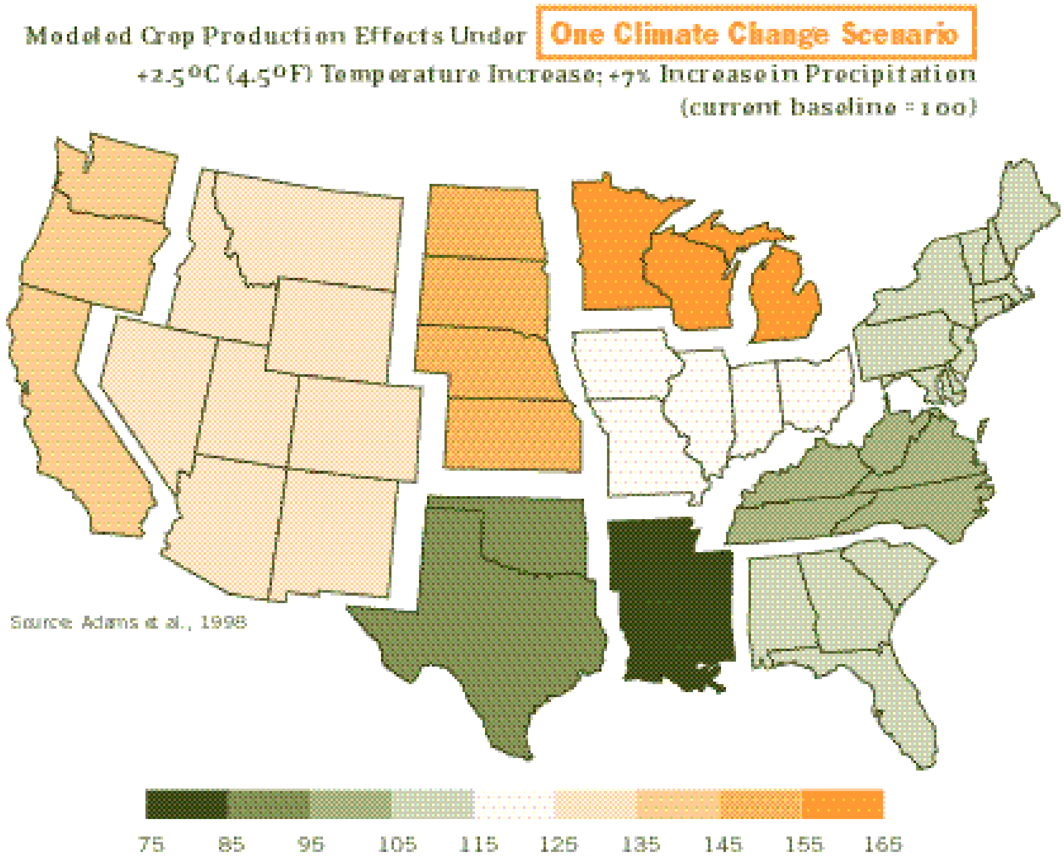
The distribution of estimated economic effects varies across both crops and regions, just as crop yields vary across crops and regions.

In existing studies, the agricultural economies of Canada, parts of the United States, and northern Europe are estimated to be buoyed by both rising cereal and feedgrain prices and more favorable growing conditions, especially under scenarios that assume both CO_2 fertilization and adaptation. In low-latitude tropical countries, grain production is generally estimated to fall, even with CO_2 fertilization and adaptation. However, price-level changes are more uncertain than production changes because of the strong effects of changes in demand and government policies, both of which are difficult to forecast.

Adams et al. (1998) found a pattern of increased supply from northern regions of the United States and declines in southern regions. For example, using Rosenzweig's estimated wheat yield changes for the United States (shown in Table 1), Adams et al. (1995) estimated a net increase in the U.S. wheat supply of between 4 percent and 15 percent. This increase is due to market-level responses and resulting increased wheat acreage across the GISS, UKMO, and GFDL R30 GCM scenarios for doubled CO_2. That is, the increase is due to the overall rise in the price of wheat precipitated by falling yields. Thus, market-level changes induce behavioral responses that can mitigate impacts projected by biophysical changes alone.

Figure 1 illustrates the results of Adams et al. (1998) on U.S. regional crop production for a climate change scenario of geographically uniform increases of 2.5°C and 7 percent in precipitation (generally consistent with IPCC expectations). This figure shows relative changes in regional crop production from current levels, using a crop production index where the current levels are given a baseline of 100. In this study, increases in production are predicted across most regions of the United States, except the Southern Plains and Delta states, where production decreases 16 percent and 21 percent, respectively. Under more severe conditions (beyond a doubling), losses in these two regions would be even higher and would be accompanied by crop production losses across the Southeast, Appalachia, and the Corn Belt.

Figure 1



Estimating changes in prices depends on whether net increases or decreases in supply are estimated, and whether demand is increased or decreased through changes in incomes, population, and the prices of related commodities. For many agricultural commodities (major cereal and oilseed crops in the United States such as corn, wheat, and soybeans), prices are heavily influenced by changes in global food supplies. For this reason, assessments of the effects of climate change on agriculture in one country or region need to reflect changes in world supplies of these commodities. For example, studies that incorporate trade patterns reveal that changes in the rest of the world have an effect on the agricultural sector in the United States. At the global level, Darwin et al. (1995) find that, in general, high-latitude regions (e.g., Canada) will benefit and low-latitude regions will be harmed. However, they also find that total agricultural production would be largely unaffected. Rosenzweig and Parry (1994) and Rosenzweig et al. (1995) find that patterns of global cereal production are sensitive to climatic changes and to assumptions about the level of adaptation. Under a modest level of adaptation, changes in global cereal production range from 0 percent to –5 percent, with losses of between 9 percent and 11 percent occurring in developing countries, while production in developed countries increases between 4 percent and 14 percent.

Table 2 presents indices of crop price estimates for the United States by Adams et al. (1998) and estimates by Darwin et al. (1995) for cereal grains under two scenarios: a 2.5°C temperature increase with a 7 percent precipitation increase, and a 5.0°C increase with no change in precipitation. As the index indicates, prices fall by 19 percent under the benign case but increase by 15 percent under the adverse case. Darwin et al. (1995) consistently estimate decreases in global wheat and other grain prices because of increased production, even though their estimates do not incorporate direct CO_2 effects.

Table 2

Examples of **Price Change Forecasts** by Crop Group and Climate Assumption

Study	Climate Forecast Assumption*	Region	Price Change, by Price Group
Adams et al. (1998)	5ºC warming, 0% change in precipitation, 530 ppm CO_2 level	U.S.	all crops** +15%
Adams et al. (1998)	2.5ºC warming, 7% precipitation increase, 530 ppm CO_2 level	U.S.	all crops** –19%
Darwin et al. (1995)	UKMO	global	wheat –10% other grains –6%
Darwin et al. (1995)	GISS	global	wheat –2.5% other grains –3.5%

* Adams et al. assume a CO_2 fertilization effect; Darwin et al. do not.

** Crops included in the index are corn, wheat, soybean, rice, cotton, sorghum, other small grains, and hay.

Outside of the United States, assessments of the national economic welfare effects of climate change are scarce. Table 3 compares estimated U.S. economic impacts across several climate change scenarios and studies. Although the results vary significantly across these studies, a few important observations can be made. First, at a national level, the relative impact of climate change is expected to be small compared to the overall value produced by the agricultural sector ($165 billion, or $500 billion including processing and marketing). Another important point involves the rather dramatic effects of including CO_2 fertilization in assessments. The consequences of increased CO_2 on crop yields remain

Table 3

Estimated **Effects of Climate Change** on U.S. Economic Welfare (billions of $US)

Scenario	Adams et al. (1995, 1998) With CO_2	Adams et al. (1995, 1998) Without CO_2	Mendelsohn et. al. (1994)
+5ºC, +8% precipitation	N/A	N/A	–$120 to +$35
GISS*	+$10	–$11	
GFDL*	+$5	–$19	
UKMO*	–$18	–$67	
+1.5ºC, +7% precipitation**	+$20	+$2	
+2.5ºC, +7% precipitation**	+$15	–$4	
+5ºC, +7% precipitation**	–$2	–$37	

* Source: Adams et al., 1995, Tables 3 and 4.

** Source: Adams et al., 1998, Appendix, Table 1.

uncertain, and the role of this factor in current assessments reinforces the need to accurately measure its effects. Finally, welfare damages appear to increase more drastically with the severity of climate change. That is, if CO_2 concentrations continue to rise beyond a doubling—which is eventually likely under a business-as-usual scenario—then damages may grow to become a significant loss to the U.S. agricultural economy.

Although trade is an important tool for maintaining global production of cereals to mitigate against regional welfare losses (Reilly et al., 1994), it is not clear how trade patterns for other crops, particularly export crops, may change. Wheat, corn, and rice are important export products. However, the traded shares of total production for these cereals are small compared to other agricultural products. About 20 percent of total global wheat production, 12 percent of coarse grains, and 3 percent of rice enter world markets. By comparison, 86 percent of coffee, 45 percent of tea, 82 percent of cocoa, and 85 percent of rubber products are exported, and more than 25 percent of many citrus and fiber products are exported (FAO, 1995). These are the primary exports for many developing countries. Little research has been done on potential climate change impacts to products such as these, or on how changes in yields might affect national economies that are highly dependent on export earnings from such products.

In addition, food imports for many countries are already relatively high. Whether those countries can afford to import additional food to cover yield reductions is not known. Ratios of food import value to export earnings are already high among low-latitude countries, which are most likely to suffer agricultural losses due to climate change.[7] Furthermore, some countries have food import financing problems, measured as the ratio of the value of food imports to total export earnings. Box 3 describes some issues and vulnerabilities of global food production and the risks of hunger that could result due to changes in climate.

Box 3

Effects of World Hunger and Food Distribution

Research results indicate that global food production is most likely to be only modestly affected by climate change, although some countries could be more adversely affected than others. Consequently, global capacity to feed the world's population is not expected to be seriously threatened as a result of climate change in the foreseeable future. However, global capacity to grow food is currently greater than that required to eliminate hunger, and yet hunger is endemic in a number of areas of the world because of poverty, scarce capital, civil strife, and droughts and famines. If climate change adversely affects agricultural markets in areas of the world where hunger is, or is expected to be, a significant problem, the added stress could pose a serious threat to the local or regional food supply. The result would be an increase in the risks of hunger in these regions. Unfortunately, these are precisely the areas that appear to be most prone to losses of agricultural production from climate change.

Population growth, economic pressures, land degradation, and political instability stress a nation's ability to satisfy food requirements and can diminish the ability to cope with climate change. Although these factors are difficult to estimate over the long run, Fischer et al. (1994) estimate that in the absence of climate change, the number of people at risk of hunger and malnourishment will increase from 500 million today to over 640 million by 2060 (though falling as a percentage of the world population).

Rosenzweig et al. (1995) found that all of the scenarios of future climate change used in their study (i.e., GISS, GFDL, and UKMO) increased estimates of the number of people at risk of hunger. Their analysis also showed that reduced population growth could do the most to minimize the impacts of climate change, followed by increased trade liberalization and higher economic growth rates.

Norse (1994) assessed the vulnerability of food security to threats from environmental degradation, economic growth, population growth, and climate change, and found that sub-Saharan Africa is the region most at risk in terms of food security. It is more vulnerable to reduced rainfall, change in rainfall variability, and greater evapotranspiration than any other region. About half of its arable land is already arid or semiarid, only 2 percent of its cropland is irrigated, and the high cost of irrigation development limits its use for low cost staple foods. Much of the soil has low water holding capacity, and this could be reduced further by higher soil temperatures, leading to greater rates of soil organic matter breakdown. On the economic side, the anticipated low GDP growth rates imply that people and countries will be unable to overcome domestic food production problems through purchased imports.

In summary, overcoming the potential increased risk of hunger may require efforts to improve the food distribution system, to limit population growth, to raise the level of economic development, and to reduce trade barriers. Furthermore, continued agricultural research to improve crop varieties and production methods as well as to provide technical assistance to developing countries will be necessary to limit the vulnerability of at-risk countries.

VI. Environmental Effects of Agricultural Production

A. Impacts of Climate Change on Critical Agro-ecosystems

Shifts in crop production and expansion in irrigated acreage imply changes in demands or pressure on environmental and natural resources, including water quantity and quality, wetlands, soil, fish and wildlife. For example, a northward shift in corn and soybean production (through the Dakotas to southern Canada) may exacerbate the loss of critical prairie wetlands by making drainage and conversion to crop production profitable. A westward shift in the production of these two crops would increase wind and water erosion of the fragile soils of the western Great Plains. The substantial increase in irrigated acreage (2 million to 18 million acres) suggested in several studies, including Adams et al. (1990), enhances the likelihood of groundwater and surface water depletion and pollution. Obtaining water to facilitate increased irrigated acreage also implies more and larger reservoirs, which in turn implies greater pressure to develop the relatively few remaining undammed rivers in the United States (Hurd et al., 1998). In addition, adaptation may have unintended environmental consequences; e.g., the drive to increase production increases pesticide use, irrigation, and use of marginal lands, all of which help degrade environmental quality (Adams et al., 1988; Crosson and Anderson, 1994).

One aspect of climate change may be an increased intensity of rainfall (Karl and Knight, 1998). Globally, all GCMs predict an increase in precipitation. Regional changes may be quite different, but at least some areas are likely to experience more rain even as others get less. Increased intensity of rainfall is a threat to agriculture and the environment because heavy rainfall is primarily responsible for soil erosion, leaching of agricultural chemicals, and runoff that carries livestock waste and nutrients into water bodies. For example, the growth of a hypoxic zone (area of water depleted of oxygen and thus unable to support marine life) in the Gulf of Mexico followed flooding of the Mississippi River, which carried heavy loads of nutrients into the Gulf. Normally, agricultural chemicals in surface water exist at levels that do not cause obvious harm. High concentrations during high rainfall can, however, result in fishkills. While related environmental effects of climate change have not been analyzed, studies have found that adopting practices to control agricultural pollutants is likely to increase costs (Heimlich and Barnard, 1995).

Global warming could exacerbate air pollution through both natural processes and increased electricity use (e.g., associated with increased air conditioning). Specifically, several forms of air pollution either are the direct result of photochemical processes in the atmosphere or are enhanced under elevated temperatures. The most pervasive of these types of pollution is tropospheric ozone, a photochemical oxidant created from several precursor pollutants.

The adverse effects of air pollution on vegetation, including crops, are well documented (Heck et al., 1984; U.S. EPA, 1996). Ozone is one of the major air pollutants in the United States, and it accounts for over 90 percent of vegetation damage. The long-range transport of ozone results in elevated ozone levels in rural areas. As a result, ambient pollution concentrations in important agricultural production areas are sufficiently high to reduce crop yields (U.S. EPA, 1996).

The economic consequences of ozone on agricultural production are substantial. For example, Adams et al. (1986) estimate that current levels of exposure of crops to ozone result in over $3 billion in damages in the United States. In addition, losses to forests and horticultural plants are estimated to be in excess of $2 billion in the United States (Callaway et al., 1985). The degree to which concentrations of tropospheric ozone will increase due to rising global temperatures is uncertain, given the complex nature of the ozone formation process and the difficulty in forecasting future levels of precursor pollutants. However, there is strong circumstantial evidence that ozone and its precursors will increase. A 4°F warming (about 2°C) in the Midwest with no other change in weather or emissions could increase concentrations of ozone by as much as 8 percent (U.S. EPA, 1996).

B. Impact of Climate Change on Agricultural Water Supplies

Increased spatial and temporal variability in rainfall and reductions in snowpack predicted by climate models along with rising commodity prices will increase pressure for irrigation. Expansion of irrigated acreage has been forecast in some economic assessments. Such increased agricultural demand is likely to add to current overdraft and groundwater quality problems in many regions of the West, highlighting both the uncertainties and the importance of groundwater in dealing with climate change. Competing demands from, for example, domestic users, are also likely to increase. When coupled with diminished supply, this could lead to reallocations from agriculture to urban areas, as witnessed in recent California droughts with the use of water banking schemes to redirect water toward higher valued uses.

Much of the expansion of irrigation in the western United States over the past three decades came from increased use of groundwater, motivated by higher commodity prices. To the extent that climate change increases crop prices, the economic feasibility of groundwater pumping increases. However, the hydrology of groundwater transport is complex. Even with increased runoff in some areas, the slow rate of groundwater recharge implies that overdrafting will continue or even accelerate in many western regions. Ultimately, the long-term feasibility of groundwater pumping will depend on changes in pumping lifts, energy costs, pumping efficiencies, and so forth.

On the other hand, severe flooding could be a serious problem in many regions of the United States. The Missouri River floods of 1993 and the 1998 flooding in the fruit and vegetable growing regions of California caused significant losses in these important agricultural regions. In addition to the serious harm to farmers, farm workers, and local economies, for example, the 1998 California floods reduced supplies of specialty crops to the national market.

VII. Mitigation and Societal Responses to the Problem of GHG Emissions

While this paper does not focus on reduction of greenhouse gas emissions and its effects on agriculture, it is worth noting that mitigation strategies present both potential costs and opportunities for the agriculture sector. For example, mitigation policies that increase energy prices, such as fuel taxes, would increase farm production costs (these changes also could cause industries in general to re-evaluate energy use and conservation strategies). Reducing emissions of greenhouse gases from agriculture (such as methane) could also increase costs as some production is displaced and production costs increase (see Box 4).

Efforts to mitigate GHG emissions also provide opportunities for agriculture. These include increased demand for biofuels produced by agriculture if prices for oil, gas, and coal rise because of policies aimed at reducing carbon emissions. Agriculture also has the opportunity to sequester carbon in soils through changes in tillage and other cropping practices and through afforestation. Some have envisioned carbon sequestration as another source of revenue for farmers, produced along with their regular crops (see Box 4).

Box 4

Role of Agriculture in Mitigating Climate Change

Agriculture is both a receptor of possible climate changes arising from greenhouse gas emissions and a source of greenhouse gases, including CO_2, methane (CH_4), and nitrous oxide (N_2O). The agricultural sector is an energy-intensive industry but because it is a relatively small share (less than 3 percent) of the economy, it is a relatively minor user of fossil fuels and hence a minor contributor to U.S. CO_2 emissions. Nonetheless, agriculture constitutes 40 percent of anthropogenic sources of methane (primarily from rice and cattle production), and 68 percent of N_2O (mainly from nitrogen fertilizer).

The understanding of agriculture's contribution to these emissions has increased considerably over the past decade, leading to several potential strategies for reductions. Methane reduction strategies include changes in animal feed rations in the short run and genetic and dietary improvements in the long run, as well as changes in rice fertilization and other management practices. Reduced use of nitrogen fertilizer, particularly those easily volatilized forms such as anhydrous ammonia, could reduce N_2O emissions, as could the use of advanced fertilizer techniques (controlled release and better placement), better management of manure use, and better timing of applications.

In the short term, reduced use of nitrogen fertilizer and feeding systems that produce less methane from livestock are expected to reduce yields or increase costs. Such effects, in turn, suggest higher food costs and, hence, losses to consumers. In the long run, improved breeding programs for livestock, better management of nitrogen in rice and other crop production, and improved crop breeding to reduce fertilizer dependence are needed to reduce emissions.

Policies to reduce carbon emissions from fossil fuel combustion, such as a national tradeable permit scheme, are expected to result in energy price changes. Estimates of the carbon "price" in a permit trading system and its impact on energy prices vary significantly, depending on assumptions about how such a system is implemented. In the short to medium time frame, implementation of carbon emission control policies are more likely to adversely affect agriculture through, for example, higher fuel and fertilizer costs than climate changes over the same period.

Although policies to reduce greenhouse gas emissions may impose costs on agriculture, they also create substantial economic opportunities for agricultural producers. For example, afforestation (planting trees) to sequester carbon is a prominent strategy for mitigating greenhouse gas emissions, and is a potential opportunity for agriculture because enough marginal agricultural land exists in the United States to offset a considerable amount of carbon emissions. The potential benefits of this strategy are broad-based: planting trees creates a low-cost source of biomass, alternative fuels, and carbon-based materials. Some estimates suggest that tree planting on marginal agricultural lands can be a significant contributor to mitigation at a relatively low cost compared with reducing carbon emissions from fossil fuels (IPCC, 1996b).

Additional amounts of carbon can be sequestered in soils by relatively minor changes in agricultural practices. "Growing carbon" on agricultural lands would create a new crop for farmers. The use of so-called "tradeable permits" that allowed firms who needed to reduce carbon emissions to instead purchase reductions or sequestration is one way that these opportunities for agriculture could be created. In combination with a tradeable permit system and government incentives to sequester carbon in soils, there could be substantial increases in returns to farmers in some regions.

VIII. Conclusions

The preceding discussion summarizes some of the principal findings on the potential consequences of climate change on U.S. agriculture. As with any research on difficult and complex topics, there are uncertainties in the numbers, and it is important not to attach a great deal of significance to any specific number or result. There are, however, some common observations that can provide insight into the nature and significance of possible climate change effects on agriculture:

1. Crops and livestock are sensitive to climate changes in both positive and negative ways. Understanding the direct biophysical and economic responses to these changes is complicated and requires more research. In addition, indirect effects—such as changes in pests and water quality and changes in extreme climate events—are not well understood.

2. The emerging consensus from modeling studies is that the net effects on U.S. agriculture associated with a doubling of CO_2 may be small; however, regional changes may be significant (there will be some regions that gain and others that lose). Beyond a doubling of CO_2, the negative effects are more pronounced both in the United States and globally.

3. The impact of climate change on U.S. agriculture is mixed. Clearly, there are regions, such as the Northern Great Plains and Great Lakes, where productivity may increase as a result of warmer temperatures, increased precipitation, and increased CO_2. On the other hand, the Southern Plains, Delta states, and possibly the Southeast and portions of the Corn Belt could see agricultural productivity fall. However, the form and pattern of change are uncertain because changes in regional climate cannot be predicted with a high degree of confidence. Most studies suggest that regional changes are likely in crop acreage, irrigation water consumption, farm employment, and demand for inputs.

4. Adaptation and human response are critical to the accurate and credible assessment of impacts. However, because of the long time horizons involved in climate change assessments, they are difficult to fully capture in economic models and are influenced by many factors, including government policy, prices, technology research and development, and availability of agricultural extension services.

5. Better climate change forecasts are key to improved assessments of the impacts of climate change. In the meantime, farmers and the agricultural community must consider strategies that are robust in the face of uncertainty about climate change.

6. Agriculture is a sector that can adapt, but there are some factors not included in assessments that could change this conclusion. Indirect effects of climate change, such as changes in levels of tropospheric ozone, changes in the incidence and severity of agricultural pests and diseases, and changes in soil erosion, are largely unmeasured and have not been incorporated into estimates of impacts. Few studies consider the effects of changes in the frequencies of extreme events such as droughts and floods, or changes in climatic variability. Near-term climate changes, the expected rate of change, and costs and obstacles to adaptation also need to be addressed. These omitted effects are potentially important for creating an accurate picture of the full impacts of climate change on agriculture.

Overall, the consensus of economic assessments is that climate change of the magnitudes currently being discussed by IPCC and other organizations will have only a small overall effect on U.S. agriculture and its ability to provide sufficient food and fiber to both domestic and global customers. Whether this overall effect is positive or negative depends largely on the assumed yield-enhancing effect of CO_2. However, distributional effects can be significant as consumers, producers, and local economies gain in some regions and lose in others.

Warming beyond that reflected in current studies (and associated with a continued rise in CO_2 beyond the doubling that has been commonly investigated) is expected to impose much greater costs, decreasing production in most areas of the United States and substantially limiting global production. This reinforces the need to determine the ultimate level of CO_2 and other gases in the atmosphere and the magnitude of warming that may accompany the build-up of these gases.

Endnotes

1. The issue of mitigation is largely beyond the scope of this paper. However, this is an area of active research and the Pew Center is engaged in separate work on sequestration. Also, a paper on forestry resources will be published as part of this Environmental Impacts Series.

2. The average yield for winter, durum, and spring wheat, weighted by volume of production, is based on National Agricultural Statistical Service data. The weather in wheat growing areas of the United States in 1998 was unusually favorable. A trend analysis estimates that yields in 1998 would have been 39 bushels/acre had it been a normal weather year (NASS, 1998).

3. Other analyses find evidence of a plateau in aggregate yield trends and question the validity of assumed continued yield growth (Brown, 1994). Resource degradation (e.g., soil erosion) and exhaustion of yield enhancement potential are cited as limiting factors. Investigations of these factors in other studies show little evidence of a yield plateau, note remaining opportunities for yield enhancements, and see very limited effects of resource degradation on yield (Reilly and Fuglie, 1998).

4. GCMs resolve climate at a very coarse geographic scale (typically several hundred kilometers between grid points). There is often significant weather variation between grid points that is not captured by the GCMs. With respect to temporal resolution, GCMs resolve climate at very small time steps but with little accuracy at that scale. Agronomic sciences can document the effects of floods, droughts, extreme heat, early or late frosts, or failure to meet chilling requirements. However, improved climate forecasts are needed to evaluate whether and how the frequency and magnitude of these events may change.

5. Temperature increases lead to higher respiration rates, shorter periods of seed formation, and consequently lower biomass production. For example, higher temperatures result in a shorter grain filling period, smaller and lighter grains, and therefore lower crop yields and perhaps lower grain quality (i.e., lower protein levels).

6. Reduced transpiration could be 30 percent in some crop plants (Kimball, 1983). However, stomatal response to CO_2 is affected by many environmental factors (temperature, light intensity) and plant factors (age, hormones), so predicting the effect of elevated CO_2 on the responsiveness of stomata is still very difficult (Rosenzweig and Hillel, 1995).

7. For example, average ratios in Latin America are 33 percent.

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