

Climate Change and Agriculture

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Without a doubt, climate change will be one of the most important environmental topics of the 1990s and will be high on the research agendas of many scientific disciplines in years ahead. While not yet universally accepted, it is now widely believed that anthropogenic emissions of carbon dioxide and other "greenhouse" gases have the potential to substantially warm climates worldwide. Although there is no consensus on the timing and magnitude of global warming, current climate models predict an average increase of 2.8°C to 5.2°C in the earth's temperature over the next century (Karl, Diaz, and Barnett). Changes in regional temperature and precipitation will likely accompany the global warming, but there is even less scientific agreement on the magnitude of these changes.

A variety of natural and human-mediated systems that impact human welfare are expected to undergo changes as a consequence of climate change. Chief among these systems in social importance is agriculture, which is particularly vulnerable to climatic conditions. Changes in temperature, precipitation, solar radiation, and carbon dioxide concentrations could profoundly affect the biophysical opportunities and constraints on agriculture. Also, since agricultural systems are managed, subsequent changes in response to global warming will be conditioned by the interaction among economic influences on decision making and the physical and biological processes.

While an increasingly popular view among policy makers is that U.S. agriculture will be able to adapt quite effectively to a changing climate, there is not a great deal of empirical support for this contention. This is a result of our limited understanding of the interactions among the physical, biological, and economic factors that determine the potential for adaptation. Nevertheless, over the next

several years the demand will grow for economic-impact analyses of climate change on vulnerable sectors such as agriculture. The research needs present opportunities and challenges for our profession.

The purpose of this paper is to discuss the potential impacts of climate change on agriculture. The paper begins with a discussion of the recent scientific evidence on global warming, followed by a more detailed review of the findings of three studies that have focused on the economic impacts of climate change on agriculture. In the final section, a proposed research agenda for the future study of climate-change impacts on agriculture is presented.

Scientific Evidence of the Problem

Carbon dioxide (CO₂) and other trace ("greenhouse") gases, such as methane, chlorofluorocarbons, and nitrous oxide, represent a very small proportion of the earth's atmosphere but play an important role in influencing the climate (Schneider). These gases are like the glass in a greenhouse, which allows sunlight to enter freely but traps absorbed heat and keeps it from escaping. Similarly, greenhouse gases in the earth's atmosphere allow incoming solar radiation to warm the climate system but prevent cooling of the system by trapping a portion of the outgoing thermal infrared radiation. This phenomenon is commonly referred to as the "greenhouse effect."

Greenhouse gases are indeed responsible for the present habitability of the earth, for without them the earth's average temperature would be a frigid -23°C (Rosenzweig 1989). However, as greenhouse gases in the atmosphere increase, the additional heat-trapping ability is expected to cause an increase in the global temperature. Evidence of the greenhouse effect can be observed on other planets such as Venus, which is extremely hot and has very high concentrations of CO₂, or Mars, which is cold and has low levels of CO₂. Similar evidence of the earth's greenhouse effect comes from paleoclimate data, which shows lower levels of CO₂ during the glacial periods and higher CO₂ concen-

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trations during the warmer interglacial periods (Hansen et al. 1987).

The magnitude of climate change will depend in great part on the rate of increase in emissions of CO₂ and other greenhouse gases. Since the Industrial Revolution, the level of CO₂ in the atmosphere has increased a little over 23%, from 285 ppm to 350 ppm. However, while CO₂ is emitted in larger quantities, the other greenhouse gases also contribute significantly to global warming. This is due to the fact that other gases are much more efficient in absorbing infrared radiation than CO₂. While predicting the future trajectory of atmospheric concentrations of greenhouse gases is difficult, recent projections indicate that a doubling of levels from the year 1900 should occur sometime between the years 2030 and 2080 (Schneider). The exact time will depend upon a number of factors, including future global levels of fossil-fuel consumption, the rate of deforestation, agricultural practices, and actions taken by governments to slow or halt the emissions of various greenhouse gases.

Even if the trajectory of atmospheric concentrations of greenhouse gases could be predicted with certainty, the nature of future climates would still be uncertain. This is due to the fact that the feedback mechanisms within the climate system are extremely complicated (and in some cases, poorly understood) and therefore difficult to model. As a result, existing climate models are not considered to be highly reliable. The most credible glimpses of future climate come from the global general circulation models (GCMs) of the earth's atmosphere and oceans, which are large-scale mathematical representations of the climate system.

Future Climate Predictions

To predict the potential magnitude of climate change, several GCMs have been used to simulate how temperature, precipitation, and other climatic variables would change if the level of CO₂ and other greenhouse gases in the atmosphere doubled from pre-Industrial Revolution levels. A summary of the results from five GCMs for changes in temperature and precipitation is presented in Table 1. On average, these five models predict that a doubled CO₂ concentration in the atmosphere would cause the earth's surface temperature to rise by 3.9°C. It is generally believed that the global distribution of this warming will be greatest in polar regions and least in the tropics. Because the saturation vapor pressure increases exponentially with temperature, these models also predict an average increase in global precipitation of 10%. The amount of time required for these predicted changes in tem-

Table 1. General Circulation Model Predictions of Changes in Average Global Temperature and Precipitation Due to Doubled Atmospheric Concentrations of CO₂

Model	Change in Surface Air Temperature (°C)	Change in Precipitation (%)
Princeton University Geophysical Fluid Dynamics Laboratory	4.0	8.7
Goddard Institute of Space Studies National Center for Atmospheric Research	4.2	11.0
Oregon State University	3.5	7.1
United Kingdom Meteorological Office	2.8	7.8
Average	5.2	15.8
	3.9	10.1

Source: Karl et al. (taken from Rosenzweig 1989).

perature and precipitation to take effect ranges from 50 to 100 years (Rosenzweig 1989). The average increases predicted by these studies represent unprecedented levels of change and could have tremendous implications for agriculture, especially if they were to occur within the relatively short period of time that is predicted.

Predicted changes in temperature and precipitation for various U.S. regions resulting from a doubling of atmospheric CO₂ are presented in Table 2. The predictions are based on two GCM models: the Goddard Institute of Space Studies (GISS) and the Princeton University Geophysical Fluid Dynamics Laboratory (GFDL) models. Both models predict a warming in all regions of the U.S. as global temperature rises, but the relative magnitudes of warming differ between model results. There is even less agreement between models in terms of predicted changes in precipitation. For example, on average, the GISS model predicts an 8.0% increase in annual precipitation, while the GFDL model predicts an average decrease of 0.8% in precipitation for the U.S. For agriculture, the GFDL model results are more negative: four regions have predicted higher temperature and lower precipitation. The discrepancy between GCMs is due to technical differences, such as how clouds and oceans are captured in each model.

Table 2. GISS and GFDL Model Predictions of Changes in Average Temperature and Precipitation in the U.S. Due to Doubled Atmospheric Concentrations of CO₂

Region	Change in Annual Surface Air Temperature (°C)		Change in Precipitation (%)	
	GISS	GFDL	GISS	GFDL
Northwest	4.4	4.5	23.0	2.7
California	4.9	4.9	6.2	1.8
Northern Mountains	4.8	5.5	18.0	1.7
Southern Mountains	4.9	5.1	5.0	-1.4
Northern Plains	4.7	5.9	7.0	-3.4
Southern Plains	4.4	4.5	-7.8	-0.3
Delta	5.3	4.4	2.4	0.3
Southeast	3.5	4.9	10.5	-7.8
Average	4.6	5.0	8.0	-0.8

Source: Adams et al. 1988.

Potential Economic Impacts

Most of the research to date on climate change has been done in the physical sciences and engineering. The economic research that has been completed has focused mainly on the benefits and costs of restricting greenhouse-gas emissions (e.g., Edmonds and Reilly; Manne and Richels; Nordhaus and Yohe). There has also been some research on equity issues relating to possible international treaties to limit CO₂ and greenhouse-gas emissions (e.g., Chapman and Drennen; Shue).

In terms of agriculture, existing economic research assesses the potential impacts of a changing climate based on alternative climate-change scenarios. The findings of three studies are discussed here to provide a review of the current predictions regarding climate-change impacts. These studies examine climate-change impacts on agriculture at the international level (Kane, Reilly, and Bucklin), at the national level (Adams et al. 1990), and at the farm level (Kaiser et al. 1991a; Kaiser et al. 1991b). While not exhaustive of the literature, these three studies provide a fairly broad overview of climate-change effects on agriculture at alternative market levels.

Impacts of Climate Change on World Agricultural Markets

Kane, Reilly, and Bucklin conducted a comparative static analysis of climate change on world agricultural markets. Their analysis compared the

current world market situation to what it might be under climate warming, induced by a doubling of greenhouse gases in the atmosphere. The world was disaggregated into 13 regions: U.S., Canada, European Community, Australia, Argentina, Pakistan, Thailand, China, Brazil, Soviet Union, northern Europe, Japan, and the rest of the world. The estimated effects on crop yields of this climate-change scenario for each region were taken from several previous reports. The U.S. yield effect was based on the average of three studies of individual regions: the Southeast (Peart et al.), the Great Plains (Rosenzweig 1988), and the Great Lakes (Ritchie, Baer, and Chou). The crop-yield impacts for the northern latitude and semiarid countries were obtained from a comprehensive study by Parry et al. (1988a, 1988b). Finally, the impact of a double CO₂-induced climate change on crop yields in Europe was based on results from Santer.

The estimated effects on yields are presented in Table 3. These results are fairly consistent with current theories of climate change. Countries located in the midlatitude (e.g., U.S., Canada, European Community) suffer the largest crop-yield decreases, while countries located in the northern latitudes (e.g., northern Europe, Soviet Union) experience yield increases due to climate change. The U.S., Canada, and the European Community experience large decreases in corn and soybean yields because the change in climate is predicted to be both warmer and drier. On the other hand, countries in the northern latitudes have positive yield effects due to a predicted increase in precipitation.

Table 3. Worldwide Yield Effects Due to Climate Change

Country/Region	Change in Yield (%)
United States	-20*
European Community	-20*
Canada	-18
Northern Europe	15
Australia	15
Soviet Union	10
Japan	4
China	0
Brazil	0
Argentina	0
Africa	0
Caribbean	0
Other Latin America	0
Pakistan	0
Thailand	0
Other South and Southeast Asia	0

Source: Kane, Reilly, and Bucklin (based on estimates from several studies—see text).

*Yield reductions by crop are -12% for wheat, -27% for corn, and -30% for soybeans.

The assumed yield effects were used in a partial-equilibrium international trade model (SWOPSIM) to estimate global-market effects of climate change. The SWOPSIM model consists of crop supply and demand equations for each country that is represented by own and cross-price elasticities. The effects of various agricultural commodity programs are modeled as simple price wedges.

According to Kane, Reilly, and Bucklin's results, world prices for most agricultural commodities would increase due to climate change. Corn and soybean prices would experience the largest price increases (36% and 34%, respectively) because the majority of the world's production of these crops is produced in the midlatitudes, which is the area most severely affected by the change in climate. World prices for wheat and coarse grains other than corn would also experience sizable price increases of 11% and 13%, respectively. These price increases are smaller than those for corn and soybeans because the yield effects of wheat and coarse grains other than corn would not be as severe under the assumed climate-change scenario. The price increase for rice, in contrast, is not very large (4%) because the majority of the world's rice production occurs in regions that would not be as severely affected by the change in climate.

In terms of economic surplus, consumers are the big losers in this climate-change scenario due to increasing prices. On the other hand, farmers, in general, gain from climate change because the price increases more than offset production decreases. Most countries face net losses in terms of consumer plus producer surplus. Two exceptions are Argentina and Australia, both of which export a large percentage of their agricultural production. While most countries experience a decline in economic surplus, Kane, Reilly, and Bucklin's results indicate that these losses are usually less than 3% of national income.

Impacts of Climate Change on U.S. Agricultural Markets

Adams et al. (1990) conducted a comparative static analysis of the potential effects of climate change on the regional comparative advantage of U.S. agriculture. The U.S. was divided into 64 production regions. The predicted changes in precipitation and temperature from the GISS and GFDL climate models (assuming doubled atmospheric concentrations of greenhouse gases) were used in crop simulation models to predict regional yield impacts (Rosenzweig 1988; Peart et al.). Unlike the previous study, Adams et al. (1989) generated two separate yield impacts due to climate change, one

including a positive CO₂ "fertilizer effect" and the other not including a fertilizer effect.¹ Four scenarios were examined: the GISS-predicted climate change with and without the CO₂ fertilizer effect, and the GFDL-predicted climate change with and without the CO₂ fertilizer effect. Crop yields for both irrigated and rain-fed crops were also included.

The impact of the climate-change scenarios predicted by both the GISS and GFDL models on nonirrigated crop yields was negative. There were tremendous differences in predicted yield impacts between the GISS and GFDL climate models. Similar to Kane, Reilly, and Bucklin's findings, Adams et al. (1990) found that the more severe climate change predicted by the GFDL model resulted in larger yield reductions than the yield effects from the GISS climate scenario. Not surprisingly, crops that were irrigated did not have as severe yield reductions as rain-fed crops. Under the CO₂ fertilizer effect scenario, the negative impacts of climate change on crop yields were substantially mitigated and, in some cases, yields actually increased. In terms of regional distribution of yield impacts, regions in the northern U.S. were generally less severely affected, while regions in the south suffered the largest yield losses due to climate change.

The yield effects for the four scenarios were used in a sector-level mathematical programming model of U.S. agriculture to simulate climate-change impacts on prices, regional and national production, consumption, consumer and producer surplus, and other market variables (Cheng and McCarl). The objective function was to maximize total economic surplus subject to constraints on resource endowments of land, labor, and water supplies in each of the 64 production regions. As was true for the yield results, the economic results varied tremendously in magnitude and even direction among the four scenarios.

For example, in the two scenarios without the fertilizer effect, the predicted climate change by the GISS model results in a decrease in U.S. crop production of 10% and an 18% increase in prices, while the GFDL climate change results in a 39% decrease in production and a 109% increase in prices. In both cases, society is worse off in terms of economic surplus (change of -\$6.5 billion and -\$35.9 billion for the GISS and GFDL scenarios,

¹ While potentially beneficial, this CO₂ fertilizer effect was incorporated into the crop simulation models in an ad hoc fashion as a scalar shift that only reflected the positive effects of CO₂ while ignoring the detrimental effects such as increased leaf temperature. This issue is discussed in greater detail in the next section.

respectively). If the potentially positive CO₂ fertilizer effect is included, the predicted market changes based on both climate model scenarios are less severe. In this case, the predicted climate change of the GISS model actually results in a 10% increase in crop production and an 18% decrease in prices. In contrast, the GFDL climate-change scenario results in a 19% decrease in production and a 28% increase in crop prices. The change in economic surplus associated with the GISS and GFDL in this case is +\$9.9 billion and -\$10.5 billion, respectively. While there is tremendous variation in these predictions of economic losses associated with a double CO₂-induced climate change, the general direction of results from three out of four scenarios suggests a need to further study CO₂ and other greenhouse-gas abatement policies.

Microeconomic Impacts of Climate Change on Agriculture

In a departure from the two previous studies, Kaiser et al. (1991a) and Kaiser et al. (1991b) developed a protocol for examining the adaptability issue of climate change at the farm level. Rather than using the comparative static framework of a doubled CO₂ climate, gradual, annual climate change over a 100-year period was simulated by a stochastic weather generator developed by Wilks (1990). Three changing climate scenarios were constructed based on the globally averaged temperature changes portrayed in the transient "scenarios A and B" of Hansen et al. (1988). In the first scenario, temperature increases by 2.5°C and precipitation increases by 10% at the time of equivalent CO₂ doubling (year 2060), with half of the changes assumed to occur between the years 2030 and 2060. Similarly, the second scenario consists of a 2.5°C increase in temperature, but a 10% decrease in precipitation, by the year 2060. The final and most severe scenario consists of a 4.2°C gradual increase in temperature accompanied by a 20% decrease in precipitation by year 2060. In addition to changes in averages, changes in climatic variability were also specified based on the limited investigations in temperature variability from GCM simulations (Rind, Goldberg, and Ruedy; Wilks 1986; Wilson and Mitchell) and precipitation variability based on Waggoner.

The climatic variables were used in a dynamic crop simulation model developed by Buttlar and Riha to predict annual values for crop yields, grain moisture content, and field time over the 100-year simulation period. A case farm in southern Minnesota that can produce corn, soybeans, and/or sorghum was used. While sorghum is currently not

grown in this region, it is included because it is fairly drought-resistant and could displace corn if climate warming is severe enough. A major difference from the two previous studies is that adaptability was incorporated in the analysis by allowing for changes in cultivars (plant varieties) and timing of planting and harvesting decisions in response to gradual climate change.

Average crop yields for one gradual climate-warming scenario (2.5°C warmer and 10% drier by year 2060) are shown in Figure 1. It is interesting that in this scenario, soybean and sorghum yields actually increase steadily throughout the 100 years, while corn yields remain relatively stable. In fact, in all three climate-warming scenarios considered by Kaiser et al. (1991b), soybean and sorghum yields consistently increased over time and corn yields declined in only the most severe case. This result, which is counter to the results of the two previous studies, is due to allowing for farmers to use adaptive production strategies in response to gradual climate warming. In particular, farmers changed planting and harvesting dates, crop mix, and cultivars over time as the change in climate evolved.

One of the more interesting results of the Kaiser et al. (1991b) study was a comparison of crop yields between when adaptation was allowed (adaptation case) and when it was assumed that farmers could not adapt by changing cultivars, crop selection, and timing of planting and harvesting (no-adaptation case). When it was assumed that farmers could not use adaptive management strategies over time, corn yields began to consistently decline after year 2000 for all three climate-warming scenarios. The major difference in corn yields is evident in Figure 2, which shows average corn yields over the 100-year period for the adaptation and no-adaptation cases for one of the climate-warming scenarios. For this climate scenario (2.5°C warmer and 10% drier by the year 2060), the difference in corn yields between the adaptation and no-adaptation cases reaches 40 bushels (about one-third of average yields in 1980) by the year 2060.²

These predicted crop yields for each climate-warming scenario were used in a dynamic, multi-stage, farm-level linear programming model to generate optimal cropping patterns, timing of field operations, and net farm revenue over the 100-year period. Because this is a farm-level model, output prices could not be endogenously determined by the economic model. Rather, crop-price trajectory-

² There are also some differences in soybean and sorghum yields between the adaptation and nonadaptation scenarios; however, the differences are relatively minor compared to those found for corn.

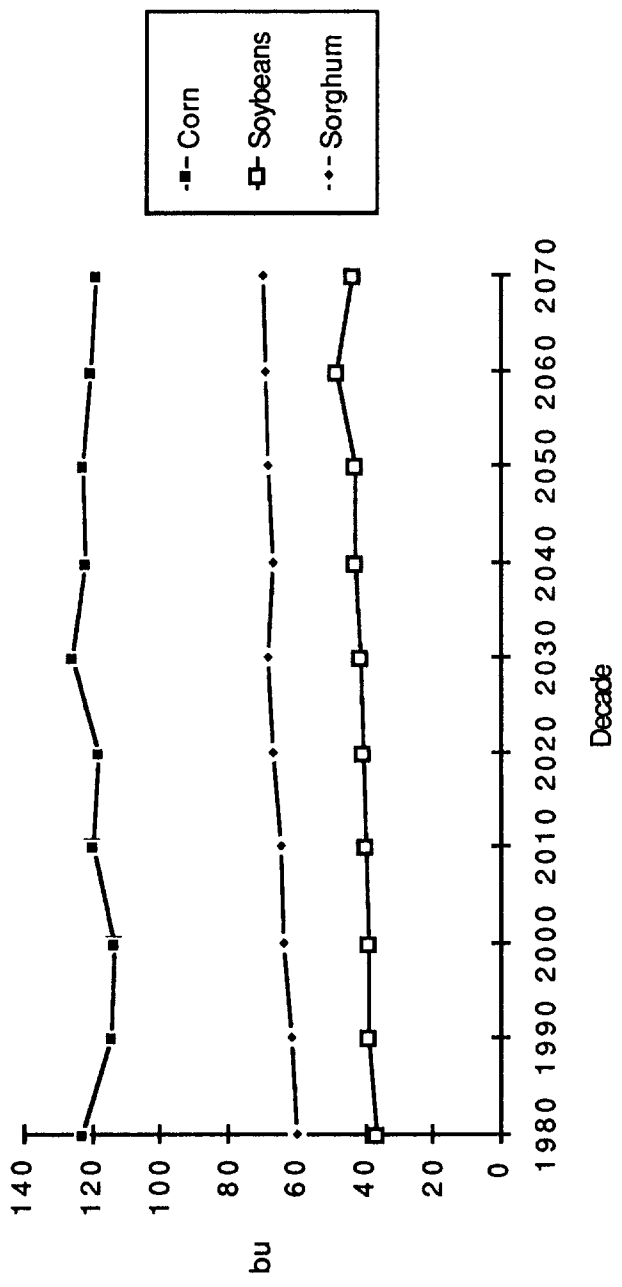


Figure 1. Average Crop Yield under Gradual Climate Warming, 1980–2070
 Source: Kaiser et al. 1991b.

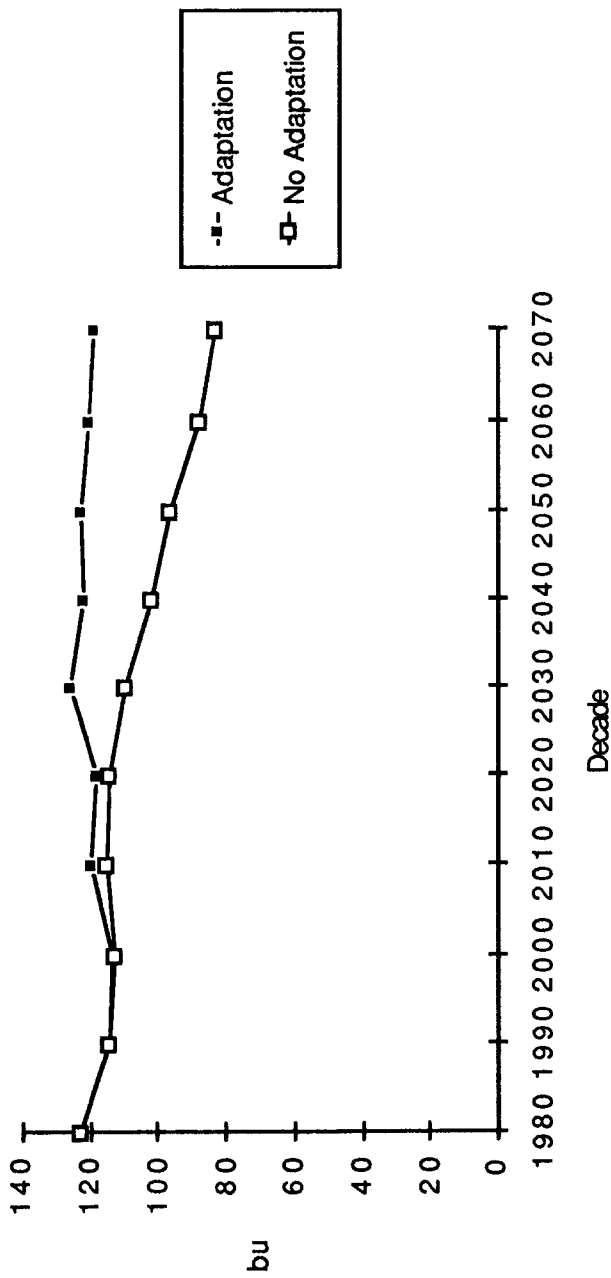


Figure 2. Average Corn Yields under Gradual Climate Warming for Adaptation and No-Adaptation Cases, 1980–2070
 Source: Kaiser et al. 1991b.

ries were constructed based on the average of the GISS and GFDL results from Adams et al (1988). Average net revenue under all three gradual climate-warming scenarios is shown in Figure 3. The general pattern for all scenarios is for net revenue to rise after year 2000, with levels somewhat higher than the base level in 1980. These results show that farmers located in this region are able to adapt to gradual climate warming by adjusting crop mix, switching to later-maturing, higher-yielding cultivars, and changing planting and harvesting dates. While the results are insufficient to form definite conclusions about climate warming, this study does illustrate the importance of adaptation to climate change. Consequently, studies that project crop yields under climate change without allowing for adaptation will seriously overstate yield reduction and negative revenue impacts. This is an important methodological consideration previously overlooked.

To summarize, the results of the above studies generally suggest that prices will increase due to climate change. While predicted changes in prices due to climate change vary from study to study (and within study), they tend to be higher for corn and soybeans than for wheat and coarse grains other than corn. These price increases are due to declines in overall production, particularly in the U.S., European Community, and Canada. In the U.S., regions that are located in the south are predicted to suffer larger decreases in production than regions in the north. The yield impacts vary widely depending on the climate model scenario and whether a CO₂ fertilizer effect is assumed. Moreover, these predicted decreases in production may be less severe if the role of adaptation is as important as suggested by the last study reviewed. In addition, all of these studies have ignored the role of technological change, which will tend to offset the effects of climate change on yields. In this context, it is important to note that whatever the change in climate, it will occur slowly and gradually. Thus, technological change and adaptation will play an important role in the ultimate agricultural impacts of climate change.

Future Research Needs

These and other economic studies have provided valuable insight into the potential market impacts of climate change. However, as is evident from the wide variations in results, additional research is needed before any definitive conclusions can be made. The following section outlines a possible agenda for additional research on climate change

and agriculture. The discussion is organized to address three fundamental issues regarding climate-change research. First, what are the major limitations of current physical and biological models and what areas of research are necessary for improving these models? Second, what is the role of economics given that there are deficiencies in the physical and biological models? Finally, assuming there is a role for economics at this point in time, what are the research priorities for economic analyses of climate-change impacts on agriculture?

Limitations of Physical and Biological Models

One major observation from previous studies is the tremendous discrepancies in predictions among climate models. There is disagreement on the magnitude and even the sign of predicted changes in precipitation due to climate change. Furthermore, the discrepancy among model results becomes larger as the region being studied gets smaller. This is due primarily to the relatively coarse spatial resolutions specified in these models. General circulation models divide the globe into grids that have spatial dimensions typically about 4° latitude by 5° longitude (Rosenzweig 1989). This is quite a sizable area and one that does not capture smaller-scale climate factors.

One of the most important research needs is to improve the climate models in order to achieve a higher degree of accuracy and consistency. There is ongoing research that may produce more accurate climate models in the future. Some of this research includes improving the representation of land surfaces and clouds in existing models. Another area involves adding a dynamically interactive component for oceans, which have a very important influence on climate. These and other areas of research by atmospheric scientists should improve the overall accuracy of general circulation models in the future.

Predictions of general circulation models have been used mainly to examine changes in mean values of climatic variables due to climate change. However, there is also scientific evidence to suggest that changes in climatic variability will occur due to climate change (Rind, Goldberg, and Ruedy). Changes in climatic variability, such as frequency of drought, will likely have as much impact on agricultural productivity as changes in mean values. In addition, because some crops are more drought-resistant than others (e.g., sorghum vs. corn), failure to capture the potential increased frequency of drought may result in erroneous predictions in regional cropping patterns. Consequently,

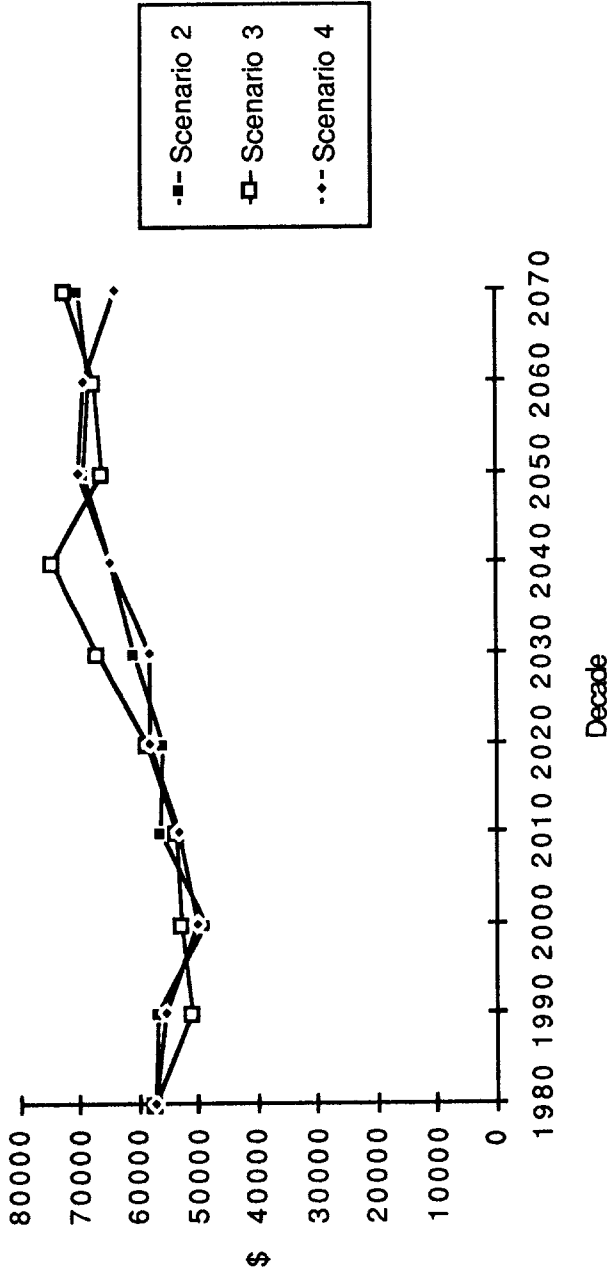


Figure 3. Average Net Farm Revenue under Three Gradual Climate-Warming Scenarios, 1980–2070
 Source: Kaiser et al. 1991b.

another important research area is generation and analysis of climatic variability due to climate change.

One of the most critical research needs for crop simulation models revolves around consideration of CO₂ as a fertilizer (Acock and Allen). The beneficial effects of increasing atmospheric concentrations of CO₂ on plant growth have either been ignored (e.g., Kane, Reilly, and Bucklin; Kaiser et al. 1991a; Kaiser et al. 1991b) or have been incorporated in an ad hoc way as a scalar shift (e.g., Adams et al. 1990). For example, studies that have incorporated a CO₂ fertilizer effect have modeled only the positive effects of increased atmospheric CO₂, while not adding any of the potentially negative effects, such as increased leaf temperature. In addition, studies to date have assumed that all the enhanced radiative forcing is attributable to CO₂. In reality, other greenhouse gases represent a significant proportion of the enhanced radiative forcing, and these gases will have no impact on crop yields.³ In order to obtain a more accurate picture of climate-change impacts on production, modifications in crop simulation models to more accurately account for the CO₂ fertilizer effect are essential.

Role of Economics

Some may question the role or need for economic assessment when the results of climate models themselves are highly suspect. However, there is clearly a role for economics in climate-change research and the policy debate. There are four reasons why economists should play an important role. First, as Adams points out, "even in the absence of data with which to measure correctly the costs of various policy alternatives, economics provides a useful perspective in terms of recognizing opportunity costs and framing policy questions." The role economists play in introducing economic notions to physical scientists in and of itself is an important reason for economic involvement.

Second, when faced with a high degree of uncertainty with respect to climate change, sensitivity analyses with economic models may provide useful information. For example, one could use economic models with a wide variety of climate-change scenarios. While it is impossible to assign probabilities to possible climate-change outcomes, the economic results of "worse" and "best" case scenarios could be used as upper and lower bounds for economic

impacts. Policy makers could then look at the range of potential outcomes and use this information to make their own assessments of the situation.

Third, it is important that economists be involved with climate-change research from the start so that researchers from other disciplines understand the needs of economic models in relationship with the physical and biological models. For instance, modifications in climate and/or crop simulation models may be necessary to be compatible with the data demands of economic models.

Finally, and most importantly, it must be recognized that the agricultural ecosystem is human-managed, and therefore economic influences on decision making will greatly influence this system's response to climate change. An understanding of only the physical and biological processes will fail to provide an adequate description of potential impacts. Economic incentives and disincentives of market signals and government policies will be just as important as physical and biological forces in determining the potential for agricultural adaptation to climate change.

Economic Research Priorities

Given that there is an important role for economics in climate-change research at this time, there are several areas that need to be addressed to improve our understanding of climate-change impacts. Each of these areas is discussed separately below, and no priorities are assigned.

There is a need for additional studies on the potential effects of climate change on global agricultural markets. Kane, Reilly, and Bucklin's study is a good start, but additional models should be used. For instance, a global analysis of climate change within a general-equilibrium framework would be valuable. Computable general-equilibrium models that allow for greater input substitutability are especially important for studying climate change, which will impact virtually all resources to a certain extent. The results from partial-equilibrium models may overstate potential climate-change impacts since they do not allow for the level of input substitution that will likely accompany any change in climate. Because agricultural markets are becoming even more internationalized over time, global analyses of this sort will be necessary in order to predict more accurately the price effects of climate change. There is currently a research effort sponsored by the U.S. Environmental Protection Agency and the Agency for International Development that is using a computable general-equilibrium model along with crop simulation models applied to various countries to examine world agricultural market impacts of climate

³ Actually, atmospheric increases in chlorofluorocarbons may have an indirect negative impact on crop yields because of their ozone-layer-depleting impact and subsequent increase in ultraviolet radiation.

change. Results of this study may provide better estimates of climate-change impacts on world prices, supply, demand, and trade.

Most of the market-level studies completed thus far have used a comparative static approach. However, climate change will occur gradually and a static framework fails to capture important factors that might run counter to the results predicted by static models. In reality, farmers will have to adapt to an evolving change in climate, not to a sudden, abrupt change in climate. Consequently, changes in agricultural technology that are induced by an evolving climate will lessen the negative impacts of climate change on agricultural production. It is important that technological change be incorporated dynamically in the economic models because changes in technology will also be evolutionary, not abrupt. The rate of farmer adoption of new technologies should also be made explicit. Other factors, like changes in population and income, will also have important marketwide effects and should be captured within the economic model in a dynamic framework. These factors will be especially important in the context of analyzing climate-change impacts on food availability relative to world demand.

There is a need to examine the role of government intervention in agricultural markets in the context of climate change. This issue is discussed in detail in a paper by Lewandrowski and Brazee. The authors argue that the incentives of current U.S. commodity programs would likely prevent participating farmers from adapting to climate change; that is, current provisions for setting support-price levels and acreage requirements, if not adjusted to correspond to changes in market conditions due to climate change, would hinder the adaptive process. In addition, Lewandrowski and Brazee argue that government policies affecting irrigation will become even more important if the changing climate results in less rain for U.S. crop production. Unless these programs become more flexible, these authors argue that the economic and budgetary costs will likely become greater as climate change occurs. A detailed policy analysis of various options, including current programs, deregulation, and other alternatives as they relate to climate change and social welfare, is needed.

Finally, one factor that will be an extremely important determinant of climate-change impacts is the demand and supply of irrigation. Only the Adams et al. (1990) study considered irrigation, however it was assumed that there were no limits on supply. They found that yield impacts due to climate change were much less severe for irrigated crops than for nonirrigated crops. This study also found that the

costs of irrigation would increase and irrigated acreage in the U.S. would increase substantially by 5 million (GISS result) to 18 million (GFDL result) acres, with most of the increase occurring in the Northwest and Northern Plains. This predicted expansion has major implications for natural resource and land use. Because irrigation is one of the more important strategies for adapting to climate warming, it is important that future economic-impact studies incorporate irrigation. It is also important that better model linkages are developed between changes in temperature and precipitation, and the availability and cost of irrigation.

Conclusion

The purposes of this paper were to discuss recent scientific evidence on global warming, review the potential impacts of climate change on agriculture, and present some views on what needs to be done to improve our understanding of the possible outcomes of climate change. It is now widely believed that anthropogenic emissions of carbon dioxide and other greenhouse gases will cause global warming, with current climate models predicting an increase in the earth's temperature of 2.8°C to 5.2°C over the next 50 to 100 years. The change in temperature, as well as the accompanying change in precipitation, has the potential to profoundly affect agricultural production and prices.

The results of the studies reviewed generally suggest that crop prices will increase due to climate change. Predicted changes in prices tend to be higher for corn and soybeans than for wheat and coarse grains other than corn. These price increases are due to declines in overall production, particularly in the U.S., European Community, and Canada. In the U.S., regions that are located in the south are predicted to suffer larger decreases in production than those in the north. At the same time, these predicted decreases in production may be less severe if the role of adaptation is as important as suggested by the Kaiser et al. (1991a) and Kaiser et al. (1991b) studies. Moreover, all studies to date have ignored the role of technological change, which will have a moderating influence on potential reductions in crop yields.

While these studies have provided valuable insight, more research is necessary before any definitive conclusions can be made. Several specific areas for improvement were presented. Improvements in the accuracy of general circulation models are essential for economic-impact assessment. Also, more analyses of climate-change impacts on changes in climatic variability are needed. The CO₂ fertilizer

effect should be incorporated into crop simulation models to more appropriately capture the positive and negative effects of increased atmospheric concentrations of CO₂ as well as other greenhouse gases. In terms of economic models, four major changes were discussed. First, studies have previously relied on partial-equilibrium models for deriving the economic results. In order to get a better depiction of the true range of resource substitutability, a general-equilibrium framework should be adopted. Second, greater use of dynamic models, instead of comparative static models, would be useful, particularly in understanding farm adaptability, technological change, and climate-change issues. Third, the role of agricultural programs in the context of climate change needs to be examined at both the farm and market levels. Finally, changes in the demand and supply of irrigation should also be explicitly accounted for in future economic-impact analyses.

While there is tremendous uncertainty regarding climate change and its potential implications, this should not be a justification for not actively researching the impacts on agriculture and social welfare. Economic analyses play a critical role, particularly in the policy debate over climate change. The results of future research efforts in the physical, biological, and economic disciplines should contribute greatly to our understanding of this extremely comprehensive and important topic.

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