Economic Implications of Global Climate Change for World Agriculture

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This paper challenges the hypothesis that negative yield effects in key temperate grain producing regions of the world resulting from global climate change would have a serious impact on world food production. Model results demonstrate that even with concurrent productivity losses in the major grain producing regions of the world, global warming will not seriously disrupt world agricultural markets. Country/regional crop yield changes induce interregional adjustments in production and consumption that serve to buffer the severity of climate change impacts on world agriculture and result in relatively modest impacts on world agricultural prices and domestic economies.

Key words: climate change, sensitivity analysis, SWOPSIM, welfare, world agriculture.

Introduction

Agriculture is among the more climate sensitive human activities; therefore, possible global climatic changes associated with increased atmospheric concentrations of greenhouse gases are likely to affect the efficiency of agricultural production systems. Economic impact assessments of climate change on agriculture include Adams et al. (1988, 1990), Arthur, and Mooney and Arthur. A remaining limitation of these efforts is that they focus on domestic agricultural impacts and do not consider the effects of climate change on world production and markets.

In an open economy, the effect of climate change on agriculture in any individual country cannot be considered in isolation from the rest of the world. Changes in regional climates and agricultural production affect world agricultural prices through international market transactions. Thus, it is not possible to infer the economic effects of climate change on agricultural producers and consumers on the basis of national yield change estimates alone. Aside from Liverman, who discusses some of the difficulties in applying global food system models to climate change, few researchers have empirically investigated the link between domestic crop yield effects and world agricultural markets.[1]

The article begins with a brief description of the predictions of large climate models, with a view toward identifying their implications for world agriculture. Predicted crop yield effects across broad geographic zones are then examined and provide the basis for sensitivity analysis of the likely impact of climate change on world agricultural commodity prices and domestic welfare. Because climate predictions and associated yield changes remain highly uncertain and subject to change as research continues, the sensitivity analysis illustrates broad patterns of possible effects on world commodity markets rather than highlighting a few very specific scenarios closely tied to the few existing and uncertain climate scenarios. In particular, the article focuses on the hypothesis that concurrent productivity losses in the major grain producing regions of the world in a changed global climate would cause widespread havoc in the agricultural sector.

Climate Predictions

To estimate the agricultural impacts of long-term global climate changes, we first must have some understanding of the direction and magnitude of climate changes of relevance to agriculture. Climate change

projections rely on large, complex computer models, known as General Circulation Models (GCMs). They synthesize our knowledge of the physical and dynamic processes in the overall (atmosphere–ocean–land) climate system, and allow for the complex interactions between the various components. The Intergovernmental Panel on Climate Change (IPCC 1990a) provides a recent summary of the scientific consensus on climate change.

(a) Global mean surface warming as greenhouse gases partially block or absorb heat radiating from the earth. The rate of increase of global mean temperature is predicted to be about .3°C per decade. This will result in an increase in global mean temperature of about 3°C before the end of the next century.

(b) Regional climate changes different from the global mean. Models predict that surface air will warm faster over land than over oceans and that the warming will be 50–100% greater than the global mean in high northern latitudes in winter. Temperature increases in Southern Europe and central North America also are predicted to be higher than the global mean.

(c) Increased precipitation in the order of 5–10% in middle and high latitude continents (35–55°N) in winter; reduced summer precipitation and soil moisture in Southern Europe and central North America.

(d) An average rate of global mean sea level rise of about 6 cm per decade over the next century mainly due to thermal expansion of the oceans and the melting of some land ice. A sea level rise of about 65 cm is predicted by the end of the next century.

Climate Effects across Broad Geographic Zones

Although GCM predictions are not ideal for agricultural impact analysis, they serve as a suitable benchmark for estimating the potential effects of climate change on crop and livestock productivity for different regions of the world.[2] Mathematical crop response models have been used to translate modified weather conditions into crop yield changes by simulating plant growth rates for a particular crop, combining information on physical conditions (sunlight, temperature, rainfall, and soil type) with growth processes. Crop response models employ a variety of estimation techniques including statistical, simulation, and extrapolation from historical record. Summaries of the quantitative results from experiments with regional crop response models are provided by the U.S. Environmental Protection Agency (U.S. EPA), Parry, and the IPCC (1990b).

Current climate limitations on crop production and the global pattern of climate change summarized by the results of crop response models suggest several different broad geographic zones across which climate change effects on agriculture may differ (fig. 1). Increased precipitation and warming in the high northern latitudes generally would be expected to enhance agricultural production potential in the northern regions of the Soviet Union, Canada, and Europe (Kettunen et al.; IPCC 1990b).[3] Similarly, increased precipitation is predicted to improve agricultural productivity in the southern middle lattitudes (Pittock; Pittock and Nix; Walker et al.; IPCC 1990b). Drying in the interior of continents in the northern middle latitudes combined with warming would be expected to lead to negative crop and livestock effects in the United States, Western Europe, and the most agriculturally productive regions of Canada (Williams et al.; Smit; U.S. EPA; Santer; IPCC 1990b).

There are exceptions to these broadly generalized climate patterns. While China falls within the category of northern middle latitude countries, climate and crop response models do not strongly support reduced agricultural yield. Global warming could lead to a weaker winter, but stronger summer monsoon (IPCC 1990a). Rainfall receipt thus would increase in already rainy areas and would extend further westward and northward than at present. Under a 1°C warming and with precipitation increases of 10 cm, yields of rice, corn, and wheat are estimated to increase by about 10% overall nationally, though there may be modest decreases in the north and east (Zhang).

Yields in Japan similarly are predicted to increase. Yoshino et al. estimate an average increase in rice yields of 2–5% on average for the country under a warming of 3–3.5°C, and a 5% increase in annual precipitation. Net primary productivity of natural vegetation in Japan is expected to increase by about 15% in the north and by 7% in the center and south of Japan (Yoshino et al.).

Chinese and Japanese yield results most likely differ from the mid-latitude pattern because agriculture is located near coasts and therefore is not subject to the prevalent interior continental drying predicted by GCMs.

Much less is known about the effects of climate change on agriculture in the tropical latitudes encompassing much of Africa, Latin America, and Southeast Asia. Production potential here depends on crop water availability, yet the regional pattern of possible changes in precipitation is unclear at present. However, it is likely that crop water availability will decrease in some regions (IPCC 1990b).[4] This may occur even without any deviations from current precipitation patterns. Because evapotranspiration (the

REGION

Northern latitudes

Northern
mid-latitudes

Tropics

Southern
mid-latitudes
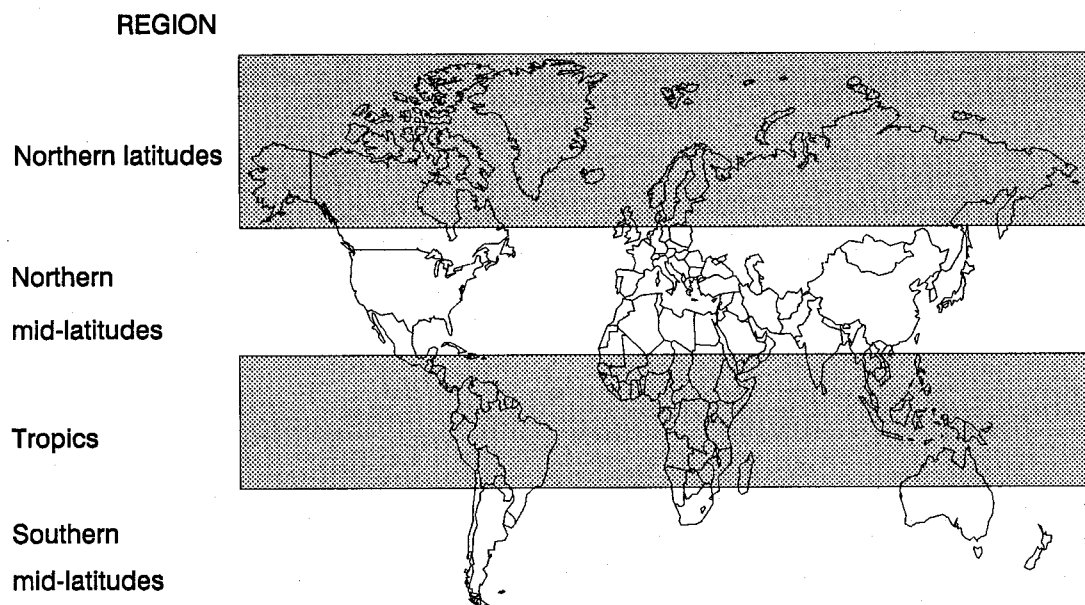
Northern latitudes: Above average warming, increased precipitation, and increased yields.

Mid-latitudes (north): Above average warming, dryer summers, and reduced yields.

Tropics: Warming, uncertain precipitation and yield changes.

Mid-latitudes (south): Warming, some precipitation and yield increases.

Figure 1.   Effects of climate change on world agriculture

amount of moisture that plants return to the air) increases nonlinearly with temperature, the potential for drought with a one degree rise in temperature in areas with already high average temperatures is greater than in cooler areas. In addition, cooler temperate areas may be able to shift to warm weather crops, whereas already warm areas may have fewer immediate alternatives.

Climate Change Impact Experiments

Among the feared effects of global climate change are concurrent productivity losses in the major grain producing regions of the world. Regional studies have shown a degree of consistency in predicting yield declines in the United States, Canada, and the European Community (EC), thus providing the basis for such fears. We construct three simulation experiments to consider the effects of a range of simultaneous yield reductions in these regions. In each experiment, a world commodity market model [Static World Policy Simulation (SWOPSIM) model] is simulated for concurrent yield reductions in the United States, Canada, and the EC of 10, 20, 30, 40, and 50%. Thus, each experiment is a set of five model simulations. The three experiments are:

Experiment one: Yield increases of 25% in the USSR, Northern Europe, China, Japan, Australia, Argentina, and Brazil, with no change in other countries.

Experiment two: A neutral effect in all other countries.

Experiment three: Yield increases of 25% in the USSR, Northern Europe, China, Japan, Australia, Argentina, and Brazil, with decreases of 25% in Africa and the remaining countries in Asia, Latin America, and the rest of the world.

The experiments are differentiated by the possibility of offsetting positive yield effects in several countries and yield declines in additional countries. The USSR, Japan, and China are the three largest net cereal importers (FAO). At the same time, the United States, France, Canada, Australia, and Argentina are among the largest net cereal exporters. Adverse or beneficial changes in agricultural potential in these "breadbasket" countries due to climate change will have the greatest impact on the quantity, price, and type of food products bought and sold on the world food market.

While this set of experiments does not encompass all the possible combinations of yield increases or decreases among the 13 countries/regions separately identified in the SWOPSIM model, it includes some of the scenarios of policy concern. Most notable is that the experiments do not evaluate yield increases in the United States, the EC, and Canada. In assuming yield decreases in these regions, we do not take account of the potential of the CO_2 fertilization effect and changes in agricultural management and production technology to mitigate the predicted negative effects of climate change.[5] Some recent efforts show that with the direct positive effects of CO_2 and increased consideration of adaptive responses such as changed planting dates, crops, cultivars, and cropping practices, yields could increase in some of these middle latitude regions (Mooney and Arthur; National Climate Program Office; U.S. EPA).[6] For this reason, the experiments are more likely to overstate than understate the actual changes that might occur in the United States, the EC, and Canada.

Model Structure

GCMs and crop response studies serve as the basis for our analysis of the economic effects of climate change on agriculture. Their suggested crop effects are introduced into the SWOPSIM model of world food markets. SWOPSIM describes world agricultural markets through a system of domestic supply and demand equations that are specified by matrices of own and cross-price elasticities. It has the desirable feature of encompassing all regions of the world at a considerable degree of commodity disaggregation. The model contains 20 agricultural commodities, including eight crop, four meat/livestock, four dairy product, two protein meal, and two oil product categories. For the purposes of this study, the world market was constructed to separately identify the United States, Canada, the EC, Australia, Argentina, Thailand, China, Brazil, the USSR, other Europe (Sweden, Finland, Norway, Austria, and Switzerland), and Japan. All other countries are grouped together into "rest of the world" (ROW).

The model's structure is straightforward.[7] For each country/region i and commodity j (or k) in the model, a demand and supply function is specified:

$$D_{ij} = D_{ij}(CP_{ij}, CP_{ik})$$

$$S_{ij} = S_{ij}(PP_{ij}, PP_{ik}),$$

where CP_{ij} and PP_{ij} are domestic prices facing consumers and producers of commodity j. CP_{ik} is the cross-product consumer price for commodity k (for all relevant ks); PP_{ik} is an input and/or product substitute or complement producer price with respect to commodity j. Trade is the difference between domestic supply and demand:

$$T_{ij} = S_{ij} - D_{ij}.$$

Domestic prices depend on the level of consumer and producer support wedges (CSW_{ij} and PSW_{ij}) and world prices denominated in local currency:

$$CP_{ij} = CSW_{ij} + F(E_i \cdot WP_j)$$
$$PP_{ij} = PSW_{ij} + G(E_i \cdot WP_j),$$

where CSW_{ij} and PSW_{ij} are measures of the level of government support in each country, as measured by producer and consumer subsidy equivalents (PSEs/CSEs). The PSE/CSE is a broader measure of policy support than the nominal rate of protection (see Webb, Lopez, and Penn). It includes direct income payments, input, marketing, and structural assistance as well as market price support. E_i is the exchange rate defined as local currency (i) dollar, and WP_j is the world price of commodity j.

World markets clear when net trade of a commodity across all countries is equal to zero. For commodity j, this occurs when:

$$\sum_{i=1}^{n} T_{ij} = \sum_{i=1}^{n} S_{ij} - \sum_{i=1}^{n} D_{ij} = 0.$$

Primary commodity price index

Percent yield reductions in the United States, EC, and Canada

Scenario 1:

Key: — — — — ·   Yield increases of 25% in USSR, Northern Europe, China, Japan, Australia, Argentina, and Brazil, with no change in other countries.

Scenario 2:

——————   Neutral effect in all other countries.

Scenario 3:

••••••••••••   Yield increases of 25% in USSR, Northern Europe, China, Japan, Australia, Argentina, and Brazil, with yield decreases of 25% in Africa, and remaining countries in Latin America, Southeast Asia, and the rest of the world.
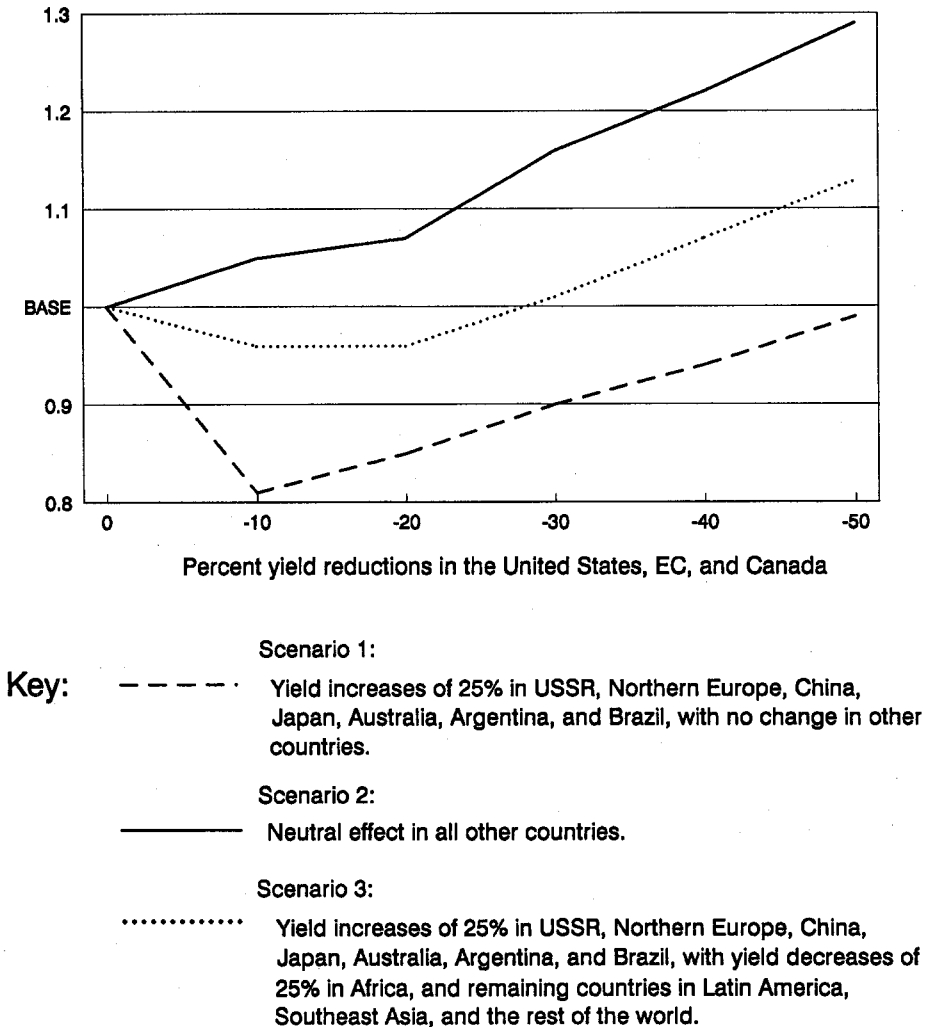
Figure 2.   Sensitivity of world agricultural prices to yield changes

The commodity supply and demand equations are parameterized to reproduce 1986 base period data for each country's supply, demand, prices, and trade. The data set is published in Sullivan, Wainio, and Roningen. When a change is introduced to the model, world trade, production, consumption, and prices are rebalanced. The pattern of prices and quantities observed in the base period is then compared to the pattern that emerges from the model.[8]

Replication of base period data is not, in itself, evidence that the model is valid. Rather, validity is determined by the reasonableness of the properties of the model. An important property of considerable interest is the measure of producer and consumer response to price changes. In an assessment of the validity of the SWOPSIM model, Roningen and Dixit found that the parameters used in the model to estimate these responses (the aggregate supply and demand elasticities) are consistent with the literature, including the models used by the Organization for Economic Cooperation and Development (OECD) and Parikh et al. The responsiveness of commodities to changes in prices also is derived. This is the partial net trade elasticity. Roningen and Dixit tested this responsiveness for the United States largely because of the availability of such information for comparative purposes. Again, they found that the net trade elasticities compare favorably with the empirical estimates provided by the literature.

The SWOPSIM modeling framework has some appealing characteristics for our purposes. Among these

Table 1.   Welfare Effects of Climate Change as a Percentage of the Value of 1986 Agricultural Output

Country/ Region	Percent Yield Reductions in the United States, EC, and Canada									Value of 1986 Agri- cultural Output ($1,000)
	Experiment one[a]			Experiment two[b]			Experiment three[c]			
	−10	−30	−50	−10	−30	−50	−10	−30	−50	
	Percent									
Argentina	1.81	5.30	11.47	1.36	5.59	13.07	6.69	9.60	18.19	$ 12,179
Australia	−.42	1.84	5.30	1.22	4.34	8.75	5.14	7.28	12.80	9,190
Brazil	1.93	1.94	3.44	−.44	−.68	.68	1.97	2.66	5.65	28,888
Canada	−1.73	−2.28	−4.34	−.17	−1.73	−5.48	−.96	−1.86	−5.35	21,609
China	5.64	6.15	7.49	−.13	−.16	.27	7.69	8.55	11.01	112,290
EC	.85	−.63	−2.11	−.83	−3.11	−5.74	−1.18	−2.35	−4.69	170,708
Japan	−2.79	−5.53	−8.89	−1.50	−4.96	−9.24	−7.64	−9.35	−13.32	54,393
Northern Europe	.50	−.23	−.89	−.45	−1.41	−2.39	−.60	−.92	−1.48	25,614
Thailand	−2.71	−1.30	1.22	.81	3.26	7.50	−5.10	−4.89	−2.77	4,842
United States	.55	.30	−1.56	.03	−.98	−4.06	−.25	−.87	−3.70	138,458
USSR	2.34	1.57	1.40	−.62	−1.74	−2.59	1.61	1.70	2.36	102,628
Rest of world	.65	.08	−.42	−.27	−.74	−1.00	−2.29	−2.76	−3.67	235,177
World total	1.54	.66	−.21	−.52	−1.73	−3.05	−1.22	−1.82	−3.05	915,976

[a] Experiment one: Yield increases of 25% in USSR, Northern Europe, China, Japan, Australia, Argentina, and Brazil, with no change in other countries.
[b] Experiment two: Neutral effect in all other countries.
[c] Experiment three: Yield increases of 25% in USSR, Northern Europe, China, Japan, Australia, Argentina, and Brazil, with yield decreases of 25% in Africa, the remaining countries in Latin America, Southeast Asia, and rest of world.

is its ability to estimate the welfare effects of agricultural production disturbances. In contrast, most empirical models of agriculture ignore traditional welfare and resource efficiency measures. Welfare effects are measured by the change in consumer and producer surplus, and government payments.[9]

SWOPSIM also has some limitations. First, it is a partial-equilibrium model and does not capture agricultural interactions with other economic sectors. This is not a serious limitation since in industrialized and semi-industrialized countries, agricultural production is only a small part of total output and therefore has very modest effects on resource allocations in other sectors. Moreover, in a general equilibrium study of climate change in the United States, Kokoski and Smith show that the welfare effects of fairly large, single-sector impacts can be adequately measured in a partial-equilibrium setting.

Second, the SWOPSIM modeling framework does not explicitly incorporate resource inputs. Rather, the model implicitly assumes that uses of resource supplies, including arable land, will be appropriately altered to fulfill new demand and supply conditions following a shock to the system. It would be useful to have resource inputs in the model in order to introduce exogenous changes to them and to ensure that, for large shocks to the system, constraints on resources (especially cultivated areas) are not binding.

Price and Income Effects

The aggregate primary crop price effects and domestic welfare effects resulting from the introduction of climate-induced changes in yields specified in the three experiments are shown in figure 2 and table 1, respectively.[10] The results illustrate three interesting features regarding the impact of climate change on agriculture. First, even under the assumption of relatively large and negative domestic yield effects, the economic impacts on national economies (as a percentage of agricultural output) are estimated to be modest, with some winners and some losers. As a percentage of gross domestic product (GDP), the estimated effects of global climate change are even smaller. This is due to the fact that agriculture accounts for a small percentage of GDP in most economies, particularly large developed economies (3% in industrial market economies and 19% in developing economies in 1986) (World Bank).

Second, as experiment one illustrates, reduced production potential in the United States, Canada, and the EC may be balanced by gains in other geographic areas, leading to improvements in world welfare. Even under experiment three, with yield declines in the United States, Canada, the EC, Latin America, Africa, and Southeast Asia, world agricultural prices fall because of compensating yield increases in the USSR, Northern Europe, China, Japan, Australia, Argentina, and Brazil.

	Large net importer	Large net exporter
Yield Effect		
Strongly negative	Negative net welfare effect (likely)	Ambiguous net welfare effect
Strongly positive	Ambiguous net welfare effect	Positive net welfare effect (likely)

	Large net importer	Large net exporter
Yield Effect		
Strongly negative	Ambiguous net welfare effect	Negative net welfare effect (likely)
Strongly positive	Positive net welfare effect (likely)	Ambiguous net welfare effect

Figure 3(a). Net welfare effects of climate change assuming an increase in world agricultural prices

Figure 3(b). Net welfare effects of climate change assuming a decrease in world agricultural prices

Third, the pattern of welfare effects among countries depends not only on domestic yield changes, but also on changes in world commodity prices and the relative strength of the country as a net agricultural importer or exporter. Consider the case of Argentina under experiment two (in which world agricultural commodity prices rise). Because Argentina is a large net exporter of agricultural commodities, the country stands to gain overall from an increase in the world price of agricultural products, even without any deviation from current domestic agricultural productive potential. A summary of the nature of the interdependence between yield changes, world price changes, and the pattern of welfare effects is presented in figure 3.

These discussions highlight the role of induced price changes in promoting interregional adjustments in production and consumption. Their importance also can be illustrated by comparing the SWOPSIM results with other models that consider climate change effects on a single country. Adams et al. (1988) examined the economic impact of climate change on U.S. agriculture using the GISS and GFDL climate models. They found net welfare reductions for the United States under the two scenarios to be about $6 and $34 billion, respectively (assuming no growth in technology or demand, and no plant growth effects from a carbon-enriched atmosphere). Yield changes in the two scenarios are in the order of 20% and 40%, respectively.

In contrast, the net welfare impacts on the United States under our experiments one, two, and three, when U.S. yields are reduced by 40%, are −$.5 billion, −$3 billion, and −$2.7 billion, respectively. In all experiments, the net welfare effects are considerably smaller than those estimated by Adams et al. (1988). The different results are an illustration of the importance of international price changes in promoting interregional adjustments in production and consumption.[11]

Other Considerations

In addition to the difficulties inherent in scientifically predicting climate changes and the limited applicability of GCM models to regional agricultural analysis, our ability to predict how climate change may affect agricultural production also is constrained by several other important considerations about which we have only a limited understanding at present. They include greater competition from weeds, increased plant and animal disease, changes in soil nutrients and pests, and increased conflicts for available water. Several studies have explored these issues (Adams et al. 1988; U.S. EPA; IPCC 1990b; Hillel and Rosenzweig), but we are far from concluding what their combined effects imply for the cost of agricultural production and their impact on agricultural resources and the environment.

They are likely less important than the impact that increased carbon in the atmosphere may have on plant growth. Some crop response studies have attempted to take into account both altered climatic conditions and the direct effect of climate change on plant growth. Their analyses suggest that the increase in yields from enhanced carbon levels could be significant. By one estimate, it could result in as much as a 33% increase in yields (Kimball). Parry, Carter, and Konijn (Vol. 1) found that in sub-Arctic regions of the USSR, inclusion of the CO_2 fertilization effect would result in a 17% increase in yields. The U.S. EPA found that, for the United States, inclusion of the positive effects of CO_2 on plant growth generally balanced yield reductions in the GFDL $2 \times CO_2$ scenario, and resulted in modest to large increases under

the GISS 2 $\times$ CO_2 scenario. Adams et al. (1988) compared the change in U.S. economic surplus under a GISS 2 $\times$ CO_2 climate with and without the CO_2 fertilization effect and found that its introduction increased economic surplus from $-\$5.9$ billion to $+\$10.6$ billion.

Finally, crop response models estimate potential effects based on present-day management and technology. However, adaptive responses to a changing climate and technological advances are expected to play an important role in agriculture (Rosenberg et al.; Kaiser et al.). Both offer the possibility to reduce climate change-related yield losses or increase the yield benefits from more favorable climate regimes. By one estimate, the agricultural community could adapt completely in 25 years to a 2 $\times$ CO_2 climate (National Climate Program Office). This rate of adaptation is certainly within the bounds of the climate change phenomenon, expected to take place in the time frame of 50 to 100 years.

A variety of adaptive alternatives requiring only relatively modest modifications in management practices are possible. One alternative involves the substitution of different varieties of a particular crop. Both Parry, Carter, and Konijn and the U.S. EPA found that choosing crop varieties better suited to changed climatic conditions reduces the negative effects of climate change considerably. Another alternative involves adjustments to the timing of farm operations. Earlier plantings have been shown to offset heat and moisture stress and could be used to adapt to a warmer, and possibly drier, summer (Easterling, Parry, and Crosson). In many cases, the best adaptive response to climate change may consist of a combination of these types of management adjustments. For example, a recent case study of Japan (Yoshino et al.) found that rice yields increase dramatically under altered climatic conditions when adjustments in planting dates are combined with the substitution of different strains of rice.

Other possible management responses include enhanced conservation of soil and water. Soil moisture is a significant factor in corn, soybean, wheat, and sorghum yields (Decker, Jones, and Achutuni). Erosion control and soil water management can be improved through the use of minimal tillage farming techniques, the use of windbreaks, drip irrigation, more efficient fertilizer and pest management, and the adoption of appropriate cultivars.

Concluding Comments

This article challenges the hypothesis that negative yield effects in key temperate grain producing regions would have a serious impact on world food production in a changed global climate. It is shown that even with concurrent productivity losses in the major grain producing regions of the world, global warming may not cause widespread havoc in the agricultural sector. Simulations of country/regional crop yield changes show that interregional adjustments in production and consumption will serve to buffer the severity of climate change impacts on world agriculture and result in relatively small impacts on domestic economies. The results underscore the fact that an assessment of climate change winners and losers cannot be made on the basis of domestic yield effects alone. How yield effects alter world food prices and the structure of world agricultural trade also must be considered.

The world agricultural model used in the analysis is static in the sense that it does not assume any farm responses to changing climatic conditions, and does not introduce changes in technology, population, or other growth conditions. Thus, the empirical results provide a "snapshot" of the economic effects that a doubling of CO_2 levels might have on world agriculture, given present agricultural technologies, structure of production, and demand conditions. The literature used to construct the climate change experiments also does not generally assume CO_2 fertilization effects. These considerations would reduce climate change-related yield losses or increase the yield benefits from more favorable climate regimes. For these reasons, the experiments are more likely to overstate than understate the actual changes.

Notes

[1] The U.S. Environmental Protection Agency currently is funding a research effort that is aimed at increasing our understanding of climate change impacts and world agriculture, particularly in vulnerable areas.

[2] Limitations associated with the use of GCM predictions for agricultural impact analysis include poor regional resolution, limited ability to project differences between average summer and winter temperatures, and limited ability to project climate fluctuations during the transition period to equilibrium climatic conditions.

[3] In some high latitude regions, soils and terrain may not enable much of this increase in productive potential to be realized.

[4] One exception is Brazil. More precipitation in the center west of Brazil likely would increase productivity in soybeans and corn, and, in the south, of wheat (IPCC 1990b). Climate change effects on agriculture in the northeast of Brazil depend on whether increases in precipitation are sufficient to compensate for increased potential evapotranspiration due to higher temperatures.

[5] A carbon enriched atmosphere, like that under doubled CO_2 concentrations, is widely believed to promote plant growth and also to lead to increased efficiency in water use. This positive influence of climate change on plant growth is termed the CO_2 fertilization effect.

[6] Mooney and Arthur found that changes in crop production in Canada are sensitive to the degree of drying and changes in the structure of production. Crop yields and net farm revenue are estimated to increase if drying is not as extreme as some GCM models would predict, and if warming allows a longer growing season, new cropping options, and greater cropping area.

[7] This description follows Krissoff, Sullivan, and Wainio.

[8] A complete description of the SWOPSIM modeling framework can be found in Krissoff, Sullivan, and Wainio; Roningen; and Roningen and Dixit.

[9] SWOPSIM uses Marshallian measures of economic surplus. Marshallian measures do not take account of income effects associated with price changes. In a multimarket framework, the Marshallian measure can be considered a true measure of welfare change if it is assumed that consumer preferences are identical, that there are no income changes, and that goods are consumed in the same ratio at the same relative prices regardless of income level. The mass of empirical evidence suggests that these are not realistic assumptions. Nevertheless, Marshallian measures remain popular empirical tools because they are easily estimated. Haley and Dixit have shown that the Marshallian welfare measure is well suited for use in the SWOPSIM modeling framework. Following Willig's theorem, we argue that it provides a reasonable estimate of the true change in economic welfare.

[10] Primary products include wheat, corn, other coarse grains, rice, soybeans, other oilseeds, cotton, sugar, and tobacco.

[11] We also note that comparisons between models are limited by the fact that the structure and economic properties of alternative models are likely to be significantly different.

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