THE CONTRIBUTIONS OF ECONOMIC MODELING TO ANALYSIS OF THE COSTS AND BENEFITS OF SLOWING GREENHOUSE WARMING†

Climate Change and Agriculture: The Role of International Trade

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Economic studies of the impact of climate change on agriculture have been included in Louise Arthur (1988), Martin Parry et al. (1988), Richard Adams et al. (1990), and Sian Mooney and Arthur (1990). A limitation of these efforts was that they focused on domestic agricultural impacts and did not consider the effects of climate change on world production and markets. The central premise of this paper is that for open economies the effect of climate change on agriculture in any individual country cannot be considered in isolation from the rest of the world. A small-country argument can justify an analysis limited to that country if environmental change occurs wholly within the country. Where effects occur simultaneously throughout the world, however, the only way to justify considering a subglobal region is to assume that the economy of the region is closed. There are significant trade-distorting policies in agriculture (the target of the recent GATT round), but these distort rather than close off trade.

Following Sally Kane et al. (1992) and James Tobey et al. (1992), this paper investigates the agricultural effects of climate change recognizing that effects will simultaneously occur worldwide. We summarize this earlier work and find that, based on new yield estimates, the broad conclusions of that work are generally supported. Section I of the paper reviews predictions of future climate and atmospheric conditions, identifying the implications for agriculture in different areas of the world. Section II describes the SWOPSIM (static world policy simulation) model used to evaluate the worldwide economic effects of climate change. Section III reports an economic sensitivity analysis of concurrent yield losses in major grain-producing regions considering the possibility of concurrent changes in production potential elsewhere in the world. Section IV, taking advantage of recent work by Cynthia Rosenzweig et al. (1993), evaluates agricultural impacts of climate change based on three general circulation models (GCM's). Section V offers caveats and conclusions.

I. Climate Predictions

Potential changes in climate are summarized elsewhere (J. T. Houghton et al., 1990). The forecasted changes suggest potentially enhanced agricultural production in the northern regions of the Soviet Union, Canada, and Europe, where agricultural production is limited by cold temperatures and short growing seasons, and reduced crop

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yields in the United States and most of Europe due to increased drought (see Tobey et al., 1992).

It has sometimes been observed that climate impacts may be less severe in equatorial regions than in temperate regions because climate models predict temperature increases in the tropics on the order of 2°C compared with 4°C–12°C for temperate and polar regions. However, considerations of (i) water use, (ii) adaptation potential, and (iii) adaptation capability in these regions alter this conclusion. (For a lengthier discussion see Rosenzweig, et al., 1993). Briefly, the effects may be summarized as follows:

Water Use.—Precipitation patterns are poorly predicted but evapotranspiration (the plant's demand for water) increases more than proportionally with temperature increase. For example, a 2°C increase in already warm regions (tropical developing countries) would increase the potential for drought stress more than a 2°C increase in cooler regions.

Adaptation Potential.—Tropical regions are more likely to be at the limits of adaptation measures and thus may have less potential to adapt. Examples of adaptations include shifts from cool-season crops to crops that perform better in warmer climates; shifts from crops sensitive to drought stress; choice of planting dates to avoid high temperatures, to avoid dry periods of the year, or to obtain multiple crops during the year; choice of tillage practices, seeding rates, row spacing, fallow periods; and irrigation as appropriate for moisture availability.

Adaptation Capability.—Generally, the capability to adapt may be less in developing countries. Poorly developed markets for crop inputs (fertilizer, seeds, and machinery) or for outputs may limit the ability of farmers to obtain inputs useful for adapting to climate change or to sell excess production of crops favored under new climates. Infrastructure considerations including education of farmers and the existence of crop experiment and testing stations and transportation, crop storage, and crop processing facilities may limit detection of climate change and the identification of suitable responses.

An additional consideration for agriculture is that atmospheric CO_2 acts as a plant fertilizer and increases water-use efficiency in plants. Higher levels of ambient atmospheric CO_2 are therefore expected to increase yields. The growth response to elevated CO_2 is greater in C_3 crops (e.g., wheat, rice, barley, root crops, and legumes) than in C_4 crops (e.g., corn, sorghum, millet, sugar cane); however, water-use efficiency may be greater in C_4 crops. Whether the full effects of CO_2 fertilization observed in experimental conditions will be realized in the open environment is an issue of debate.

II. SWOPSIM Model Structure

We used the SWOPSIM model of world food markets, developed by Vernon Roningen et al. (1991), to simulate economic effect of climate change. Discussion of the model presented here relies heavily on Roningen et al. 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 the sensitivity study reported in Section III, the model was constructed to identify separately the United States, Canada, the European Community (EC), Australia, Argentina, Thailand, China, Brazil, the former Soviet Union, other European countries (Sweden, Finland, Norway, Austria, and Switzerland), Japan, and ROW (the rest of the world). The commodity supply and demand equations were set to reproduce 1986 base-period data for each country's supply, demand, prices, and trade. For the specific GCM scenarios reported in Section IV, the model was updated to a 1989 base and reconstructed into 33 separate countries/regions to facilitate analysis by country-income class.

For each country/region i and commodity j in the model, constant-elasticity demand and supply functions are specified. For country i and commodity j quantity demanded (QD) and supplied (QS) are given as:

$$(1)\qquad \mathrm{QD}_{ij} = d_{ij}(1+\mathrm{sd}_{ij}) \prod_{k=1}^{n} CP_{ik}^{\alpha_k}$$

$$(2)\qquad \mathrm{QS}_{ij} = s_{ij}(1+\mathrm{ss}_{ij}) \prod_{k=1}^{n} PP_{ik}^{\beta_k}$$

where CP_{ik} and PP_{ik} are domestic consumer and producer prices of commodity $k = 1,\dots,n$. For $k = j$, the α_k and β_k are the own-price demand and supply elasticities (uncompensated) and for $k \neq j$ they are cross-price elasticities. The d_{ij} and s_{ij} are base quantities sd_{ij} and ss_{ij} are demand- and supply-shift parameters, which are zero under the base data. In the climate-impact scenarios, percentage yield changes by crop and country as developed from crop-response models are used as a measure of the ss_{ij}. Domestic consumer and producer prices reflect world prices, government interventions in production (PSW_{ij}), and consumer subsidies and interventions (CSW_{ij}). These interventions lead prices in any one country to differ from the world price and cause the consumer price for a country to differ from the producer price. The price-linkage equations are

$$(3)\qquad \mathrm{PP}_{ij} = \mathrm{pp}_{ij} + w_{ij}\mathrm{WP}_{ij}^{\gamma_{ij}} + \mathrm{PSW}_{ij} + \mathrm{TP}_{ij} + \mathrm{NW}_{ij}$$

$$(4)\qquad \mathrm{CP}_{ij} = \mathrm{cp}_{ij} + \mathrm{PP}_{ij} + \mathrm{CSW}_{ij} + \mathrm{PSW}_{ij}.$$

The w_{ij} are dummies (1 for traded or 0 for nontraded commodities), and NW_{ij} are domestic price changes, which are zero when $w_{ij} = 1$. The pp_{ij} and cp_{ij} are constants and the TP_{ij} are trade (export and import) interventions. The γ_{ij} are price-transmission elasticities and reflect additional government interventions that limit the transmission of world price changes to domestic prices.

Market equilibrium is characterized by excess world demand equal to zero for all commodities. A numerical solution is obtained in the model through iteration. Once a solution is obtained, producer and consumer surplus changes are measured as welfare triangles by calculating the value of the integral of the supply and demand functions between the initial price and the new equilibrium price. We report economic effects in terms of changes in economic welfare that include changes in consumer surplus, producer surplus, and changes in government payments (revenues) that result implicitly from the world price-transmission elasticity and explicitly from other government interventions. As a caveat we note that SWOPSIM is a partial-equilibrium model. Mary F. Kokoski and V. Kerry Smith (1987) show that the climate-change welfare effects of fairly large, single-sector impacts are adequately measured in a partial-equilibrium setting. SWOPSIM treats resource and other inputs implicitly through specification of supply parameters.

III. The Sensitivity of Agriculture to Yield Losses in Major Grain Producing Regions

Among the feared effects of climate change are concurrent productivity losses in the major grain-producing regions in the United States, the plains of Canada, and the European Community. In this section, we examine the economic impact of significant yield losses in these areas while including varying assumptions of how yields may change outside these areas. We identify three types of countries: TEMP (United States, Canada, and the EC), temperate areas where reduced soil moisture is usually predicted to lead to yield declines; COLD (former Soviet Union, northern Europe, China, Japan, Australia, Argentina, and Brazil), areas that some evidence suggests could see increased yields from warming; and ROW, the rest of the world. We constructed three simulation experiments to consider the effect of a range of simultaneous yield reductions in these regions. In each experiment, SWOPSIM was simulated for concurrent yield reductions in region TEMP of 10, 20, 30, 40, and 50 percent. Thus, each experiment is a set of five model simulations. The three experiments were as

TABLE 1—GLOBAL WELFARE LOSSES AND YIELD CHANGES (MILLIONS OF 1989 U.S. DOLLARS)

Yield loss in TEMP (percentage)	Region		
	TEMP	COLD	ROW
Experiment 1:			
−10	2,052	8,914	4,797
−30	−1,290	7,513	557
−50	−7,497	8,531	−3,146
Experiment 2:			
−10	−1,588	−1,699	−2,052
−30	−7,878	−4,437	−5,436
−50	−18,595	−5,551	−7,190
Experiment 3:			
−10	−2,873	8,061	−17,749
−30	−6,294	8,927	−21,343
−50	−16,000	12,891	−28,138

Notes: Region TEMP = temperate areas (United States, Canada, EC); region COLD = cold areas and others that could benefit (former Soviet Union, northern Europe, China, Japan, Australia, Argentina, Brazil); region ROW = rest of the world. The experiments were as follows:

Experiment 1.—yield increases of 25 percent in COLD, no change in ROW, with losses as given in table for TEMP;
Experiment 2.—no yield change in COLD or ROW;
Experiment 3.—yield increases of 25 percent in COLD with yield decreases of 25 percent in ROW and with losses as given in table for TEMP.

follows:

Experiment 1.—Yield increases of 25 percent in region COLD, with no change in ROW;
Experiment 2.—A neutral effect in COLD and ROW;
Experiment 3.—Yield increases of 25 percent in COLD and decreases of 25 percent in ROW.

The welfare effects resulting from the introduction of climate-induced changes in yields specified in the three experiments are shown in Table 1. 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 welfare losses are small relative to GDP for all countries identified in the study. The largest impacts measured as percentages of GDP were in China and Argentina in experiments 1 and 3 where net economic benefits ranged between 2 and 6 percent of GDP. For all other countries in all other experiments, the effects ranged from a few hundredths to a few tenths of a percent of GDP. Agriculture accounts for a small percentage of GDP in most economies, particularly large developed economies (3 percent in industrial market economies and 19 percent in developing economies in 1986 [World Bank, 1988]).

Experiment 1 illustrates that reduced production potential in the United States, Canada, and the EC may be more than balanced by gains in other geographic areas, leading to improvements in world welfare. The experiments also demonstrate that 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 2 (in which world agricultural commodity prices rise). Because Argentina is a large net exporter of agricultural commodities, the country gained overall from an increase in the world price of agricultural products, even without any increase in crop yields. In contrast, Japan suffered net welfare losses over all experiments, despite yield increases of 25 percent in experiments 1 and 3. Japan's welfare losses were very similar as a percentage of GDP to the EC's because of Japan's dependence on food imports. As would be expected, consumer effects (e.g., welfare losses when world prices rose) dominated in determining the sign of the net welfare effect for most countries. The exceptions were very large agricultural exporters for which producer effects dominated. Tobey et al. (1992) provide greater detail.

These discussions highlight the role of induced price changes in promoting interregional adjustments in production and consumption. A comparison of SWOPSIM results with other models that consider climate-change effects on a single country further demonstrates the role of global price changes. Adams et al. (1990) examine the economic impact of climate change on U.S. agriculture using the Goddard Institute of Space Studies (GISS) and Geophysical Fluid Dynamics Laboratory (GFDL) climate models. They find net welfare reductions for the United States under the two scenarios to be about \$6 billion and \$34 billion, respectively (assuming no growth in technology or demand and no CO_2 fertilization effects). Yield changes in the GISS and GFDL scenarios were on the order of 20 percent and 40 percent, respectively.

In contrast, the net welfare impact on the United States in our experiments 1, 2, and 3 under 40 percent U.S. yield losses were −\$0.5 billion, −\$3.0 billion, and −\$2.7 billion. In all experiments, net welfare effects for the United States are considerably smaller than those estimated by Adams et al. (1990). The different results provide an illustration of the importance of international price changes in promoting interregional adjustments in production and consumption.

IV. Results Based on GCM Simulations

Rosenzweig et al. (1993) have recently concluded an assessment of yield changes for the entire world under three separate GCM scenarios. The study used equilibrium, doubled-trace-gas climates as predicted by the GISS, GFDL, and the United Kingdom Meteorological Office (UKMO) GCM's. The climate scenarios differ among these models in terms of the seasonality, regionality, and overall magnitude of temperature and precipitation change. The changes between the $2 \times CO_2$ equilibrium and the control climate in global mean surface temperature and global precipitation for the models were: GISS, +4.2°C and +11 percent; GFDL, +4.0°C and +8 percent; UKMO, +5.2°C and +15 percent. The Rosenzweig et al. (1993) study estimated yield changes for each GCM scenario using crop-response models run for multiple sites in 23 countries. They estimated yields with and without adaptation, with and without the yield-enhancement effect of increased ambient CO_2 levels, and three levels of adaptation (none, moderate, and significant). We report here only results with no adaptation and moderate adaptation. They combined the new crop studies with existing estimates for other regions to estimate yield changes worldwide for all crops. They simulated economic and production shifts using the "basic linked system" (BLS) model developed at the International Institute for Applied Systems Analysis (IIASA).

The principal advantage of the SWOPSIM model over the BLS model is that production and price changes are summarized as changes in welfare. Welfare measures are more directly useful for comparing the benefits of avoided climate change with the costs of emissions reductions and for considering, for example, what level of monetary transfers might be required to compensate countries suffering particularly large losses. Our findings were as follows:

(i) For the three GCM's net global welfare changes without adaptation and without (with) the carbon dioxide effect in billions of 1989 U.S. dollars were: GISS, −\$115.5 (−\$.1); GFDL, −\$148.6 (−\$17.0); UKMO, −\$248.1 (−\$61.2). That is, under the GISS climate the positive effects of carbon dioxide fertilization offset all but \$0.1 billion of the losses due to climate change alone.

(ii) For the three GCM's the net global welfare changes with the carbon dioxide fertilization effect and without (with) adaptation were: GISS, −\$.1 (+\$7.0); GFDL, −\$17.0 (−\$6.1); UKMO, −\$61.2 (−\$37.6). That is, the adaptations considered were worth on the order between \$7 billion and \$25 billion. Carbon dioxide fertilization was worth on the order of between \$115 billion and \$190 billion.

(iii) Even under the GISS GCM climate with carbon dioxide fertilization and adaptation, where the net welfare effect for the world is positive, all three developing-country income-class groups suffered welfare losses (Table 2). This result stemmed from a combination of effects. While crop prices generally de-

TABLE 2—WELFARE EFFECTS BY COUNTRY GROUP (MILLIONS OF 1989 U.S. DOLLARS)

	GCM		
Country group	GISS	GFDL	UKMO
< $500 per capita	−210	−2,573	−14,588
$500–$2,000 per capita	−429	−2,927	−10,669
> $2,000 per capita	−603	−534	−1,021
Eastern Europe/former Soviet Union	2,423	−125	−4,875
OECD	5,822	25	−6,470
Total:	7,003	−6,135	−37,623

clined in this scenario, creating consumer surplus gains and producer surplus losses, many of the tropical regions suffered yield losses that exacerbated producer losses to the extent that they were larger than consumer gains. This was true in most developing countries. Economic effects in developing-country areas where average incomes are generally above $2,000 per capita are particularly interesting. Many of these countries are large agricultural producers and exporters. They suffered large producer surplus losses under the GISS climate because world crop price declined, even though in some cases yields for some crops increased (e.g., crop yields increased in Argentina except for wheat). While the GFDL climate created global net losses, the developing countries with average incomes of more than $2,000 per capita fared better than they did under the GISS climate because producers in these countries benefited from rising world crop prices. Under the far more severe UKMO scenario, this country group showed the smallest increase in net losses among the groups, again because of producer gains. The poorest regions are largely food importers and thus show very large consumer surplus losses relative to producer gains. The principal exception to this was China which generally showed yield gains and net surplus gains across all three climate scenarios. Under the UKMO scenario, the net gain for China was $3.2 billion. This means that losses for the rest of the countries with average incomes of less than $500 per capita were $3.2 billion greater, or nearly $18 billion.

These three conclusions confirm those of Rosenzweig et al. (1993). In particular, the disproportionate impact in the developing countries is emphasized in their study. Trade can shift gainers and losers, but the pattern of effects is highly dependent on the original yield estimates. In the future we plan to compare SWOPSIM results directly with the BLS results. Such a comparison would be beneficial because the BLS models the dynamic adjustment of agriculture in the context of changing population and technology.

V. Caveats and Conclusions

Significant sources of error remain due to underlying uncertainties in, for example, the climate scenarios, agronomic factors such as competition from weeds and plant and animal disease, and increased competition for land or water because of increased demand from other sectors due to climate change. Further, the model used in the analysis does not include technological change, population growth, or other changes that may accompany economic growth and development. The yield estimates from GCM's reflect conditions under equilibrium climates. Given current scientific opinion that a central estimate is a warming of 3°C from current global temperatures by about 2100, the 4°–5°C increases in Section IV may be unlikely until 2125 or 2150. Effects occurring between now and then may be important for current decisions.

With the above caveats, the findings of earlier work, supported by new results from GCM scenarios suggest the following. (a) 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 from a doubled CO_2 climate. (b) Evaluation of climate-change winners and losers requires consideration of global market changes as well as domestic yield effects. An important implication is that the incentives countries have to reduce greenhouse-gas emissions depend on global price changes as well as country-specific changes in yield. Following from the yield results of Rosenzweig et al. (1993) and confirming their economic analysis, (c) developing countries appear at a greater disadvantage, and the beneficial effects of carbon dioxide fertilization are critical in limiting the economic impacts.

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