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Climate Change

Economic Implications for World Agriculture

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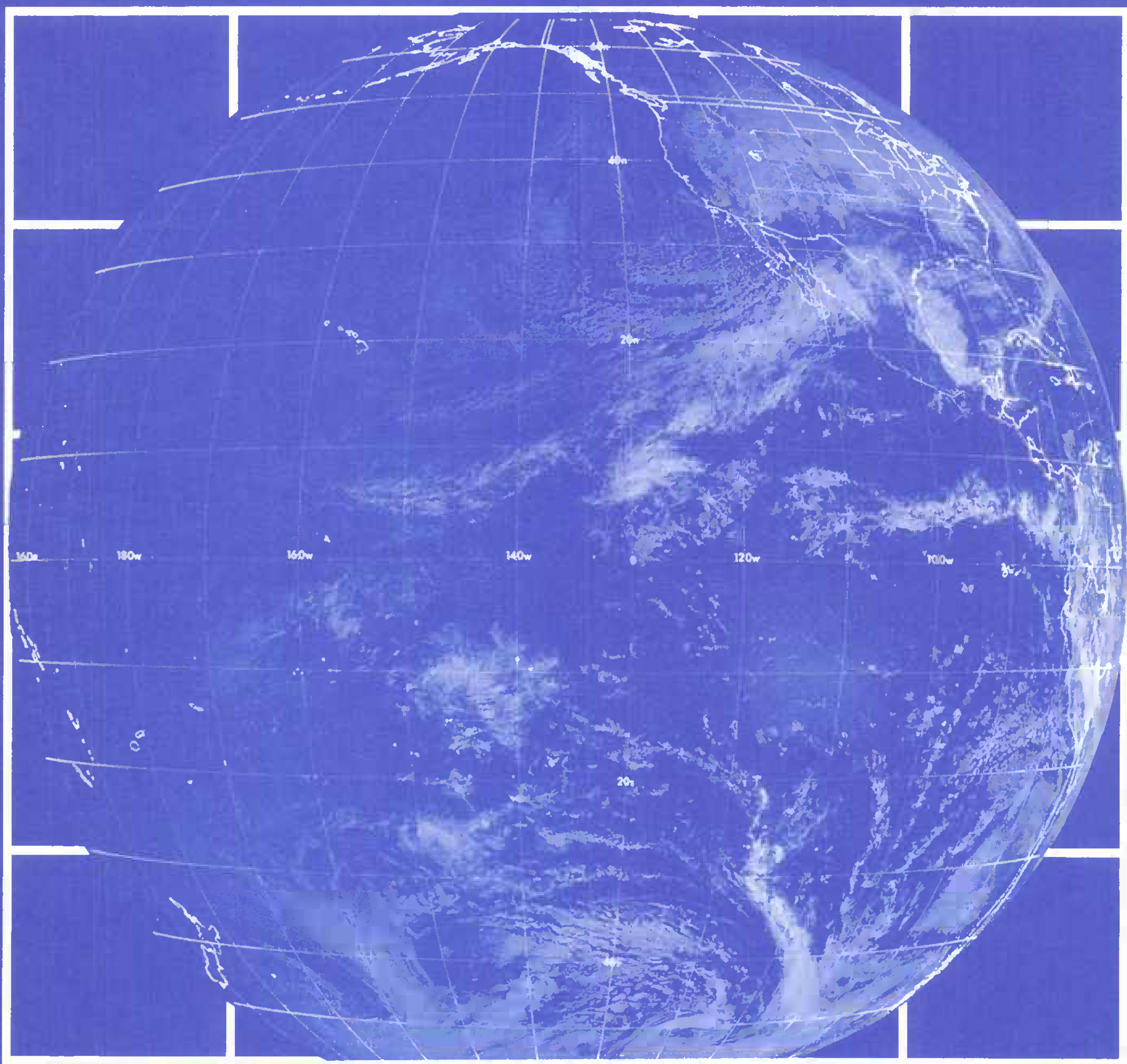

Climate Change: Economic Implications for World Agriculture. By Sally Kane, John Reilly, and James Tobey, with contributions from Bruce Larson and Ronda Bucklin. Resources and Technology Division, Economic Research Service, U.S. Department of Agriculture. Agricultural Economic Report No. 647.

Abstract

Agricultural activities contribute to global climate change, and crop production will be affected if and when climate changes. Despite substantial yield effects of climate change, the economic effect on national and world economies is estimated to be small, as reduced production potential in some areas is balanced by gains in others. A slight increase in world output and a decline in commodity prices are estimated under a moderate climate change impact scenario. There remain major uncertainties in estimating future emissions of greenhouse gases that contribute to climate change, costs of controlling climate change, and the effects of climate change on society.

Keywords: Climate change, world agriculture, SWOPSIM, welfare, producer and consumer surplus, sensitivity analysis

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Summary

Attempts to estimate the potential effects of global climate change on agriculture caused by the global warming of the Earth are a severe test of our understanding of basic global agricultural-resource-climate interactions. This study provides a preliminary assessment of the economic effects of a doubling of carbon dioxide levels on world agriculture, given present agricultural technologies and structure of production, population, and world agricultural demand conditions.

Long-term climate change may substantially reduce some crop yields. But, the overall effect on the world and domestic economies would be small as reduced production in some areas would be balanced by gains in others, according to an economic model of the effects of climate change on world agricultural markets. The model reviewed in this report estimates a slight increase in world output and a decline in commodity prices under moderate climate change conditions.

Although there would be some winners and losers, interregional adjustments in production and consumption would buffer severe effects of climate change on world agriculture. As a result, there should be relatively small effects on domestic economies. Income loss in the United States is estimated to be small (less than 1 percent) as a percentage of total income.

Any analysis of the net effect of climate change on world agriculture is considered preliminary due to remaining uncertainty of (1) scientific predictions of long-term climate changes, (2) physical responses, such as crop growth changes, and (3) economic modeling. Assessing the economic importance of physical responses is difficult since the relevant time period ranges from 50 to 100 years. Response of the agricultural sector is in large part dictated by the development of new production technologies that can efficiently exploit changes in growing conditions. It is nearly impossible to make credible projections of technological development, structural changes, and patterns of international agricultural commodity trade over a long period of time.

Scientific predictions of long-term climate changes, and our results, are based on the assumption of an effective doubling of carbon dioxide. This is a convenient but arbitrary assumption for comparing climate models and effects. However, further accumulation of greenhouse gases could intensify climate effects. Stabilization of doubled carbon dioxide concentrations is not likely without stringent emissions control policies.

We used the Static World Policy Simulation (SWOPSIM) modeling framework to estimate how regional changes in food production would affect world food supply, prices, and demand. SWOPSIM describes world agricultural markets through a system of supply and demand equations. Climate changes are entered as changes in base yield for specific countries/regions. The model then solves for a new equilibrium set of production, consumption, and price relationships.

The results demonstrate that the evaluation of climate change gainers and losers cannot be made on the basis of domestic yield effects alone; it also depends on the relative size of the agricultural producing and consuming sectors and the direction and magnitude of world price effects. Incentives to reduce greenhouse gas emissions should not be based solely on predicted national

agricultural production changes, but rather on how these yield effects alter global agricultural markets, and consequently, domestic welfare.

Empirical findings of this report do not incorporate changes in agricultural management and production technology to changes in climate. These responses could be just as important as the actual physical weather changes in determining domestic crop yield effects. Nor have we attempted to predict economic and population growth rates that could alter the structure of demand and supply conditions of the estimating model. For these reasons, the results of the SWOPSIM model should not be viewed as an accurate representation of the agricultural consequences of climate change on specific economies. Rather, the results highlight general directions and the order of magnitude of change, as well as demonstrate some straightforward, but important, general economic principles. In spite of the difficulties that arise, when used carefully, impact assessments are useful inputs in the policymaking process.

Climate Change

Economic Implications for World Agriculture

Sally Kane, John Reilly, James Tobey*

Introduction

Public interest in prospective climate change resulting from the phenomenon known as the "greenhouse effect" has increased significantly over the past several years. The predicted warming trend of the Earth and its lower atmosphere by trapped solar radiation is presently the subject of national and international debate. Discovery of ozone "holes" over the polar caps and increased concentrations of carbon dioxide, methane, nitrous oxide, chlorofluorocarbons (CFC's), and other greenhouse gases in the atmosphere lend evidence to the perception that human activity can affect the global environment and major Earth systems. While not conclusively linked to human activity, record hot weather in the 1980's, combined with extreme heat waves, floods, and droughts occurring in 1988, increased public awareness of the possible effects of human activity on the Earth's climate.

Tremendous uncertainty exists in linking human activities with climate change. While increased trace gas concentrations have undeniable effects on the radiative balance of the Earth, the specific effects on temperature, precipitation, and other climatological phenomena are only beginning to be unraveled. Despite this uncertainty, global environmental issues such as climate change are now topics of international meetings and conferences of policymakers and scientists. In addition, substantial research is being conducted to understand the economic and social implications of global environmental issues. This report attempts to increase understanding of how climate change may affect U.S. and world agriculture.

Climate change may affect not only agriculture, but several other economic systems as well. For example, climate change might affect marketed goods and services (such as water resources, recreation, forestry, fisheries, coasts, and transportation systems) and nonmarket goods and services (such as amenity values, human health, and biological diversity). An evaluation of relative costs and benefits of policies dealing with the effects of climate change (such as scientific research, regulations and charges to reduce greenhouse gas emissions, and adaptation strategies) is necessary. In evaluating costs and benefits, three areas should be considered: (1) emission sources and their time path of generation, (2) consequences of climate change for economic activities, and (3) the relative efficiency of various policy responses. Area two is the focus of this report. But, first we briefly explore how agriculture contributes to greenhouse gas emissions. Then, using results from our climate change model (see appendix), "optimal" policy responses to climate change are discussed.

The next section of the report begins the discussion on consequences of climate change for economic activities. A presentation of large climate models and their predictions is made with a view toward identifying their implications for world agriculture. Because scientific uncertainty is a critical feature of climate change policy discussions, we attempt to uncover the shortcomings of these climate change models for agricultural impact analyses.

The report also examines regional crop yield effects expected to result from broad changes in climate. Based on the review of yield effects, we impose crop supply shifts in a model of world agriculture to approximate the effect of climate change on world agricultural prices and welfare. Sensitivity analysis is also conducted. These empirical estimations can best be labeled as informed speculation. However, empirical demonstration of even general economic principles can make important contributions to the policy debate surrounding uncertain long-term climate change.

The report concludes with a discussion on the importance of adaptive responses in agriculture to climate. These responses, by increasing the production flexibility inherent in the economic system, are likely to play a critical role in determining the actual impact of prospective climate change on agriculture.

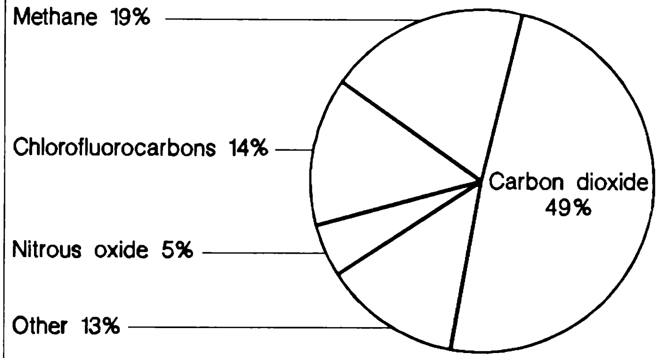
How Agriculture Contributes Toward Greenhouse Gas Emissions

A complete understanding of the pattern of greenhouse gas emissions within and across countries, and their value to economic growth, is essential to

* Bruce Larson and Ronda Bucklin also contributed to this report.

the consideration of international programs to achieve emissions reductions. Increases in the atmospheric concentrations of at least 25 trace gases contribute directly (via chemical reactions) or indirectly to the retention of solar radiation by the Earth (radiative forcing). The radiative forcing properties offer an approximate equivalency basis to compare, for example, carbon dioxide concentrations of parts per million with chlorofluorocarbon (CFC) concentrations of only parts per trillion. The carbon dioxide accumulation in the atmosphere during the 1980's contributed about one-half of the total estimated radiative forcing, methane contributed about 19 percent, CFC's 14 percent, nitrous oxide 5 percent, and other gases about 13 percent (fig. 1). Other gases include halons, changes in ozone, and changes in stratospheric water vapor.

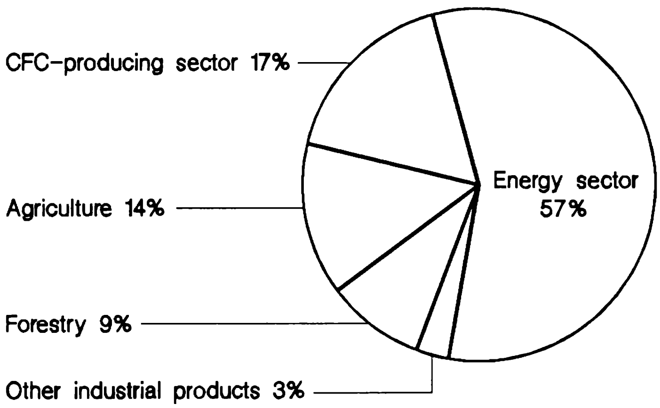
Figure 1
The contribution of greenhouse gases to increased radiative forcing in the 1980's



Source: U.S. Environmental Protection Agency.

The principal worldwide contributing sectors to global warming include the energy sector (57 percent), the CFC-producing sector (17 percent), agriculture (14 percent), forestry (9 percent), and other industrial products (3 percent) (fig. 2). Agriculture contributes to the increasing atmospheric concentrations of carbon dioxide, methane, and nitrous oxide. Flooded rice cultivation, nitrogen fertilizer use, ruminant animals, improper soil management, land conversion, and biomass burning all contribute to agricultural emissions of greenhouse gases.

Figure 2
Sources of greenhouse gas emissions



Source: U.S. Environmental Protection Agency.

Rice cultivation, enteric fermentation in ruminant animals, and biomass burning are estimated to contribute approximately 15, 9, and 8 percent, respectively, of total global methane production (Intergovernmental Panel on Climate Change (IPCC), 1990b).[1] Both the industrial sources (from fossil fuel combustion) and the agricultural sources of nitrous oxide are uncertain. However, it is estimated that the use of nitrogenous fertilizers accounts for between 0.2 and 20 percent of the current global nitrous oxide production (IPCC, 1990b). Landclearing and biomass burning contribute between 10 and 30 percent of current greenhouse gases through increases in emissions of carbon dioxide, methane, and nitrous oxide (IPCC, 1990b).

Reducing Agricultural Emissions

While a variety of methods to reduce agricultural emissions of greenhouse gases have been suggested, their economic feasibility is still unclear. Reductions of methane emissions from flooded rice cultivation possibly may be achieved through the introduction of water management regimes, development of cultivars, and efficient use of fertilizers. Reductions of methane emissions from livestock may be achieved through animal waste management, supplemental feeding practices and diet modification, and increased use of growth-enhancing agents with appropriate safeguards for human health concerns. Fertilizer-derived emissions of nitrous oxides may be reduced by using fertilizers that have been technically engineered to conform to rates of plant uptake and slower conversion rates. To reduce global landclearing and biomass burning, economic conditions that encourage the conversion of land to crop and pasture land would need to be carefully assessed and altered.

Based on current trends and expectations, agricultural sources of emissions may increase slowly, but

[1] Names in parentheses refer to authors cited in the References at the end of this report.

are likely to comprise a declining share of total emissions, even without the introduction of any of the mitigating activities described above (Reilly and Bucklin). The contribution of deforestation is ultimately limited by the stock of carbon in forests. Burning of brush by farmers during the dry season in Africa, however, is a somewhat different case since it does not usually involve destruction of forests. Methane from rice production is thought to be related more to the area under paddy cultivation than to the yield. Basic constraints on agricultural land area limit areal expansion of paddy rice production. Finally, nitrogen fertilizer demand growth has slowed in recent years.

Policy Responses to Climate Change

There are three basic policy responses for the control of greenhouse gas emission levels: emissions reduction, adaptation, and research. We have developed a dynamic and stochastic control model of climate change to identify the conditions for an economically efficient level of greenhouse gas emissions (presented in the appendix). The model captures some important characteristics of the climate change problem, including scientific uncertainty, effects across a long time path, and the role of adaptive activities. The model also demonstrates the complexities of making the "right" policy decision under conditions of uncertainty.

The model is solved for an economically efficient level of greenhouse gas emissions when there are two possible policy options: (1) reductions in greenhouse gas emissions and (2) adaptation. Consistent with other externalities models (see Oates), we find that an economically efficient level of greenhouse gas emissions requires that three important conditions be fulfilled. First, emissions should be at a level such that the sum of marginal benefits of a unit reduction in emissions equals the marginal costs of abatement. Second, resources should be devoted toward adapting to climate change to the point where the additional benefits from using another unit of variable input for adaptation just equal the marginal loss in benefits from sacrificing the output which that unit of variable input could have produced. Third, the marginal costs of reducing the damage from climate change by adaptation should equal the marginal cost of reducing this damage through prevention. This last condition ensures a least-cost combination of methods for the control of greenhouse gas emissions.

Predictions from Global Climate Models and Their Implications for Agriculture

To estimate the agricultural effects of long-term global climate changes, we must understand the direction and magnitude of climate changes relevant to agriculture. Climate change projections rely on large, complex computer models, known as General Circulation Models (GCM's). These models synthesize our knowledge of the physical and dynamic processes of the overall (atmosphere-ocean-land) climate system, allowing for the complex interactions between the various components. The Intergovernmental Panel on Climate Change (IPCC), composed of hundreds of scientists worldwide, recently released a scientific assessment of climate change. Based on current model results, the IPCC (1990a) predicts:[2]

(1) 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 0.3°C per decade. This will result in a likely increase in the global mean temperature of about 3°C before the end of the next century.

(2) 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 is expected to be 50–100 percent greater than the global mean in high northern latitudes in winter. Temperature increases in southern Europe and central North America are also predicted to be higher than the global mean.

(3) Increased precipitation on the order of 5–10 percent in middle and high latitude continents (35–55°N) in winter. Reduced summer precipitation and soil moisture in southern Europe and central North America.

(4) An average rate of global mean sea level rise of about 6 centimeters (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.

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[2] These predictions are also consistent with the general scientific consensus on the broad equilibrium effects of a doubling of atmospheric carbon dioxide summarized by the National Research Council, Board on Atmospheric Sciences and Climate (1987).

Other changes, such as the variability of temperature and precipitation and the frequency of severe storms, heat waves, and damaging frosts, are also possible.

Limitations of Global Climate Models for Impact Assessments

Limitations associated with the use of GCM predictions for agricultural impact studies include timing, geographic scale of predictions, seasonality, and time scale of predictions.

Timing

Climate models have, for the most part, been developed to project the equilibrium state of climatic conditions under an effective doubling of carbon dioxide concentrations in the atmosphere. They do not typically provide information on the time it will take to reach the new equilibrium climate. Timing of climate effects depends upon estimates of future greenhouse gas emissions and physical lags between changes in trace gas concentrations and climate effects. Calculating greenhouse gas concentrations in the atmosphere many decades in the future is inherently difficult. For example, interactions between physical sources and sinks and changes in climate are not fully understood; nor is the contribution of many economic activities to the total level of trace gas emissions.

Climate fluctuations during the transition period to the equilibrium state could also have important economic consequences. Even though it is generally presumed that the longrun temperature trend will be a fairly persistent increase with year-to-year variations, the transient response of temperature change to increased trace gas concentrations is not well understood and may not be linear.

Geographic Scale of Predictions

GCM's currently agree strongly about many globally averaged phenomena, the best example of which is surface air temperature (see table 1). However, on regional scales, there are significant differences. The difference in some estimates of temperature changes for the Midwestern United States is more than 3°C in the summer season (Grotch). The grid size of the GCM's determines the level of detail of predictions. The smallest grid size of GCM's is currently on the order of 90,000 square miles, too large for reliable regional and local impact assessments.

Poor regional resolution also limits the ability of researchers to predict changes in soil moisture levels, a critical element in determining plant growth potential. Thus, agricultural impacts are hard to predict. Soil moisture levels are dictated by precipitation, which is a localized climate feature, and consequently are not well simulated by GCM's.

Seasonality

GCM's have only a limited capability to project seasonality; that is, the difference between average summer and winter temperatures. Seasonality is an important determinant of crop production systems. Changes in precipitation and temperature would have very different effects on crop production depending on their seasonal distribution.

Table 1—Changes in surface air temperature if carbon dioxide concentration doubles

Variable and model	Domain of comparison			
	Global	Northern Hemisphere	Contiguous United States	Midwestern United States
	Degrees centigrade			
Increases in median temperatures:				
December–January–February—				
GCM [1]	3.72	3.74	3.10	3.32
GFDL [2]	4.50	5.65	4.76	5.04
GISS [3]	4.64	5.58	5.14	5.57
OSU [4]	3.19	3.12	3.35	3.54
June–July–August—				
GCM [1]	3.30	2.85	2.99	3.36
GFDL [2]	4.06	5.64	6.49	6.65
GISS [3]	4.33	3.35	3.71	3.80
OSU [4]	3.03	3.33	3.56	3.64

[1] Model developed by National Center for Atmospheric Research, Boulder, Colorado.
[2] Model developed by Geophysical Fluid Dynamics Laboratory, Princeton, New Jersey.
[3] Model developed by the Goddard Institute for Space Sciences, Greenbelt, Maryland.
[4] Model developed by Oregon State University, Corvallis.
Source: Gushee and others. Based on a study by Grotch.

Time Scale of Predictions

Crop yield impacts are assessed using daily precipitation and temperature estimates, not currently available directly from GCM's.

Climate Effects Across Broad Geographic Zones

Although GCM predictions are not ideal for agricultural impact analysis, they serve as a suitable benchmark for our global economic analysis directed at evaluating general directions and relative magnitudes of change. In particular, GCM predictions suggest broad geographic zones across which climate change may affect agriculture (fig. 3). Increased precipitation and warming in the high northern latitudes could enhance agricultural production potential in the northern regions of the Soviet Union, Canada, and Europe.

Drying in the interior of continents in the northern middle latitudes, combined with warming, could lead to negative crop and livestock effects in the United States, western Europe, and the most agriculturally productive areas of Canada. These regions include the largest grain-producing areas of the world. Other northern middle latitude regions, including southeast Asia, could suffer from coastal inundation.

There are exceptions to the broadly generalized climate patterns sketched by the IPCC. While China falls within the category of northern middle latitude countries, climate models do not strongly support increased aridity. Some estimates suggest crop production potential could increase (Zhang).

Regions of agricultural importance in the southern middle latitudes include Argentina and Australia. The climate change effects on agriculture in Argentina are not well known. However, some projections show a wetter, and therefore more agriculturally productive, climate for the major agricultural regions in Australia (IPCC, 1990b; Walker and others).

Much less is known about the possible agricultural effects of climate change in the tropical latitudes encompassing regions of Africa, Latin America, and southeast Asia. Temperature changes are generally expected to be smaller in equatorial regions than in higher latitudes, but there is very little agreement on changes in precipitation and soil moisture. Both magnitude and direction of effects on agriculture are consequently uncertain. However, less severe temperature changes may not necessarily result in less severe agricultural effects. Evapotranspiration increases nonlinearly with temperature. Thus, the potential for drought with a 1-degree rise

Figure 3
Effects of climate change on world agriculture[1]

[1]Based on GCM predictions.

Northern latitudes: Above-average warming and increased precipitation, increased yields.
Northern mid-latitudes: Above-average warming and dryer summers, reduced yields.
Tropics: Warming, uncertain precipitation and yield changes.
Southern mid-latitudes: Warming, some precipitation, and yield increases.

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 grains, whereas already warm areas may have fewer immediate alternatives.

Effects of Climate Change on Crop Yields

The broad changes in climate projected by GCM's offer some guidance for assessing agricultural effects, but they must be complemented with more detailed information in order to evaluate region-specific effects on crop growth. Mathematical crop growth models are 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 Growth Models

Many types of crop-weather models have been used in agricultural impact studies, including empirical/statistical, simulation, and extrapolation from historical record. Predictions from these models must be interpreted carefully in light of the manifold problems that exist. Limitations of statistical models include the following: multicollinearity among predictor variables; nonlinearity between precipitation, yield, and temperature; noncompatibility of spatial scale between data on climate and agricultural yield; limited time-scale of data sets that precludes capturing changes in soil characteristics such as organic content and soil erosion; and the use of historical data that frequently do not include extreme events that may result from climate change (see Katz; Santer; Liverman; and Arthur).

We review a number of yield estimates found in the literature on effects of climate change on crop growth, including U.S. Environmental Protection Agency (EPA); Parry, Carter, and Konijn; and Santer. While not a comprehensive global assessment, these studies have examined a wide range of region-specific changes in yields induced by changes in climate as suggested by GCM's, under existing cropping patterns, management practices, and production technologies. Selective summaries of the results of these studies are shown in tables 2, 3, and 4. Even though each producing area was examined by a different team of experts using different models and methods of analysis, the findings of these studies generally support the conclusion that middle latitude yields will fall and northern latitude yields will rise with a doubling of carbon dioxide (CO_2) levels.

Santer found modest positive effects on crop yields in northern Europe, and modest negative effects in southern Europe. Parry, Carter, and Konijn examined the effect of climate variation on agriculture in semi-arid regions in Australia and the USSR, and northern latitude agriculture in Canada, sub-Arctic USSR, Finland, Japan, and Iceland. The effects of predicted climate change were generally positive on northern latitude agriculture where production is currently limited by short growing seasons and cool temperatures. Icelandic yields of hay were estimated to increase by 64 percent. In Finland, barley yields were estimated to increase 9–14 percent in the south. Spring wheat and oat yields were estimated to increase by 10–20 and 13–18 percent, respectively. In the northern regions of the USSR examined in the study, rye and spring wheat yields were estimated to decrease by 13 and 3 percent, respectively, due to excessive soil moisture.

In the semi-arid regions examined by Parry, Carter, and Konijn, estimates for a doubling of CO_2 were made for wheat in Canada, the USSR, and Australia. Both the USSR and Australia showed increased yields due largely to the predicted increase in precipitation. Canada, however, showed decreased yields of 18 percent for spring wheat due to the adverse effects of increased temperature and reduced soil moisture.

The EPA study compared the agricultural effects of predicted climate change under effective CO_2 doubling based on two different climate model forecasts. Both the Goddard Institute for Space Studies (GISS)

Table 2—Projected impact of climate change on wheat and spelt[1] yields in EC countries using empirical/statistical model,[2] 1975–79 average yields

Country	BMO model[3]	GISS model[4]
	Percent	
Denmark	+18.7	+1.1
Netherlands	+1.2	+.3
Luxembourg	+7.8	+6.1
Belgium	−9.5	−6.8
France	−9.8	−12.3
Federal Republic of Germany	−1.1	−8.6
Italy	−.8	−1.2

[1] Spelt is a cereal intermediate between wheat and rye.
[2] "HANUS" country model developed for the European Community.
[3] BMO is a GCM developed at the British Meteorological Office.
[4] GISS is the Goddard Institute for Space Studies, National Aeronautics and Space Administration.
Source: Santer.

and Geophysical Fluid Dynamics Laboratory (GFDL) climate models predicted warming and drying for most agricultural areas of the United States. The GFDL model predicted more severe warming and drying with heightened effects during the summer growing season. The GISS climate model predicted yield declines in the range of 16–35 percent, while the GFDL model predicted yield declines in the range of 25–60 percent.

Other Considerations

In addition to temperature and precipitation changes, climate change may also affect agriculture through greater competition from weeds, increased plant and animal disease, changes in soil nutrients and pests, and increased conflicts for available water. While these damaging effects are probably controllable, we have yet to know what they may do to the cost of agricultural production and how they will affect agricultural resources and the environment.

More important is what increased carbon in the atmosphere will do to plant growth. A carbon-enriched atmosphere, like that under doubled CO_2 concentrations, is widely believed to promote plant growth and also lead to increased efficiency in water use. This positive influence of climate change on plant growth is termed the CO_2 fertilization effect. To date, there are no reliable estimates of its precise magnitude. Existing "chamber" studies of plant growth test separately for the effects of controlled climatic conditions and varying levels of carbon in the atmosphere.

Despite the limits of scientific knowledge, 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. Parry, Carter, and Konijn found that in sub-Arctic regions of the USSR, inclusion of the CO_2 fertilization effect increased yields 17 percent. The EPA study found that inclusion

Table 3—Projected climate change and impact on crop yields, by country/region

Country/region	Climate change		Crop yields						
			Hay	Pasture	Rye	Barley	Oats	Spring wheat	Rice
	Degrees centigrade, percent precipitation		*Percent*						
Canada:									
Saskatchewan	+3.4,	+18	—	—	—	—	—	-18	—
Iceland	+3.9,	+15	+64	—	+48	—	—	—	—
Finland:									
Helsinki	+4.1,	+73	—	—	—	+9	+18	+10	—
Oulu	+5.0,	+109	—	—	—	+14	+13	+20	—
USSR:									
Leningrad	+4.2,	+52	—	—	-13	—	—	—	—
Cherdyn	+2.7,	+50	—	—	—	—	—	-3	—
Saratov	+3.3,	+22	—	—	—	—	—	+13	—
Japan:									
Hokkaido	+3.5,	+5	—	—	—	—	—	—	+5
Tohoku	+2.9,	+12	—	—	—	—	—	—	+2
Australia	+1.0,	+50	—	—	—	—	—	+10–20	—

— means no change, or not reported.
Source: Parry, Carter, and Konijn.

Table 4—Projected impact of climate change on U.S. crop yields, by crop and climate model

Climate model	Corn (Dry)	Corn (Irrigated)	Soybeans (Dry)	Winter wheat (Dry)
		Percent		
GISS[1]	-23.7	-24.2	-34.6	-16.0
GFDL[2]	-54.7	-28.5	-59.7	-30.9

[1] GISS is the Goddard Institute for Space Studies, National Aeronautics and Space Administration.
[2] GFDL is the Geophysical Fluid Dynamics Laboratory, National Oceanic and Atmospheric Administration.
Source: Peart, Jones, and Curry; Ritchie, Gaer, and Chou; and Rosenzweig in U.S. Environmental Protection Agency.

of the positive effects of CO_2 on plant growth generally balanced yield reductions in the GFDL scenarios,[3] and resulted in modest to large increases under the GISS scenario (U.S. Environmental Protection Agency). A recent study conducted by the National Climate Program Office (NCPO) concluded that, under the assumption that no other factors are limiting, the fertilization effect from an effective doubling of CO_2 concentration could be expected to enhance crop yields by about 15 percent. Beyond this point, or with CO_2 levels in excess of 600 parts per million (ppm), most of the benefits of the direct effect on plant growth are exhausted (fig. 4).

The Effects of Climate Change on World Agricultural Prices and Welfare

As concerns over the potential for climate change have increased, so have the number of analytical studies of the potential economic effects of climate change on agriculture. As already indicated, several recent climate change, crop growth models estimate the crop yield effects of a doubling of atmospheric CO_2 on specific regions. In most cases, these studies infer the economic effects of climate change on the basis of national yield change estimates, without considering how altered yields may translate to price changes through domestic and international markets.

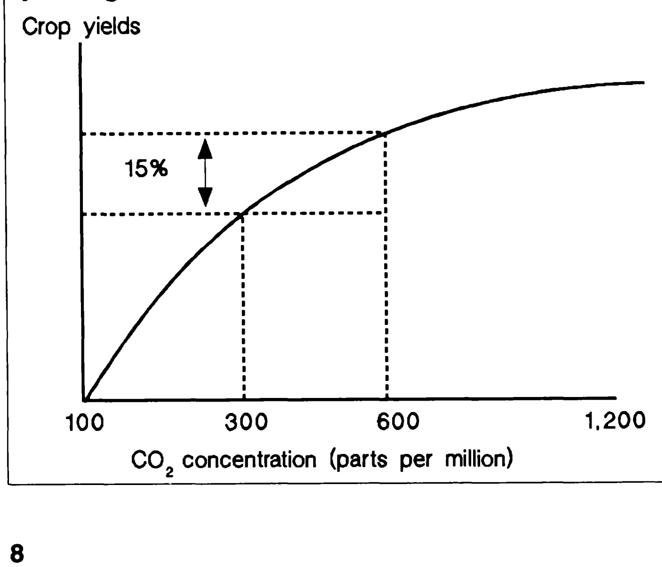
Agricultural market analyses of climate change use results from crop growth models and enter them into an economic model to capture secondary supply and demand responses. Efforts of this type include Adams and others (1988) and (1990), Arthur, and Kellogg and Severin. Adams and others incorporate climate change into a spatial equilibrium model to determine its effects on U.S. agricultural supply and demand. Arthur uses a linear programming model to calculate the effect of climate change on net revenues in the Canadian agricultural sector, and an input/output model to estimate production effects in other sectors of the Canadian provincial economy. Kellogg and Severin introduce climate variables in a model of the Soviet economy.

Our analysis takes these market analyses a step further by examining global, rather than only domestic effects. In an open world economy, the effect of climate change on 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. The important second round impact of changing world agricultural commodity prices on domestic production and consumption must also be captured. 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.[4]

The Static World Policy Simulation Model

The GCM climate models 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 a world food model, the Static World Policy Simulation (SWOPSIM) modeling framework. SWOPSIM describes world agricultural markets through a system of domestic supply and demand equations that are specified by matrices of variables that describe the responsiveness of the quantity of agricultural commodities supplied and demanded to changes in commodity prices (that is, own and cross price elasticities). It is a primary tool for policy analysis of international agricultural markets, developed by the U.S. Department of Agriculture's Economic Research Service. Descriptions of the SWOPSIM model can be found in Krissoff, Sullivan, and Wainio; Roningen; and Roningen and Dixit.

Figure 4
Effect of increased carbon levels on plant growth



[3] With the exception of the Southeast where, even with CO_2 fertilization, soybean yield declines were generally in the range of 20-80 percent.

[4] The U.S. Environmental Protection Agency is currently funding a research effort aimed at increasing our understanding of climate change impacts and world agriculture.

SWOPSIM 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 8 crop, 4 meat/livestock, 4 dairy product, 2 protein meal, and 2 oil product categories. SWOPSIM is flexible enough to allow separate identification of up to 36 countries/regions of the world. For the purposes of this study, we decomposed the world into 13 countries/regions including the United States, Canada, the European Community (EC), Australia, Argentina, Pakistan, Thailand, China, Brazil, the USSR, other Europe (Sweden, Finland, Norway, Austria, and Switzerland), and Japan. All other countries are grouped together. This level of disaggregation covers the major agricultural importing and exporting regions and several areas projected to be among the most strongly affected by climate change.

The model's structure is straightforward.[5] 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 (that is, the consumer price of other commodities that affect the demand for j); PP_{ik} is the price of an intermediate input to product j, and/or the price of another product that affects the price of 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:

$$CP_{ij} = CSW_{ij} + F(E_i * WP_j)$$

$$PP_{ij} = PSW_{ij} + G(E_i * WP_j)$$

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 (PSE's/CSE's). 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.

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

World markets clear when net trade of a commodity across all countries is equal to 0. For commodity j, this occurs when world supply of a commodity equals its world demand:

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

The commodity supply and demand equations are parameterized to reproduce 1986 base period data for supply, demand, prices, and trade for each country/region. 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 with the pattern that emerges from the model.

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 find 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 in Organization for Economic Cooperation and Development (OECD) and Parikh and others. The responsiveness of commodity trade to changes in prices is also derived. This is the partial net trade elasticity. They 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 desirable characteristics for our purposes. Among these 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 (Haley and Dixit). Welfare effects are measured by the change in consumer and producer surpluses. Consumer and producer surpluses are commonly used empirical measures of how much better off, or worse off, consumers or producers are when commodity prices are altered. Consumer surplus is defined as the area under the demand curve and above the price line. It represents a willingness to pay beyond what is actually paid. Producer surplus is defined as the area below the price line and above the supply curve. It measures the excess of gross receipts over total variable costs.[6]

SWOPSIM also has some limitations that should be noted. First, it is a partial-equilibrium model and does not capture agricultural interactions with other economic sectors. However, we do not believe that this is a serious limitation. In industrialized and semi-industrialized countries, agricultural production is only a small part of total output and therefore has relatively little effect 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 base system. It would be useful to have resource inputs in the model in order to exogenously change them and to ensure that, for large shocks to the system, constraints on resources (especially cultivated area) are not binding.

[6] SWOPSIM uses Marshallian measures of economic surplus. Marshallian measures do not take account of income effects associated with price changes. That is, income is held constant. 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 show that the Marshallian welfare measure is well suited for use in the SWOPSIM modeling framework. We would argue that it provides a reasonable estimate of the true change in economic welfare. Willig's theorem shows that even without exactly satisfying the above conditions, Marshallian consumer surplus provides a very close approximation of the true changes in welfare.

Moderate Impacts Climate Change Scenario

SWOPSIM does not include explicit climate variables. Climate changes are introduced as an exogenous increase or decrease in base yields for specific countries/regions. Once entered into SWOPSIM, the model then solves for a new set of consumption, production, and price relationships. Our "moderate impacts" scenario (presented in table 5) was used in some of the preliminary research undertaken by the Intergovernmental Panel on Climate Change, Working Group 2 on Impacts (Parry). It reflects our review of the results of crop response studies such as those described earlier. We have not assumed any CO_2 fertilization effects. Farmer responses to climate change are also not included. For these reasons, the assumed yield changes are more likely to overstate than understate the actual changes.

The estimated price effects of the best guess estimate of crop yield estimates generated by SWOPSIM are presented in table 6. There is a small predicted decline in the price of primary products, and a small predicted increase in the price of secondary products. Corn and soybean prices increase by approximately 10 percent, but prices of all other primary products fall. This result is not surprising since most corn and soybean crops are produced in regions of the world that are expected to be adversely affected by climate change. Of the secondary agricultural products, oil

Table 5—Yield effects under moderate impacts scenario

	Percentage change in yield				
Countries/regions	Wheat	Corn	Soybeans	Rice	Other[1]
			Percent		
United States	−10	−15	−15	0	−10
Canada	−15	+5	+5	0	−10
European Community	−10	0	0	0	−5
Northern Europe	+15	+30	0	0	+10
Japan	−5	0	+15	+10	+5
Australia	+10	+10	+10	+15	+10
China	+10	+10	+10	+10	+10
USSR	+10	+15	+15	0	+10
Brazil			No change		
Argentina			No change		
Pakistan			No change		
Thailand			No change		
Rest of the world			No change		

[1] Other coarse grains, groundnuts, cotton, sugar, and tobacco.

and meal prices increase by the highest percentage, representing their direct dependence on soybeans and other oilseed intermediate inputs. These changes in commodity prices lead to a marginal net global welfare increase equivalent to 0.01 percent of 1986 world gross domestic product (GDP) (table 7).

Table 6—World agricultural price changes from yield shifts induced by double CO_2 based on SWOPSIM model results

Variables	Price change
	Percent
Primary products:	
Grain and oilseeds—	
Wheat	-0.9
Corn	9.2
Other coarse grains	-1.2
Rice	-8.1
Soybean	10.6
Other oilseeds	-2.8
Other primary commodities—	
Cotton	-4.5
Sugar	-1.5
Tobacco	-5.3
Composite price change:	
Primary products	-4.0
Secondary products:	
Beef	.4
Pork	.6
Mutton, lamb	.7
Poultry	0
Soymeal	4.9
Soyoil	4.4
Dairy—	
Milk	0
Eggs	.6
Butter	.2
Cheese	.1
Milk powder	.2
Composite price change:	
Secondary products	+1.0

Table 7—Welfare effects of moderate impacts climate change scenario

Country/region	Welfare change	Percentage of 1986 gross domestic product
	Million dollars 1986	*Percent*
United States	+194	0.005
Canada	-167	.047
European Community	-673	.019
Northern Europe	-51	.010
Japan	-1,209	.062
Australia	+66	.038
China	+2,882	1.28
USSR	+658	.032
Brazil	-47	.017
Argentina	+95	.120
Pakistan	-50	.153
Thailand	-33	.081
Rest of world	-67	.002
World total	+1,509	.01

The moderate impacts scenario results illustrate three interesting features regarding the effect of climate change on agriculture. First, the crop yield effects of global climate change, as predicted by existing crop response models, are unlikely to severely disrupt the world's total food productive capability, as reduced production potential in some areas is balanced by gains in others. The very modest effects on commodity prices are a result of similarly modest effects on total world food production.

Second, the economic effects on national economies are estimated to be small, with some winners and losers. The small effects are related to the fact that agriculture accounts for a small percentage of GDP in most economies (3 percent in industrial market economies, and 19 percent in developing economies in 1986) (World Bank).

Third, the pattern of welfare effects among countries depends not only on domestic yield changes, but also on changes in world commodity prices. The importance of induced price changes in promoting interregional adjustments in production and consumption can be illustrated by comparing the SWOPSIM results with those of other models that consider the climate change effects on a single country. Adams and others (1988) examine the economic effect of climate change on U.S. agriculture using the GISS and GFDL climate models. They find net welfare reductions for the United States under the two scenarios to be about $7 billion and $34 billion, respectively. Referring to table 2, we notice that the crop yield effects in the United States under the GISS climate model roughly resemble our U.S. yield changes specified in the modest impacts scenario. However, we find a welfare gain of $0.2 billion. This value is considerably smaller than the predictions of Adams and others. We interpret the difference as an indication of the role of international price changes in promoting interregional adjustments in production and consumption.[7]

Sensitivity Analysis

There are some important limitations of both crop response models and the GCM's that they rely on. As a result, rather than specifying a particular set of specific yield effects for any country or region, it may be more useful to view the effects of climate change on yields as falling within a range of possibilities. For this reason, we explore the sensitivity of world food systems to a broad range of potential yield assumptions.

[7] 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.

Based on our grouping of the broad geographic zones across which climate change may affect agriculture (fig. 3), we have constructed three climate change scenarios. In each scenario, changes in world agricultural commodity prices are estimated for a range of concurrent yield reductions of 0–50 percent in the United States, Canada, and the EC. The three scenarios are:

Scenario one: Yield increases of 25 percent in the USSR, northern Europe, China, Japan, Australia, Argentina, and Brazil, with no changes in other countries.

Scenario two: A neutral effect in all other countries except the United States, Canada, and the EC.

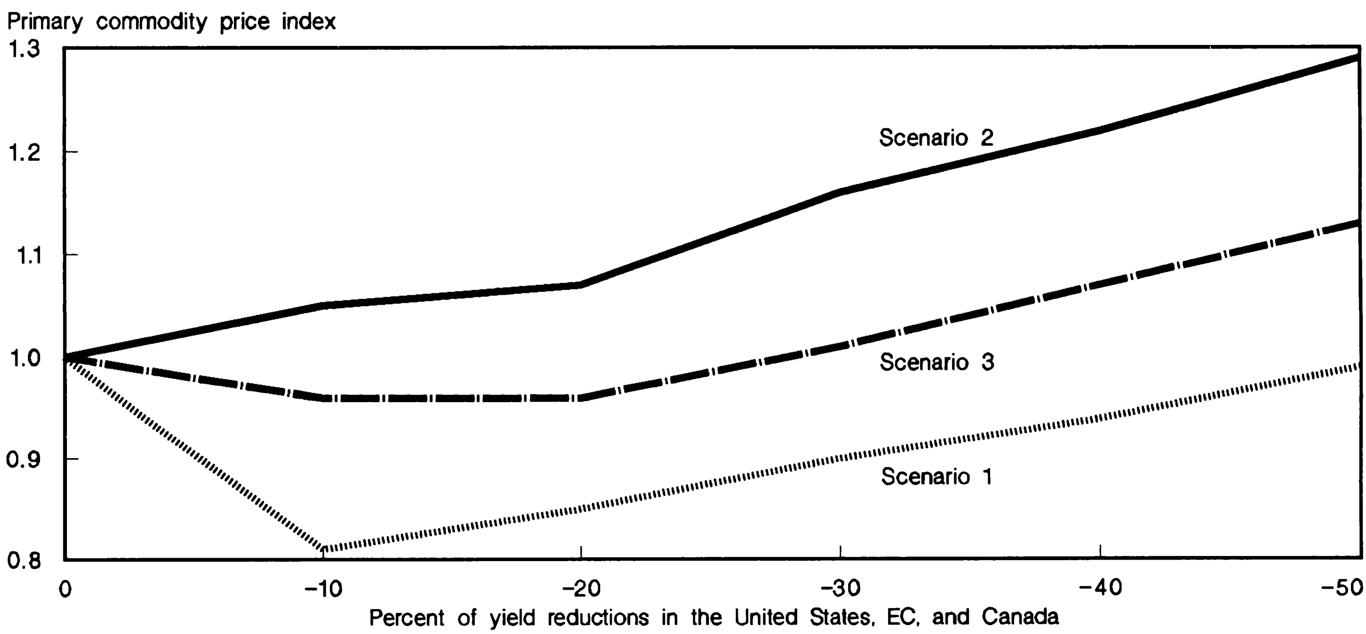
Scenario three: Yield increases of 25 percent in the USSR, northern Europe, China, Japan, Australia, Argentina, and Brazil, with decreases of 25 percent in Africa and the remaining countries in Asia, Latin America, and the rest of the world.

All three sensitivity scenarios emphasize both the predicted negative effect of climate change on agricultural production in the major world grain producers in the northern middle latitudes, and the uncertainty embodied in predictions of yield effects.

The three scenarios capture the important climate effects on the major food exporting and importing countries. The USSR, Japan, and China are the three largest net cereal importers (Food and Agriculture Organization of the United Nations). 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.

The aggregate primary crop price effects and domestic welfare effects resulting from the introduction of climate-induced changes in yields specified in our three scenarios are shown in figure 5 and table 8, respectively. These scenarios show that reduced production potential in the United States, Canada, and the EC may be balanced by gains in other areas when the negative yield effects are relatively modest.

Figure 5
Sensitivity of world agricultural prices to yield changes



Scenario 1: Yield increases of 25 percent in USSR, northern Europe, China, Japan, Australia, Argentina, and Brazil with no change in other countries.
Scenario 2: Neutral effect in all other countries except the United States, Canada, and the EC.
Scenario 3: Yield increases of 25 percent in USSR, northern Europe, China, Japan, Australia, Argentina, and Brazil with yield decreases of 25 percent in Africa, and remaining countries in Latin America, Southeast Asia, and the rest of the world.

For example, as scenario one illustrates, reduced production potential in the United States, Canada, and the EC may be balanced by gains in other areas, leading to improvements in world welfare. Even under scenario 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.

As we found earlier under the best guess scenario, the welfare effects as a percentage of world GDP from these scenarios are generally quite modest (with the exception of China and Argentina in scenarios one and three). Also, the pattern of welfare effects on domestic economies depends critically on a country's net trade position. The producer surplus gain will be large relative to the consumer surplus loss if the country is a large net exporter. Consider the case of a large net importer and a large net exporter when climate change produces yield declines in both countries (shifting supply curves from S_0 to S_1) and an increase in world agricultural prices (from P_0 to P_1). These two cases are shown diagrammatically in figure 6. Panel 1 represents the case of a large net exporter. The loss in consumer surplus is given by the area A, the area under the demand curve between the old and new price. The gain in producer surplus is given by (A + B) − (E + F), the area above the old supply curve between the old and new price, less the area under the old price that is lost when the supply curve shifts inward.

Straightforward algebra tells us that if the area B is greater than the area (E + F), there is a net gain in consumer plus producer surplus. Panel 2 represents the case of a large net importer. The loss in consumer surplus is given by the area (A + B + C). The gain in producer surplus is given by (A − E). Thus, if (B + C) is greater than E, there is a net loss in consumer plus producer surplus.

A summary of the nature of the interdependence between yield changes, world price changes, and the pattern of welfare effects is provided in figure 7 (a and b). The most likely winners under a price rise are large net exporters with positive domestic yield effects (for example, Argentina, Australia, Brazil, and China in scenario three). Likely losers under a price rise are large net importers with negative domestic yield effects (for example, rest of the world in scenario three).

The most likely winners under a world agricultural commodity price decline are large net importers with positive domestic yield effects (for example, China and the USSR in scenario one). Likely losers under a price decline are large net exporters with negative domestic yield effects (for example, Canada under scenario one).

Table 8—Welfare effects of climate change as a percentage of 1986 GDP

Country/region	Percent of yield reductions in the United States, EC, and Canada:								
	−10	−30	−50	−10	−30	−50	−10	−30	−50
	(Scenario one)[1]			(Scenario two)[2]			(Scenario three)[3]		
					Percent				
Argentina	0.28	0.82	1.77	0.21	0.86	2.02	1.03	1.48	2.81
Australia	−.02	.10	.28	.06	.23	.46	.27	.38	.68
Brazil	.21	.21	.37	−.05	−.07	.07	.21	.28	.60
Canada	−.11	−.14	−.26	−.01	−.11	−.33	−.06	−.11	−.33
China	2.81	3.06	3.73	−.06	−.08	.14	3.83	4.26	5.48
EC	.04	−.03	−.10	−.04	−.15	−.28	−.06	−.12	−.23
Japan	−.08	−.15	−.25	−.04	−.14	−.26	−.21	−.26	−.37
Northern Europe	.03	−.01	−.04	−.02	−.07	−.12	−.03	−.05	−.07
Thailand	−.33	−.16	.15	.10	.39	.90	−.62	−.59	−.33
United States	.02	.01	−.05	0	−.03	−.13	−.01	−.03	−.12
USSR	.12	.08	.07	−.03	−.09	−.13	.08	.09	.12
Rest of world	.16	.02	−.11	−.07	−.19	−.25	−.58	−.70	−.93
World total	.09	.04	−.01	−.03	−.10	−.17	−.07	−.10	−.17

[1] Scenario one: Yield increases of 25 percent in USSR, northern Europe, China, Japan, Australia, Argentina, and Brazil with no change in other countries.
[2] Scenario two: Neutral effect in all other countries except the United States, Canada, and the EC.
[3] Scenario three: Yield increases of 25 percent in USSR, northern Europe, China, Japan, Australia, Argentina, and Brazil, with yield decreases of 25 percent in Africa, the remaining countries in Latin America, southeast Asia, and rest of world.

Adaptation: Management and Technology Alternatives

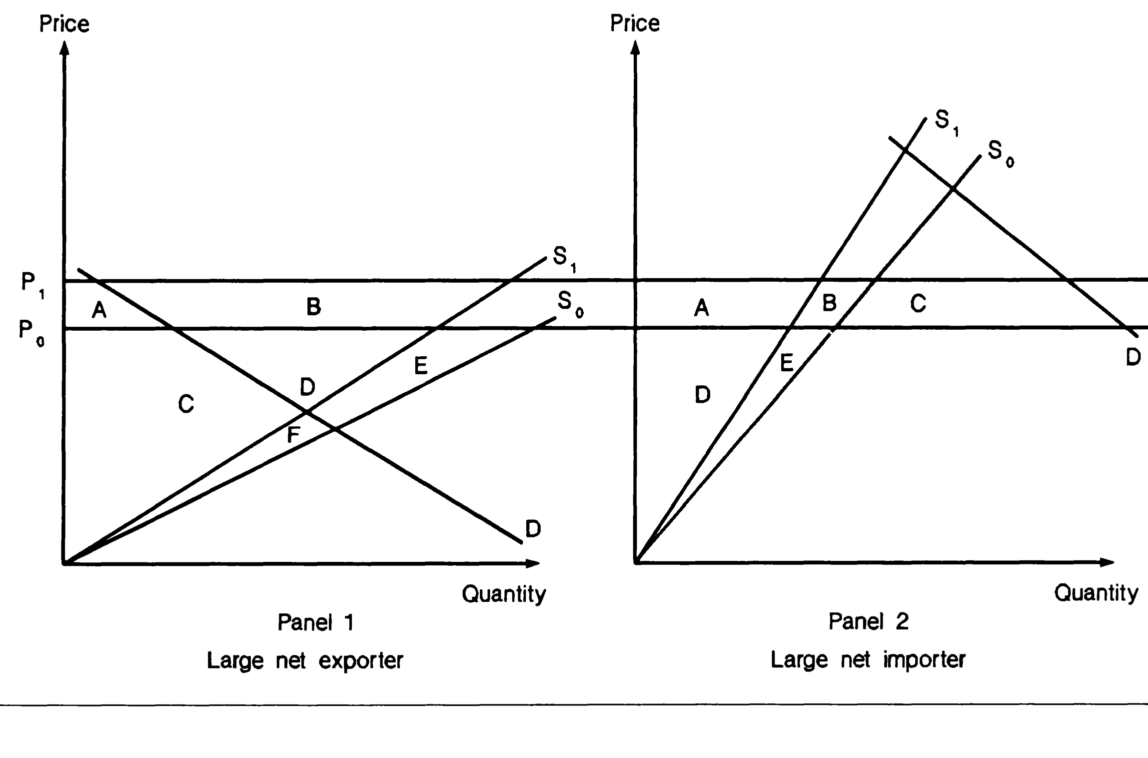
The above effects of climate change on agricultural markets assume no changes in agricultural management and production technology over the relevant time period. However, adaptive responses to a changing climate and technological advances are expected to play an important role in agriculture (Rosenberg and others). Both offer the possibility to reduce climate-change-related yield losses or to increase the yield benefits from more favorable climate regimes. By one estimate, the agricultural community could adapt completely in 25 years to a doubled 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 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 EPA find 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 and others) finds 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.

In a recent empirical test of adaptation, Hansen uses historical U.S. climate data to study the effect of climate on corn yields in the 10 major corn-producing States. He finds that the yield effect of a long-term

Figure 6
The effects of climate change on economic welfare



temperature change is much smaller than the effect of annual variations in temperature. Climate effects on yields are studied by regressing corn yields across regions on climate and other variables that are predicted to determine yield. With cross-sectional data, the effect of climate change on yields embodies the technologies employed by farmers to maximize profits, given the climate of the particular region. Thus, Hansen concludes that some of the difference in yield effects may be explained by the increased opportunities available for adjustment of production technology over longer periods of time from capital investment and benefits of learning exceeding those available in the short term.

Figure 7a

Net welfare effects of climate change assuming an increase in world agricultural prices

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

Figure 7b

Net welfare effects of climate change assuming a decrease in world agricultural prices

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

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Appendix: An Economic Model of Uncertain Climate Change

Previous climate change models do not typically show the conditions that describe the optimal levels of mitigation (reductions of greenhouse gas emissions) and adaptation when uncertainty and a dynamic time frame exist. Nordhaus (1982) develops a dynamic model of climate change, but does not capture the effects of uncertainty or the role of adaptive activities in alleviating the economic damages from an altered climate. Heal introduces uncertainty in the capacity of the atmosphere to absorb CO_2 emissions, but does not explicitly introduce natural climate variability or the role of adaptive activities.

The dynamic control model described below emphasizes the multidimensional nature of climate change uncertainty and its interactions with decisions concerning both the optimal level of greenhouse gas emissions and adaptations to altered climatic conditions. The analysis explicitly incorporates two basic types of uncertainty that continue to enter into the policy debate: type I uncertainty exists over how greenhouse gas emissions influence the climate, and type II uncertainty exists due to natural climatic variability. Resolving uncertainty about the effects of greenhouse gas emissions would not, by itself, conclude whether or not emissions should be reduced.

Consider an economy that uses a vector of variable inputs (z) and emits a vector of greenhouse gases (s) to produce a single output according to the following production function:

$$q = f(s,z,X,\tau) \tag{1}$$

where τ in the production function is a time index which is a proxy for the state of technology; and X is an index of climate quality, where a larger value for X is associated with poorer quality. The production function $f(s,z,X,\tau)$ is increasing in s and z, decreasing in X, and concave in s, z, and X. Greenhouse gas emissions are viewed as one use of the environment in production and, therefore, an input in the production function.[8] Because the production function is decreasing and concave in X, an increase in X reduces output, and this reduction becomes more pronounced at higher levels of X. The assumption that climate changes are "bad" is common in existing discussions of climate change, although it is not clear how climate change will affect production possibilities in practice.[9]

Types I and II uncertainty influence the evolution of the climate index X, represented by its differential dX. The sources of variation in the climate index are represented in the following stochastic differential equation:

$$dX = (aX + \phi s)\, d\tau + \alpha s dy + \sigma X dw, \quad X(t) = x \tag{2}$$

where a, ϕ, α, and σ are parameters discussed below, and the variables y and w are independent Wiener processes (Brock; Chow).[10]

Equation (2), which represents a subjective view of climate change uncertainty, includes types I and II uncertainty. The term $(aX + \phi s)$ is the expected change in

[8] Alternatively, it is possible to specify q and s as joint outputs from a multiple output technology as $G(q,s,z,X,\tau) = 0$.

[9] Nordhaus (1989) provides the only overall assessment of the costs of greenhouse warming that we were able to uncover. For the United States, Nordhaus assesses climate change damages to agriculture, sea level rise, energy, other marketed goods and services (water systems, recreation, forestry) and nonmarketed goods and services (amenity values, human health, biological diversity). Nordhaus estimates that the net economic damage at the middle of the next century, in terms of those variables that are quantifiable, is likely to be around 0.25 percent of U.S. national income.

[10] See Brock and Chow for an introduction to stochastic differential equations, stochastic calculus, and optimal control. In essence, y and w are independent random variables, and the differentials dw and dy are random variables with mean zero and variance $d\tau$.

the climate index over a small period of time $d\tau$, where the term aX captures expected natural change in the climate and ϕs is the expected impact on the climate index from greenhouse gas emissions s.

The last two terms, $\alpha sdy + \sigma Xdw$, represent the standard deviation of dX and are a measure of climate uncertainty. Type I scientific uncertainty over the effect of greenhouse gas emissions on the climate index is embodied in the term αsdy. Thus, the uncertain impact of s on the change in the climate index is $\phi sd\tau + s\alpha dy$. The term σXdw represents type II uncertainty due to natural variation around the mean, which is increasing in X. This characterization of uncertainty follows analyses that suggest increasing greenhouse gases in the atmosphere may increase climate variability (Parry and Carter; Mearns, Katz, and Schneider). While there are clearly many other ways in which uncertainty could be modeled in a dynamic context, the stochastic differential specification is general enough to distinguish between the two types of uncertainty.

In the production function, policy actions to influence the climate index can come either from reductions in s (mitigation activities) or from adaptation activities that use various combinations of the inputs z. In practice, mitigating activities to reduce emissions could come from three main areas: (1) shifting energy use from more carbon-intensive fossil fuel sources to cleaner but currently more expensive energy sources, (2) reductions in chlorofluorocarbon, nitrous oxide, and methane emissions, and (3) reforestation.

Adaptation to climate change involves engaging in activities to reduce the damage from climate change that individuals or firms must absorb. In this model, adaptation occurs through adjustments in inputs z. Adaptation activities might include, for example, the construction of sea walls, the installation of new or additional air conditioning systems, the selection of different cultivars by farm operators, or variations in the timing of farm operations, including earlier planting to help offset heat and moisture stress during a warmer and, possibly, drier summer. These adaptive responses are likely to play an important role in the overall response to climate change (Rosenberg and others).

To complete the economic model, we consider a small open economy whose objective is to maximize the present value of net income from production over an infinite time horizon. Assuming prices are exogenous to the small economy, the country's optimization problem becomes:

$$\max_{x,z} E_t\left(\int_t^{\infty} e^{-rt}\,[pf(s,X,z,\tau) - cz]\,d\tau\right) \tag{3}$$

subject to the state equation (2), where r is the discount rate, p is the world output price, c is the price vector of variable inputs, and $E_t(\bullet)$ is the expectations operator given information at initial time t. The model could easily include risk aversion, but the basic quandaries facing policymakers are highlighted in the risk-neutrality framework.

In essence, society's problem (3) is identical to many dynamic resource models; the shortrun benefits from increased emissions of s must be weighed against the long-term costs of increases in the climate index X. Problem (3) is also similar to flexible-accelerator models of investment, although the logic is reversed; in this model there are shortrun benefits from increasing greenhouse gas emissions, and longrun but uncertain costs. Although adaptation activities are considered to be components of the variable inputs z, sluggish adaptation to climate change could be modeled through a capital stock equation of motion.

Implications of the Model

Stochastic dynamic programming can be used to analyze efficient choices of s and z.[11] The dynamic programming equation for the Wiener-driven model is

$$rJ(x) = \max_{s,z}[pf(s,x,z,\tau) - cz + J_x(ax + \phi s) + .5J_{xx}(\alpha^2 s^2 + \sigma^2 x^2)] \tag{4}$$

where J is the present discounted value of expected profits in problem (1), J_x is the expected marginal cost to society of an increase in the climate index x at time t, J_{xx} is the change in the expected marginal cost of a change in the climate index at time t. For simplicity, the indirect objective function J is only written as a function of x, although it depends on all other parameters of the problem.

For those with a background in optimal control for a deterministic case, the right-hand side of equation (4) is the Hamiltonian. When the Hamiltonian is evaluated at the optimal controls $s^*(x)$ and $z^*(x)$, equation (4) is also defined as the Hamilton-Jacobi equation. The Hamiltonian, which is interpreted as the expected change in the discounted value of society's income at time t, includes three general terms. First, net returns at time t are pf (s,x,z,t) − cz. Second, it is assumed

[11] Variable subscripts denote partial derivatives. See references in footnote (10) for an introduction to stochastic dynamic programming in continuous time.

that $J_x < 0$, so that $J_x(ax + \phi s)$ is the expected cost of climate changes at t. And third, the term $.5J_{xx}(\alpha^2 s^2 + \sigma^2 x^2)$ represents a value to the economy of uncertainty at time t. In general, the sign of J_{xx} could be positive or negative, although in a later section it is shown that the sign of J_{xx} depends on the sign and magnitude of f_{sz}/f_{zz}.

Assuming an interior solution, the necessary first-order conditions for (4) are:

$$pf_z - c = 0 \tag{5}$$

$$pf_s + J_x\phi + J_{xx}\alpha^2 s = 0. \tag{6}$$

Along the optimal path, equation (5) indicates usual efficiency conditions for variable inputs, where marginal revenue product of inputs z equals marginal cost. Since the marginal product of inputs z depends on the climate index, any change in X will induce adjustments in z. From equation (6), efficient emission levels occur when the marginal revenue product of emissions, pf_s, equals the total marginal cost of emissions, $-J_x\phi - J_{xx}\alpha^2 s$. Thus, for this model, once the effects of climate change are actually realized, the proper incentives are in place for firms and individuals to engage in adaptive activities. In a model that included costly adjustments of capital, the expectation of future impacts of climate change could induce current capital adjustments, such as new technologies. Also from equations (5) and (6), the optimal level of emissions and adaptive activities over time are interdependent because the production function has as arguments both greenhouse gas emissions and adaptive activities.

The implications of this model for developing a coherent climate change policy under uncertainty can now be analyzed. Essentially, the policy debate centers on how the optimal emissions policy under types I and II uncertainty should change as: (1) the expected effect of emissions on the climate is altered (the parameter ϕ is changed in the model), and (2) uncertainty over the effect of emissions on the climate is reduced (the parameter α in the model is reduced).

To give an indication of the difficulties that arise in comparing these alternative control trajectories under alternative parameter values for ϕ and α, equations (5) and (6) can be used to derive the comparative statics of the initial time period t optimal controls with respect to type I uncertainty (Stefanou). These comparative statics can be used to determine how a change in α and ϕ, for example due to new scientific information, affects the optimal emissions policy.

Taking the differential of (5) and (6) with respect to s, z, α, ϕ at the optimum, and then using Cramer's rule, the effects on the optimal emissions policy due to a marginal change in α and ϕ are:

$$\frac{ds}{d\alpha} = -\left[\frac{(\phi J_{x\alpha} + 2\alpha s J_{xx} + J_{xx\alpha}\alpha^2 s)\, pf_{zz}}{\det(H)}\right] \tag{7}$$

$$\frac{ds}{d\phi} = -\left[\frac{(\phi J_{x\phi} + J_x + J_{xx\phi}\alpha^2 s)\, pf_{zz}}{\det(H)}\right] \tag{8}$$

where

$$H = \begin{bmatrix} pf_{zz} & pf_{zs} \\ pf_{sz} & pf_{ss} + J_{xx}\alpha^2 \end{bmatrix}. \tag{9}$$

Equation (7) shows how an optimal emissions policy should change as the level of uncertainty, represented by α changes, while equation (8) shows how emissions should change as the expected impact of emissions on the climate changes. Unfortunately, theory provides no guidance about the overall signs of these derivatives, and little guidance about the signs of individual terms. As is often the case in dynamic optimization models, the third-order properties of the value function are needed to determine the signs of (7) and (8) (Stefanou; Caputo).

Some information is available. First, the dynamic programming equation (4) can be used to find third-order derivatives of J in terms of lower order derivatives. And second, assuming the production function is strictly concave, so that f_{ss} and f_{zz} are less than zero and $f_{ss}f_{zz} - f_{sz}f_{zs} > 0$, it can be shown that:

$$-pf_{ss} + f_{sz}/f_{zz} < \alpha^2 J_{xx} < -pf_{ss},$$

when $f_{sz} > 0$. Thus, the term J_{xx}, which determines whether the marginal cost of climate change is increasing or decreasing in x, could be positive or negative, although it is bounded. If the production function is additively separable between s and z, then $f_{sz} = 0$, and J_{xx} is positive. If the productivity of inputs in production are sensitive and positively related to changing emissions levels, then $f_{sz} < 0$, and it is possible that $J_{xx} < 0$. Thus, marginal effects of further climate changes could actually be declining.[12]

[12] Two other key pieces of information that are necessary to sign the derivatives in (7) and (8) are $J_{x\alpha}$ and $J_{x\phi}$, which determine how information concerning uncertainty and expected effects of emissions affect the marginal cost of climate change.

Conclusion

This model illustrates the complications of making the "right" policy decision based on the notion of economic efficiency and optimality. Limited understanding of both the global warming process and continuing natural climate variation makes it difficult, in principle, to determine an optimal emissions policy. The model shows clearly what key variables and relationships require further attention to eliminate ambiguities of "optimal" policy settings to avert prospective global warming. These are summarized by equations (7)–(9) above.

Given the complexity of predicting the behavior of the complete Earth system (ocean, atmosphere, land), attaining perfect information is unlikely. This is not to suggest that economic analysis is therefore not useful in this case. Even information on the rough relative magnitudes and signs of the important relationships may lead to unambiguous conclusions. Further, as the model shows (equation 6), the basic principle governing the "optimal" level of waste emissions remains: emissions should be at a level such that the marginal costs equal the marginal benefits of emissions reductions. As applied to the climate change issue, estimates of this economic condition (given current information) continue to provide the best input for policy decisions. The empirical effort of this report helps improve decision-making by providing estimates of one important component of the benefits of emissions reductions.

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