Chapter 4. Global Adjustments to Climate Change

Agriculture's response to climate change will depend not only on the new climatic conditions facing farmers and agriculture's interactions with other domestic sectors, but also on the responses of producers and consumers around the world as signaled through prices determined in global markets. International trade in agricultural and food products has been steadily increasing over the last several decades and now averages about $335 billion per year (FAO, 1994). This amount is still small relative to agricultural production (about 15 percent of world production), but a well-functioning international trading system gives price signals to agriculturalists to help meet increasing demands for food with more efficient allocation of production across countries. As demonstrated in early studies of the global impacts of climate change (for example, Kane and others, 1991), how international prices and production change as a result of climate change can easily be more important to a national or local economy than the initial impact of climate change on the agricultural sector of the economy. Thus, even if one's principal interest is in the effect of climate change on a single country such as the United States, it is essential to consider the impact of climate change on that country's current and potential export markets and export competitors' markets.

Several studies have examined various aspects of global climate change impacts on world agricultural production and trade. A number of these analyses used the supply shocks reported by Rosenzweig and others (1993) and Rosenzweig and Parry (1994) that were developed from an extensive set of crop-response modeling studies (Rosenzweig and Iglesias, 1994). As a result, this group of analyses do not provide fully independent estimates of potential climate change impacts. Differences between results reflect differences in the economic models used to evaluate supply changes. As demonstrated in previous chapters, different methods for estimating the initial effects of climate change (before producers and consumers respond to changing prices) can give widely varying results. Thus, we focus our comparison of the results of global studies on the group of studies that rely on the crop-response modeling studies of Rosenzweig and Parry (1994) and Darwin and others (1995), which use completely independent approaches for estimating the initial impact of climate change on crop production. In addition, the impacts and potential to adapt may affect developing countries differently. We consider a unique study investigating how climate change might affect developing countries with different 'archetype' agricultural economies (Winters and others, 1994).

The principal objectives of this chapter are to consider answers to the following questions.

- Is global food production likely to be seriously threatened by climate change?
- What is the potential for adaptation to climate change in the global agricultural economy?
- How might the effects of climate change differ regionally and can we identify potential winners and losers from climate change?
- What effects might agricultural adjustment have on patterns of land use, particularly in areas currently devoted to forests and other unmanaged or less intensively managed ecosystems?

Climate Change in Economic Models of Global Agriculture

The most important issue in assessing the economic impact of climate change on global agriculture is the modeling of climate change itself. Factors generating differences in results are (1) the climate change scenario considered, (2) the method used to estimate the initial climate change impact, (3) whether the direct effect of CO_2 on plant growth is considered, and (4) the extent to which farm-level adaptations are considered (table 4.1).

Climate Change Scenarios. General Circulation Models (GCM's) provide the most detailed projections of Earth's climate under elevated atmospheric CO_2 levels. Four GCM scenarios have been popular in assessing the economic impacts of climate change on world agriculture. These scenarios are the $2xCO_2$ simulations of the models at the Goddard Institute for Space Studies (GISS), the General Fluid Dynamics Laboratory (GFDL), the United Kingdom Meteorological Office (UKMO), and Oregon State University (OSU).[17]

Climate Change Impact Methods. Two approaches have been used to incorporate climate change impacts into economic models of world agriculture. Most authors select a GCM scenario and then use *crop-response models* to estimate impacts of climate

[17] Chapter 1 discusses GCM's in more detail, as well as methods for estimating climate change impacts.

Table 4.1--Selected studies estimating the impact of climate change on global agriculture: modeling climate change

	Study					
	Kane and others, 1991	**Reilly and others, 1994**	**Winters and others, 1994**	**Tsigas and others, 1996**	**Rosenzweig and others, 1993**	**Darwin and others, 1995**
Climate change scenarios	*Moderate impacts* scenario from IPCC, Working Group II on Impacts	General circulation models: GISS, GFDL, UKMO.	General circulation models: GISS, GFDL, UKMO	General circulation model: GISS	General circulation models: GISS, GFDL, UKMO.	General circulation models: GISS, GFDL, UKMO, OSU
Modeling of climate change	Exogenous changes in crop yields based on a literature survey of crop yield changes and sensitivity analysis linked to stylized potential regional climate impacts.	Exogenous changes in crop yields based on Rosenzweig and others, 1993.	Exogenous changes in crop yields based on Rosenzweig and others, 1993.	Exogenous changes in crop yields based on Rosenzweig and others, 1993.	Exogenous changes in crop yields from crop response models for wheat, rice, maize, and soybeans. Yields of other crop commodities were also changed (based on review of the literature).	Climate change affects productivity of land resources, and water availability
Direct effect of CO_2 on crop growth	Not considered	Simulations without and with CO_2	Simulations with CO_2	Simulations without and with CO_2	Simulations without and with CO_2	Not considered
Farm-level adaptations	Not specifically evaluated	Adaptations reflecting small shift in planting date, increased irrigation for irrigated crops, change in crop variety.	Adaptations reflecting small shift in planting date, increased irrigation for irrigated crops, change in crop variety.	Not considered	Two levels of adaptation: *Level 1*: small shift in planting date, increased irrigation for irrigated crops, change in crop variety; and *Level 2*: large shift in planting date, increased use of fertilizer, installation of irrigation systems, development of new crop varieties	Endogenous adaptations within limits of existing agricultural and silvicultural systems in a region

Climate change scenarios generated by the general circulation models of the Goddard Institute for Space Studies (GISS), the Geophysical Fluid Dynamics Laboratory (GFDL), the United Kingdom Meteorological Office (UKMO), and Oregon State University (OSU).
Compiled by Economic Research Service from studies listed above.

change on field-level crop yields. Typically, a set of yield impacts are estimated that embody various adaptations on the part of farmers to new climatic conditions (for example, shifting planting dates and switching crops or cultivars). The field-level results are then used to estimate national and regional yield impacts, which are plugged directly into economic models as changes in crop productivity.

The most comprehensive use of crop-response models to assess the impacts of climate change on crop yields is reported in Rosenzweig and Iglesias (1994). For 112 sites in 18 countries, crop-response models are run for wheat, maize, rice, and soybeans assuming climate conditions reflecting the GISS, GFDL and UKMO 2xCO_2 scenarios. Other crop-response model results are used to provide information on other crops. These studies are the basis of national and regional climate change impact shocks as developed by Rosenzweig and Parry (1994). Except for Darwin and others (1995), all studies reviewed here borrow climate change impacts on crop yields from Rosenzweig and Parry (1994) and thus are based on the Rosenzweig and Iglesias crop-response studies (table 4.1). Tsigas and others (1996) provide a useful point of comparison. This study uses the yield shocks of Rosenzweig and Parry (1994) with the same basic economic data base and general equilibrium modeling structure as that used by Darwin and others (1995). Thus, the main difference between Tsigas and others (1996) and Darwin and others (1995) is how the initial climate shock affects regional agricultural production potential.

Darwin and others (1995) apply the *spatial analogues* (IPCC, 1994) approach to incorporate climate change impacts into the Future Agricultural Resources Model (FARM) of world agriculture. The spatial analogues approach assumes that the geographic distribution of crops is primarily a function of temperature and precipitation conditions. By matching current crop production patterns with current climate conditions, one can project how current production patterns will change under alternative temperature and precipitation conditions. Darwin and others (1995) extend the spatial analogues approach by allowing all input and output markets to fully adjust to production possibilities associated with new climate conditions.

Direct Effect of Atmospheric CO_2 on Crop Growth. Numerous studies have shown that elevated levels of atmospheric CO_2 boost crop and forest growth rates, and water use efficiency under managed experimental conditions (see chapter 1).

Rosenzweig and others (1993); Reilly, Hohmann, and Kane (1994); and Tsigas, Frisvold, and Kuhn (1996) examine the sensitivity of world agriculture to CO_2 fertilization. All of these studies rely on the crop-response modeling simulations conducted by Rosenzweig and Iglesias (1994). The importance of the CO_2 fertilization effect in these analyses (see table 4.1) in terms of crop yields is demonstrated for the GISS scenario shown in table 4.2. Part A shows that when only changes in regional temperature and precipitation levels are considered, the impact of climate change on crop yields is negative across regions. For the world as a whole, yields fall 16 to 26 percent, depending on the crop. Regional yield effects may vary. In Mexico and the ASEAN region, for example, average rice yields drop by more than 43 and 35 percent. At the other extreme are Canada and the European Union, where decreases in crop yields are never more than 12 percent.

When CO_2 fertilization is accounted for, impacts of climate change on agriculture are far less adverse and in most cases beneficial. With the exception of Mexico and the ASEAN region, the adverse consequences of climate change are largely offset if not reversed (table 4.2, part B).

Farm-Level Adaptations. Increased atmospheric CO_2 levels not only affect global temperature and precipitation patterns, but also cause other changes like shifts in the geographic distributions of agricultural pests. All of these changes taken together are likely to affect the production possibilities associated with agricultural resources in much of the world. Over time, farmers in these areas can be expected to adjust their input/output mix and production technologies to best suit their new climate and economic conditions, as discussed in chapter 2.

Most studies reviewed here allow for some adaptation on the part of farmers to climate change. Rosenzweig and others (1993) incorporate adaptation by exogenously specifying sets of actions that farmers can use to respond to new environmental conditions. Rosenzweig and others (1993) is the most detailed study in this respect because it considers two levels of adaptation. *Minor* (or *level 1*) adaptations reflect actions that today's farmers could easily take and include shifting planting dates 1 month, increasing irrigation water on existing irrigated land, and switching to new, but existing, crop varieties. *Major* (or *level 2*) adaptations include shifting planting dates in excess of 1 month, increasing fertilizer use, expanding irrigation systems, and developing new crop varieties. Reilly and others (1994) and Winters

Table 4.2—Regional crop yield changes for GISS scenario[1] as estimated by Rosenzweig and Parry

	Canada	United States	Mexico	EU	China	ASEAN	Australia	ROW	World
					Percent change				
A. Impacts without the direct effect of CO_2 on crop growth									
Rice	0	-18	-43	0	-24	-35	-13	-26	-26
Wheat	-12	-21	-53	-12	-5	0	-18	-22	-16
Other grains	-5	-20	-43	-8	-21	-40	-16	-16	-18
B. Impacts with the direct effect of CO_2 on crop growth									
Rice	0	1	-24	0	-3	-8	-12	-8	-7
Wheat	27	-2	-31	8	16	0	8	5	6
Other grains	15	-16	-35	1	-14	-33	5	-3	-9

[1] Climate change scenario generated by General Circulation Model of the Goddard Institute for Space Studies (GISS).

Notes: EU denotes the European Union-12. The ASEAN (Association of South East Asian Nations) region consists of Indonesia, Malaysia, the Philippines, Singapore, and Thailand.

Compiled by Economic Research Service from Tsigas and others (1996).

and others (1994) use the yield and supply shocks generated by Rosenzweig and others (1993) and hence they consider the same set of adaptations. These studies have used only the minor (level 1) adaptation scenarios on the assumption that the major (level 2) adaptations would occur only if prices rise sufficiently to justify the additional cost, and adaptations arising from price changes are already reflected in the modeled response of supply to price changes in the economic models used in these studies.

Another method is to make adaptations to climate change endogenous in the economic model. This is the approach taken by Darwin and others. In the FARM model, each region/land-class combination is associated with a unique set of production characteristics—at least with respect to crops, livestock, and forestry. These characteristics reflect differences in land-use patterns as they are determined by land productivity (that is, relative suitability for crops, livestock, and forestry production); crop mixes (for example, wheat-intensive vs. other grains-intensive); and input mixes. Climate change can cause a given tract of land to assume production characteristics that embody all adaptations on the part of crop, livestock, and forestry producers to the new climate conditions.

Specification of Economic Models

The choices of economic framework, region and commodity specification, and frame of reference can all affect model simulation results. However, these differences appear less important in the final result than how the initial climate impacts were estimated. Structural differences in modeling approaches reflect different degrees of regional and crop detail and varying attention to agricultural sector interactions with the rest of the economy or with competing land and water using sectors (table 4.3). As a result, different models have comparative strengths for different purposes. For example, the model of Darwin and others (1995) is unique in that it has a more complete and detailed specification of climate impacts on nonagricultural sectors that compete for agricultural resources such as land and water. Land resources provide the link between economic markets and changes in climate conditions. The Basic Linked System (BLS) model used by Rosenzweig and others (1993) is able to represent dynamic economic response over time. Winters and others (1994) concentrate on modeling interactions of the agricultural and nonagricultural sectors of developing countries and how such economies interact with world markets that are not well captured in global models. The SWOPSIM model used by Kane and others (1991) and Reilly and others (1994) has considerable detail on commodities, including interaction of crop and livestock sectors, while the other models generally treat agricultural sector interactions with the rest of the economy but have less commodity detail.

Results

Climate change may cause significant declines in the productivity of existing agricultural systems in some regions of the world (table 4.2). Results from the six studies reviewed here, however, suggest that the economic impacts of these declines will be largely

Table 4.3--Selected studies estimating the impact of climate change on global agriculture: specification of economic models

	Kane and others, 1991	Reilly and others, 1994	Winters and others, 1994	Tsigas and others, 1996	Rosenzweig and others, 1993	Darwin and others, 1995
Economic model	Static World Policy Simulation (SWOPSIM) Model: comparative statics, multi-product, multi-region, partial equilibrium	Static World Policy Simulation (SWOPSIM) Model: comparative statics, multi-product, multi-region, partial equilibrium	3 archetype, comparative statics, general equilibrium models	Global Trade Analysis Project (GTAP) Model: comparative statics, multi-region, general equilibrium	Basic Linked System (BLS): multi-region, general equilibrium, sequenced through time to obtain series of temporary equilibria	Future Agricultural Resources Model (FARM): comparative statics, multi-region, general equilibrium
Benchmark	1986	1989	2050	1992	2060	1990
Regions	13 regions: USA, Canada, European Union-12, N. Europe, Japan, Australia, China, Former Soviet Union, Brazil, Argentina, Pakistan, Thailand, Rest-of-World	33 regions: USA, Canada, European Union, Other W. Europe, Japan, Australia, N. Zealand, S. Africa, E. Europe, Former Soviet Union, China, Mexico, C. America & Caribbean, Brazil, Argentina, Venezuela, Other Lat. America, Nigeria, Other Sub-Saharan Africa, Egypt, Middle East & N. Africa-Oil, Other Middle East & N. Africa, India, Other S. Asia, Indonesia, Thailand, Malaysia, Philippines, Other SE Asia, S. Korea, Taiwan, Other E. Asia, Rest-of-World	representative of low income, cereal importing countries in Africa, Asia, and Latin America	8 regions: Canada, USA, Mexico, European Union-12, China, Association of South East Asian Nations (ASEAN), Australia, Rest-of-World	34 regions: USA, Canada, European Union-12, E. Europe & Former Soviet Union, Japan, Australia, China, India, Brazil, Argentina, Pakistan, Thailand, Kenya, Mexico, Nigeria, Austria, N. Zealand, Egypt, Turkey, Indonesia, 5 Regions for Africa, 3 Regions for Other Latin America, 5 Regions for Other Asia, and Rest-of-World	8 regions: USA, Australia & New Zealand, Canada, Japan, Other East Asia, Southeast Asia, European Union-12, Rest-of-World
Commodities	22 farm & food commodities: cotton, sugar, tobacco and livestock, cereals, and oil crops commodities	22 farm & food commodities: cotton, sugar, tobacco and livestock, cereals, and oil crops commodities	8 commodities for Africa and Asia: cash crops, food crops, other agriculture, agricultural processing, energy, manufactures, construction & services, government services. 7 commodities for Latin America: cash crops, other agriculture, oil & minerals, other energy, manufactures, construction & services, government services	8 commodities: rice, wheat, other grains, other crops, livestock, processed agriculture, manufactures, services	10 commodities: wheat, rice, coarse grains, protein feeds, red meats, dairy products, other animal products, other food, non-food agriculture, non-agriculture	13 commodities: wheat, other grains, non-grain crops, livestock, forestry, energy mining, other minerals, fish-meat-milk, other proc. foods, textiles etc, other non-metallic manufactures, other manufactures, services

Compiled by Economic Research Service from studies listed above.

Table 4.4—Kane and others study: regional welfare impacts

Country/region	Welfare impact	
	Million 1986 $US	*Percent GDP*
United States	194	0.005
Canada	-167	0.047
European Union-12	-673	0.019
Northern Europe	-51	0.010
Japan	-1,209	0.062
Australia	66	0.038
China	2,882	1.280
Former Soviet Union	658	0.032
Brazil	-47	0.017
Argentina	95	0.120
Pakistan	-50	0.153
Thailand	-33	0.081
Rest of world	-67	0.002
World total	1,509	0.010

Compiled by Economic Research Service from Kane and others (1991).

offset through farm-level adaptations, international trade, and CO_2 fertilization. We first review the aggregate impacts of climate change on world welfare and world agriculture; we then consider some regional results. Next, we discuss some environmental impacts that would be consistent with study results. Finally, we consider the potential roles that CO_2 fertilization and adaptation might play in mitigating any negative impacts climate change might have on existing agricultural systems.

Global Impacts. Tables 4.4 - 4.7 detail aggregate regional and world economic impacts associated with various climate change scenarios. These results suggest that the impact of climate change on world agriculture and welfare will likely be small; whether these impacts are positive or negative, however, depends on the scenario considered and the underlying assumptions concerning CO_2 fertilization, and farm-level adaptation.

For their moderate-impacts climate change scenario, Kane and others (1991) find that world gross domestic product (GDP) increases by 0.01 percent (US$ 1.5 billion in 1986) (table 4.4). Effects on global GDP in Tsigas and others (1996) and Darwin and others (1995) are of similar magnitude. For the GISS climate change scenario and allowing for CO_2 fertilization, Tsigas and others estimate that global GDP would increase 0.007 percent (US$ 1.5 billion in 1992) (table 4.6, part B). Darwin and others find that under the GISS, GFDL, UKMO, and OSU scenarios, impacts on 1990 world GDP are 0.01, -0.01, -0.12, and 0.12 percent (table 4.7, part A).

The most pronounced climate change impacts on the world economy are reported by Reilly and others

Table 4.5—Reilly and others study: welfare impacts for selected regions by climate change scenario

Country/region	No CO_2, no adaptation			With CO_2, no adaptation			With CO_2 and adaptation		
	GISS	GFDL	UKMO	GISS	GFDL	UKMO	GISS	GFDL	UKMO
					Million 1989 US$				
United States	7,048	6,228	5,413	-775	1,374	-4,586	253	-667	-788
Canada	1,696	3,836	2,073	-9	848	896	-56	390	593
European Union-12	-11,051	-16,384	-11,476	2,228	-1,487	-6,051	3,381	628	-2,890
Japan	-12,827	-19,809	-29,082	1,290	-2,016	-7,839	2,170	-501	-4,686
Australia	4,450	7,868	18,585	-47	887	3,768	-116	378	2,206
China	-34,549	-43,603	-66,708	1,039	80	-275	2,535	2,199	3,183
Former Soviet Union	-8,866	-21,292	-49,166	1,367	-1,502	-10,403	1,859	-293	-5,020
Brazil	-2,666	672	-374	-319	19	-150	-486	-194	-908
Argentina	3,242	3,775	11,419	-373	151	3,782	-579	-107	2,039
Thailand	116	2,190	1,312	215	655	463	141	398	281
Rest of world	-62,064	-72,121	-130,120	-4,742	-13,289	-40,830	-2,099	-8,366	-31,633
World total	-115,471	-148,640	-248,124	-126	-17,028	-61,225	7,003	-6,135	-37,623

[1] Climate change scenarios generated by General Circulation Models of the Goddard Institute for Space Studies (GISS), the Geophysical Fluid Dynamics Laboratory (GFDL), and the United Kingdom Meteorological Office (UKMO).

Note: figures for rest-of-the-world calculated from data in Reilly and others (1994).

Compiled by Economic Research Service from Reilly and others (1994).

Table 4.6—Tsigas and others study: regional welfare impacts and change in consumer prices for GISS scenario

Impact	Canada	United States	Mexico	EU	China	ASEAN	Australia	ROW	World
A. With yield impacts which do not account for direct effect of CO_2 on crop growth									
					Percent change				
Consumer prices	1.57	1.14	7.58	1.46	13.29	8.68	2.19	3.16	na
Welfare change	-0.02	-0.56	-6.70	-1.02	-7.23	-7.59	-0.21	-2.48	-1.75
					$				
Welfare change	-93	-29,499	-20,356	-60,323	-33,596	-28,149	-533	-180,957	-353,505
B. With yield impacts which account for direct effect of CO_2 on crop growth									
					Percent change				
Consumer prices	0.16	0.01	2.35	-0.01	-0.20	0.84	0.04	0.07	na
Welfare change	0.50	0.04	-2.78	0.29	0.54	-1.73	0.26	-0.12	0.007
					$				
Welfare change	2,629	2,026	-8,273	17,253	2,397	-6,216	681	-8,958	1,539

Notes: Welfare change in dollars is in millions of 1990 US dollars and as a percent of 1990 GDP.A consumer price index was not calculated for the world as whole. EU denotes the European Union-12.The ASEAN (Association of South East Asian Nations) region consists of Indonesia, Malaysia, the Philippines, Singapore, and Thailand.

Compiled by Economic Research Service from Tsigas and others (1996).

Table 4.7—Darwin and others study: regional welfare impacts by climate change scenario

Scenario[1]	United States	Canada	EU	Japan	OEA	SEA	ANZ	ROW	World
				Billion 1990 $US (Percentage of 1990 GDP)					
A. Simulations with unrestricted land use									
GISS	5.7 (0.1)	11.3 (1.9)	-56.5 (-0.9)	23.1 (0.8)	3.0 (0.4)	-2.7 (-0.9)	.3 (0.1)	17.9 (0.4)	2.2 (0.01)
GFDL	-4.8 (-0.1)	13.6 (2.3)	-42.1 (-0.7)	17.2 (0.6)	3.1 (0.4)	-3.9 (-0.6)	-.9 (-0.2)	13.1 (0.3)	-2.6 (-0.01)
UKMO	1.2 (0.0)	16.5 (2.8)	-63.2 (-1.1)	10.0 (0.3)	3.1 (0.4)	-3.9 (-1.3)	-1.6 (-0.4)	13.4 (0.3)	-24.5 (-0.1)
OSU	-3.9 (-0.1)	11.0 (1.9)	-20.5 (-0.3)	21.6 (0.7)	1.6 (0.2)	-.5 (-0.2)	3.0 (0.8)	12.9 (0.3)	25.2 (0.1)
B. Simulations with restricted land use									
GISS	5.9 (0.1)	10.4 (1.7)	-68.0 (-1.1)	18.1 (0.6)	1.5 (0.2)	-4.6 (-1.6)	.7 (0.2)	9.6 (0.2)	-26.3 (-0.1)
GFDL	-11.1 (-0.2)	11.6 (2.0)	-52.3 (-0.9)	8.7 (0.3)	.2 (0.0)	4.0 (-1.3)	-.4 (-0.1)	4.7 (0.1)	-42.6 (-0.3)
UKMO	-1.2 (-0.0)	14.1 (2.4)	-77.4 (-1.3)	1.3 (0.0)	-1.4 (-0.2)	-7.8 (-2.6)	-.7 (-0.2)	-1.2 (-0.0)	-74.3 (-0.3)
OSU	-6.6 (-0.1)	9.6 (1.6)	-27.0 (-0.5)	15.5 (0.5)	-.3 (-0.0)	-1.9 (-0.6)	3.5 (1.0)	6.3 (0.1)	-.7 (-0.0)

[1] Climate change scenarios generated by General Circulation Models of the Goddard Institute for Space Studies (GISS), the Geophysical Fluid Dynamics Laboratory (GFDL), the United Kingdom Meteorological Office (UKMO), and Oregon State University (OSU).

Notes: EU denotes the European Union-12; OEA denotes Other East Asia; SEA denotes South East Asia; and ANZ denotes the aggregate of Australia and New Zealand.

Compiled by Economic Research Service from Darwin and others (1995).

Table 4.8—Reilly and others study: percentage change in world prices for agricultural and food commodities by climate change scenario[1]

Commodity	With CO_2, no adaptation			With CO_2 and adaptation		
	GISS	GFDL	UKMO	GISS	GFDL	UKMO
	Percent change					
Beef	0.74	2.19	4.82	-0.39	0.98	2.68
Pork	1.38	6.62	16.33	-1.76	2.79	9.27
Lamb	-0.14	0.14	0.41	-0.51	-0.02	-0.33
Poultry meat	1.84	6.88	16.43	-1.52	2.95	9.22
Poultry eggs	1.00	5.58	13.96	-1.60	2.33	7.86
Butter	-0.56	-1.94	-3.79	-0.05	-0.97	-2.72
Cheese	0.04	0.28	0.75	-0.15	0.10	0.36
Milk powder	0.40	1.55	3.28	-0.17	0.72	2.06
Wheat	-17.83	20.41	88.20	-21.84	2.18	49.70
Maize	24.35	43.80	91.66	1.30	19.59	44.21
Sorghum	1.02	27.19	74.10	-6.72	12.79	42.35
Rice	34.01	41.17	109.12	24.15	22.84	78.09
Soybeans	-17.14	-3.66	63.42	-20.26	-7.15	28.31
Soybean meal	0.45	10.22	37.22	-5.51	3.49	19.14
Soybean oil	-19.04	-11.21	27.76	-18.57	-10.50	12.92
Groundnuts	-21.38	-8.90	36.19	-22.76	-11.96	23.48
Groundnut meal	-2.71	6.80	30.15	-7.27	1.05	17.44
Groundnut oil	-12.22	-6.19	14.31	-12.43	-6.97	9.51
Cotton	-21.32	-12.09	42.47	-22.22	-14.23	26.61
Sugar	16.30	25.99	87.29	14.48	20.10	78.15
Tobacco	-26.43	-13.90	28.11	-42.02	-32.89	-5.39

[1] Climate change scenarios generated by General Circulation Models of the Goddard Institute for Space Studies (GISS), the Geophysical Fluid Dynamics Laboratory (GFDL), the United Kingdom Meteorological Office (UKMO), and Oregon State University (OSU).
Compiled by Economic Research Service from Reilly and others (1994).

(1994) and are based on the crop response impacts of Rosenzweig and Parry (1994). Given world agriculture as it existed in 1989 and allowing for both CO_2 fertilization and minor farm-level adaptations, these authors estimate that world GDP would increase US$ 7 billion under the GISS scenario; they also find that world GDP would decrease US$ 6.1 billion and US$ 37.6 billion under the GFDL and UKMO scenarios (table 4.5, column 3). While the magnitudes of these impacts are larger than those reported in the other studies, they are still less than 0.2 percent of 1989 world GDP.

Tables 4.8 - 4.10 present climate change impacts on world commodity markets. These results, along with results in Kane and others (1991) and Rosenzweig and others (1993), suggest that climate change is unlikely to severely disrupt global food production.

For their moderate-impacts scenario, Kane and others find that world crop prices decline an average of 4 percent (see table 6 in Kane and others). Two important exceptions, however, are maize and soybeans; world prices for these crops increase 9.2 and 10.2 percent. Because maize and soybeans are important feed crops, world prices for livestock commodities rise between 0.1 and 0.6 percent. Given the inelastic nature of aggregate food demand, Kane and others conclude that the price changes obtained in their climate change simulation would have relatively little effect on global consumption and production of agricultural commodities. This result is obtained by all studies reviewed here.

As with the net global economic impacts discussed above, global commodity market effects in Reilly and others (1994) are more pronounced than those in Kane and others. While the two studies use similar economic models, their results are not directly

Table 4.9—Tsigas and others study: world production and price impacts for GISS scenario[1]

Impact	Rice	Wheat	Other grains	Other crops	Livestock	Processed agriculture	Manufact.	Services
				Percent change				
A. With yield impacts which do not account for direct effect of CO_2 on crop growth								
World production	-4.69	-4.37	-3.03	-2.02	-2.31	-3.33	-0.85	-0.84
World price	59.31	30.98	36.99	39.78	8.98	8.26	0.20	0.08
B. With yield impacts which account for direct effect of CO_2 on crop growth								
World production	-0.35	-0.54	1.85	-0.33	0.07	-0.15	0.01	0.02
World price	10.18	-7.31	14.59	-6.50	1.02	0.30	0.03	0.05

[1] Climate change scenario generated by General Circulation Model of the Goddard Institute for Space Studies (GISS).

Notes: EU denotes the European Union-12. The ASEAN (Association of South East Asian Nations) region consists of Indonesia, Malaysia, the Philippines, Singapore, and Thailand.

Compiled by Economic Research Service from Tsigas and others (1996).

comparable, because Reilly and others analyze GCM, not generic, scenarios; and they allow for CO_2 fertilization effects and minor farm-level adaptation. With these allowances, Reilly and others find that world crop prices generally move in the same direction under the GISS and GFDL scenarios (table 4.8). Specifically, prices for soybeans, cotton, groundnuts, and tobacco fall, while prices for rice, sugar, and maize rise (table 4.8). Price movements of 10 to 24 percent are common. Prices for wheat and sorghum (allowing for adaptation) fall in the GISS scenario and rise in the GFDL scenario. Under the UKMO scenario, prices for all crops increase and these increases are always larger in magnitude than under the GISS and GFDL scenarios (5 of 9 crop commodities have price increases over 40 percent). For livestock commodities, Reilly and others obtain similar results with the GFDL and UKMO scenarios. For these scenarios, prices rise for most livestock commodities, though the magnitude of the price changes are generally less than 3 percent. Again, the magnitudes of the price effects are always larger in the UKMO scenario. In the GISS scenario, all livestock commodity prices decrease. Rosenzweig and others (1993) find similar results using the same yield impacts, focusing their analysis of global impacts on how climate change might affect the world market for cereals. In simulations that account for CO_2 fertilization and minor farm-level adaptation, world cereals prices increase by 10, 24, and 100 percent under the GISS, GFDL, and UKMO scenarios. The respective declines in world cereals production, however, are much less: 0.0, 1.5, and 5.0 percent.

World crop commodity impacts reported in Tsigas and others (1996) are qualitatively consistent with the GISS results in Reilly and others (1994). For this scenario and allowing for CO_2 fertilization, Tsigas and others find that the world price of wheat declines by 7.3 percent while the prices of rice and other grains increase 10.2 and 14.6 percent (table 4.9, part B). For livestock and processed food commodities, Tsigas and others find that world prices increase 1.0 and 0.3 percent. These results are not significantly different from the results of Reilly and others (1994), who find that world prices for processed livestock and food commodities increase under the GISS scenario that does not allow for adaptation (table 4.8). Tsigas and others (1996) is a useful comparison between crop-response estimates and Darwin and others' (1995) spatial analogue approach because both studies use the Global Trade Analysis Project (GTAP) economic database and modeling framework (Hertel, 1996). Thus, differences in the results represent primarily differences in how climate change impacts are estimated.

Darwin and others (1995) find that climate change is not likely to imperil global food production (table 4.10, part A). Across the four GCM scenarios analyzed, production of wheat and livestock increase (the respective ranges are 0.47 to 3.3 percent, and 0.72 to 0.90 percent), while production of nongrains decreases (between 0.17 and 1.25 percent). Production of other grains increases for three scenarios (the range is from 0.29 to 0.41 percent) but decreases for the OSU scenario by 0.12 percent. Finally, production in both processed food sectors

Table 4.10—Darwin and others study: percentage changes in world production and prices by climate change scenario

Commodity	Scenario[1] GISS Quantity	GISS Price	GFDL Quantity	GFDL Price	UKMO Quantity	UKMO Price	OSU Quantity	OSU Price
A. Simulations with unrestricted land use								
Wheat	1.920	-2.481	0.471	-7.771	3.293	-9.704	0.781	-4.586
Other grains	0.409	-3.468	0.287	-4.309	0.320	-6.426	-0.115	-1.022
Nongrains	-0.505	0.540	-0.432	2.949	-1.252	4.407	-0.170	0.217
Livestock	0.858	-1.855	0.744	-1.928	.0.899	-2.735	0.723	-1.169
Forestry	0.274	-1.658	0.007	-0.093	-0.014	-1.022	0.144	-0.413
Coal/oil/gas .	0.182	-0.087	0.097	-0.071	0.101	-0.138	0.145	-0.022
Other minerals	-0.409	0.157	-0.280	0.108	-0.439	0.109	-0.089	0.091
Fish/meat/milk	0.371	-0.387	0.273	-0.489	0.310	-0.677	0.294	-0.224
Other processed food	0.382	-0.824	0.161	-0.758	0.225	-1.032	0.260	-0.616
Textiles/clothing/footwear	0.120	-0.049	0.049	0.104	-0.022	0.100	0.190	-0.016
Other nonmetal manufacturing	0.098	-0.047	0.062	-0.004	-0.006	-0.046	0.162	-0.005
Other manufacturing	0.114	0.036	0.060	0.042	0.001	0.046	0.156	0.043
Services	0.023	0.044	-0.003	0.013	-0.107	0.022	0.122	0.020
B. Simulations with restricted land use								
Wheat	0.625	7.554	-0.971	0.584	1.171	3.751	-0.395	0.512
Other grains	0.006	-0.593	-0.434	1.528	-0.811	0.480	-0.532	2.399
Nongrains	-1.250	2.871	-0.596	5.711	-2.633	8.565	-0.417	2.316
Livestock	0.589	-0.851	0.340	-0.369	0.383	-0.871	0.786	-0.529
Forestry	0.117	-1.794	-0.190	0.594	-0.342	-0.986	0.027	-0.474
Coal/oil/gas	0.001	-0.090	-0.155	-0.086	-0.223	-0.162	-0.004	-0.026
Other minerals	-0.467	0.085	-0.432	0.064	-0.596	0.018	-0.186	0.066
Fish/meat/milk	-0.013	0.537	-0.207	0.763	-0.349	0.927	-0.002	0.524
Other processed food	-0.140	0.299	-0.406	0.780	-0.580	0.863	-0.070	0.330
Textiles/clothing/footwear	-0.171	0.073	-0.332	0.306	-0.509	0.324	-0.049	0.107
Other nonmetal manufacturing	-0.107	-0.021	-0.208	0.042	-0.346	0.011	-0.002	0.018
Other manufacturing	0.011	0.000	-0.095	-0.015	-0.179	-0.014	0.066	0.012
Services	-0.068	0.035	-0.147	-0.022	-0.271	0.007	0.032	0.010

[1] Climate change scenarios generated by General Circulation Models of the Goddard Institute for Space Studies (GISS), the Geophysical Fluid Dynamics Laboratory (GFDL), the United Kingdom Meteorological Office (UKMO), and Oregon State University (OSU).
Compiled by Economic Research Service from Darwin and others (1995).

increase across scenarios (the range is from 0.16 to 0.38 percent).

Regional Impacts. While climate change may have only marginally detrimental impacts on world agriculture, from a policy perspective, it is regional impacts that will shape strategies to address climate change. The studies examined here suggest that regional impacts will be more pronounced than global impacts. All studies find that climate change will hurt Southeast Asia and will benefit Japan and China. For most regions, however, the magnitude and direction of the economic impact of climate change vary from study to study and thus depend on assumptions made by the authors.

In any particular region, the economic impacts of climate change will depend on the direct effects of climate change on crop yields, the ability of producers to adjust to new climatic conditions, and trade relationships with other regions. The importance of world commodity markets in promoting interregional adjustments in production and consumption can be illustrated by comparing results in Kane and others (1991) with findings in studies that consider impacts of climate change on one country. Adams and others (1988), for example, examine the economic effects of climate change on U.S. agriculture assuming no other regions or economic sectors are affected. For the GISS and GFDL scenarios, Adams and others conclude that the United States loses about $7 billion and $34 billion. Under their moderate-impacts scenario, which was based in large part on the GISS and GFDL scenarios, Kane and others find that the United States would gain about $0.2 billion.

A relatively common result across studies is that developing regions, as a group, will be hurt by climate change. Reilly and others (1994) show that even under the GISS scenario with CO_2 fertilization and adaptation (where the global welfare impact is positive), developing countries as a group suffer economic losses. Individual developing countries, however, may experience economic impacts that differ from those indicated by the aggregate results (table 4.5). Argentina, which is a net exporter of crops, gains under all three scenarios not accounting for CO_2 fertilization and adaptation; but Argentina loses under the mildest scenario (GISS) when CO_2 fertilization and adaptation are taken into account (table 4.5). This perverse result comes about under more severe climate change scenarios because other regions are unable to supply grains, world prices rise, and Argentina is a world grain exporter. When other regions are able to supply grains, world prices are depressed and Argentina experiences an economic loss. The opposite is true for the former Soviet Union.

Winters and others (1994) find that the GISS, GFDL, and UKMO scenarios induce GDP losses for low-income, cereal-importing countries in Africa, Latin America, and Asia. These losses are largest in Africa, ranging between 6.5 and 9.5 percent. For Latin America and Asia, the reductions in GDP range from 2.1 to 6.4 percent, and from 0.2 to 3.1 percent. The relatively large economic impact for Africa reflects the authors' assumptions regarding economic conditions in 2050: (1) with no prospects for growth, the agricultural sector generates a large portion (about 38 percent) of GDP, even in the year 2050; (2) world prices of competing cash crops are projected to decline due to global climate change; (3) agricultural production in Africa has small supply response; and (4) consumers in Africa cannot take advantage of relatively cheaper food imports due to a low elasticity of substitution between imported and domestic foods.

The Asian countries suffer less than Latin American countries, even though the Asian agricultural sector is projected to remain important in the year 2050 (accounting for 18 percent of GDP), whereas in Latin America it accounts for 7.6 percent. These results suggest that the degree of dependence of an economy on agriculture is a relevant consideration, but it is equally important that an economy have the capacity to substitute for more expensive domestic foods with less expensive imported foods.

Results in Tsigas and others (1996) suggest that consumers in most regions will have to pay higher prices, with consumers in Mexico and the ASEAN region paying 2.3 and 0.8 percent more (table 4.6 part B). Consumer prices in China are projected to decline by 0.2 percent. Overall, welfare in Mexico and the ASEAN region is estimated to decline by 2.7 and 1.7 percent. All other regions will experience a relatively small increase in welfare, measured as a change in real income, ranging from 0.04 percent for the United States to 0.54 percent for China. Welfare in the Rest-of-the-World region will decline by 0.12 percent. The two extreme cases in Tsigas and others are Canada and Mexico. Canada is a net exporter of agricultural commodities and it gains the most in crops productivity due to climate change (see table 4.2, part B). Mexico, on the other hand, is a net importer of agricultural commodities and it loses the most in productivity. In Canada, agricultural production increases, and the nonfood part of the economy shrinks. Consumer prices increase because nonfood prices increase, but gains in producer surplus offset loses in consumer surplus and welfare increases by about $US 2.6 billion. In Mexico, agricultural production declines, but the nonfood part of the economy shrinks too. Consumer prices increase because food prices increase; both producers and consumers lose and welfare declines by $US 8.3 billion.

Finally, Darwin and others (1995) find that there are significant differences in regional welfare impacts. Canada, Japan, Other East Asia, and the Rest-of-the-World are projected to benefit from climate change under all scenarios (table 4.7, part A). The European Union and Southeast Asia are projected to lose from 0.3 to 1.1 percent, and from 0.2 to 1.3 percent of GDP. The direction of welfare impacts for the U.S. and the aggregate region of Australia and New Zealand varies from scenario to scenario, but welfare impacts are no more than 0.1 percent of GDP for the United States, and no more than 0.8 percent of GDP for Australia and New Zealand.

Agriculture and the Environment. Aside from exogenously specified shifts in global temperature and precipitation patterns, the six studies reviewed here do not explicitly consider any other environmental implications of climate change. Land-use results in Darwin and others (1995), however, do provide some insights. Globally, Darwin and others identify 43 unique region/land-class combinations, some of which match up reasonably well with broad ecosystem types. For example, an area of about 2.27 billion hectares is assigned to land class 1, which mainly represents arctic and alpine areas where cold temperatures limit growing seasons to a maximum of 100 days.[18] For the four climate change scenarios analyzed by Darwin and others, the global endowment of land class 1 is projected to decline by 32.57 to 62.45 percent (see table 13 in Darwin and others). Hence, this result suggests that climate change may severely stress many arctic and alpine ecosystems.

Darwin and others (1995) assign an area of about 2 billion hectares to land class 6 in the Rest-of-World region, which mainly represents tropical moist forest systems. Across scenarios, this region/land-class combination declines by 18.4 to 51.0 percent. Hence, it appears that climate change may stress many tropical forest ecosystems. Furthermore, when Darwin and others investigate changes in land-use patterns in the Tropics, they find that increased competition from agriculture could aggravate any climate-induced losses of tropical moist forests (see Darwin and others, page 31).

With respect to agricultural resources, Darwin and others find that more land and water will be devoted to agricultural production due to climate change. Depending on the scenario considered, global cropland increases by 7.1 to 14.8 percent and global pasture increases by 1.5 to 4.7 percent. Changes in total crop and livestock production, however, range from -0.3 to zero percent and from 0.7 to 0.9 percent. These results suggest that while climate change may increase the global area of land suitable for agriculture, this land may be less productive (that is, lower average yields per hectare). As for water, Darwin and others find that global supplies (which depend on runoff and regional storage capacities) increase by 6.4 to 12.4 percent across scenarios. Furthermore, of 32 scenario-region combinations analyzed (4 GCM scenarios and 8 regions), there are only 5 cases where a region's water supply decreases (see table 16 in Darwin and others).

[18] Darwin and others do not consider Antarctica in their study.

CO_2 Effects on Crop Growth. There is considerable uncertainty regarding the direct impact of a 2xCO_2 climate on existing agricultural systems. However, it is generally believed that the direct effect of CO_2 on crop growth positively affects world agriculture (Reilly and others (1994), Rosenzweig and others (1993), and Tsigas and others (1996)). Inclusion of the CO_2 fertilization effect reduces losses $115-$190 billion in Reilly and Hohmann (1993). Gains from CO_2 fertilization amount to $355 billion for the world as a whole in Tsigas and others for the GISS scenario (table 4.6, part A+part B). However, there remains scientific debate about the CO_2 effect. Issues include the extent to which the full effect will be realized in a commercial agriculture setting; how it may affect different regions and crops depending, for example, on nutrient availability, farm management, crop species, and competing weed varieties; and the broader effects of elevated CO_2 on, for example, water use and yield quality. Resolving these issues will be important for resolving how climate change as caused by elevated atmospheric CO_2 will affect agriculture.

Adjustments and Adaptations. Results in Tsigas and others (1996) and Darwin and others (1995) provide estimates of the impacts of different assumptions concerning the degree of adaptation and adjustment in modeling climate change. Tsigas and others examine the GISS scenario, which does not incorporate the direct effects of CO_2 on crop growth, and they find that global welfare declines by $353 billion (1990 $US) (table 4.6, part A). The model in Darwin and others allows land-intensive sectors a greater degree of adjustment in response to climate change. For the GISS scenario, Darwin and others find that global welfare increases by $2.2 billion (1990 $US) (table 4.7). These results suggest that longrun adjustments in global agriculture have the potential to significantly offset direct climatic effects. The long run refers generally to the time to CO_2 doubling (see fig. 1). Tsigas and others do not consider farm-level adaptation either. These results can also be contrasted with those of Reilly and others (1994) who compare scenarios with and without farm-level adaptation (level 1 as specified by Rosenzweig and Parry, 1994) in both cases with the direct effect of CO_2 on crop growth. They find that these farm-level adaptations reduce global losses by $7-$25 billion (1989 $US).

For some regions, the difference in results is more pronounced than for the world as a whole: Southeast Asia loses only 0.9 percent of 1990 GDP in Darwin and others (table 4.7, part A), but it loses 7.59 percent in Tsigas and others; Canada gains 1.9 percent in Darwin and others, but it loses 0.02 percent in Tsigas and others. On the other hand, the European Union loses 0.9 percent in Darwin and others and 1.02 percent in Tsigas and others.

Darwin and others (1995) specifically address the potential for changes in land use, whereas this is not explicit in the other studies. They find that the world, as a whole, suffers greater losses due to climate change when land-use patterns are constrained (table 4.7, part B) as would be expected, but the magnitude of the additional loss is not large: for example, for the UKMO scenario, the global welfare loss increases from 0.12 percent to 0.35 percent of 1990 GDP. Regional welfare impacts do not seem to be influenced a great deal by the assumption of unrestricted land use. The importance of this consideration is that detailed global data on soil quality is not available. An ongoing concern of researchers doing agricultural impact studies is that while climatic zones may shift northward, the soils in northern regions such as Canada and Russia may not be highly productive or that land-use change would not be possible because of the desire to maintain the status quo of currently uncropped areas. Darwin and others (1995) estimate impacts constraining agricultural production to current cropland area as an upper-bound estimate of losses if no expansion onto new land is possible. Their unconstrained case is a lower-bound estimate of losses (upper-bound estimate of gains) if expansion is possible and soil quality in newly cropped areas allows a sustainable level of productivity.

The studies reviewed here suggest that climate change may adversely affect agriculture, or at least important components of agriculture, in some regions of the world. Thus, it is plausible that some agricultural interest groups may pursue government intervention rather than switching to alternative input/output mixes and production technologies. From a policy perspective, it is important to determine the impacts of climate change on agriculture under alternative trade policy regimes.

Rosenzweig and others (1993) examine the impacts of climate change under freer trade policies. They establish an alternative baseline scenario where, in addition to population and economic growth, they considered *full* agricultural trade liberalization. They find that the negative impact of climate change on global cereals production is slightly reduced by trade liberalization.

Summary and Conclusions

This chapter has reviewed six studies that assess the economic impact of climate change on agriculture taking into consideration international trade. All studies are based on projections of Earth's climate under an atmospheric CO_2 level that is twice current levels. The climate scenarios are derived from popular General Circulation Models (GCM's). Most authors use crop-response models to estimate impacts of climate change on crop yields; they also estimate crop yield impacts that embody adaptations on the part of farmers to new climatic conditions. One study assumes that the geographic distribution of crops is primarily a function of temperature and precipitation conditions. Hence, by matching current crop production patterns with current climate conditions, the authors project how current production patterns would change under alternative climate conditions. The major findings of these studies may be summarized as follows:

- Some declines in the productivity of regional agricultural systems can be expected, but these declines will be offset by productivity gains in other regions. Thus, the global economic impact of climate change on world agriculture will likely be small.

- Regional economic impacts of climate change will likely be more pronounced than global impacts and it is almost certain that some regions will lose relative to others. For example, studies suggest that Southeast Asia will be hurt by climate change while China and Japan will benefit. For most regions, however, the magnitude and direction of the economic impact of climate change vary from study to study. Because negative economic impacts are likely to generate pressure on governments to protect domestic producers and/or consumers with domestic and border policies, policymakers should know what conditions suggest negative impacts for their region.

- Climate change will likely stress several natural ecosystems because it will alter temperature and precipitation patterns, and lead to changes in land-use patterns. Tropical and arctic ecosystems appear to be particularly vulnerable.

- Most recent studies have addressed adaptation. The most recent study investigating the longrun potential to adapt suggests that economically viable adaptation is able to offset most losses due to climate change even without considering the beneficial effect of CO_2. The longrun equilibrium nature of the study does not allow the investigation of adjustment costs. Now that studies have been conducted with minimal adaptation and with longrun adaptation, it is possible to bracket the potential contribution of adaptation to mitigating the negative impacts of climate change or enhancing the positive effects.

- Estimates of the economic impacts of climate change on world agriculture are subject to several uncertainties. In particular, there is much debate regarding the magnitude of any CO_2 fertilization effect on crop productivity. If this effect approximates what has been used in economic models to date, climate change will positively affect world agriculture on average. Another important uncertainty is the amount of land that warmer climates might make suitable for agricultural production (primarily in the northern latitudes). Finally, there are no good estimates of the transient effects of climate change. All studies reviewed are based on a doubled CO_2 climate, which is not likely to occur until near or after 2100.