7.2 Impacts of Rising Concentrations of Greenhouse Gases

Due to climatic and other consequences, rising greenhouse gas concentrations affect agricultural and ecological resources worldwide. Some areas incur benefits, while other areas suffer losses. The precise location and magnitude of such changes is highly uncertain. The extent to which losses are avoided and gains obtained will depend on how farmers adapt their production processes to new climatic and other conditions.

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Atmospheric concentrations of greenhouse gases such as carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O), have increased since the Industrial Revolution. Major human sources of these greenhouse gases are the combustion of fossil fuels, deforestation that accompanies the expansion of agricultural land, as well as rice and livestock production. (See box, "Trends in Greenhouse Gas Concentrations".) Changes in the atmospheric concentration of these gases affect agricultural and environmental resources worldwide. In the short term, increasing the atmospheric concentration of CO_2 enhances the agricultural productivity of land resources because of its direct beneficial effects on crop growth. Over the long run, increasing concentrations of greenhouse gases modify the extent and productivity of agriculture indirectly due to their warming effect on Earth's climate. (See box, "Greenhouse Gas Concentrations and Climate Change".) The impacts of global warming on land, water, and biological resources vary from one location to another around the world. Some areas benefit, while other areas suffer damages. Because of the potential economic and ecological damages of global climate change, the world community of nations initiated the United Nations Framework Convention on Climate Change (FCCC) in 1992. (See box, "Governmental Response to Climate Change".)

Agricultural Impacts of Greenhouse Gases

An increase in atmospheric CO_2 enhances the agricultural productivity of land resources because of its direct beneficial effects on crop growth. Over the long run, however, increasing concentrations of greenhouse gases warm Earth's climate and thereby modify the potential extent and productivity of agriculture. The direct effects of CO_2 on plant growth and the indirect effects of climate change also will modify the potential extent and productivity of Earth's ecosystems. Human responses to changing agricultural opportunities will interact with ecosystems, as well.

Direct Effects of Atmospheric CO_2 on Crop Growth

Higher levels of CO_2 in the atmosphere tend to increase plant growth (Reilly et al., 1996). This "fertilization" effect is due to CO_2's influence on water use and photosynthesis. Stomata, cellular pores which are located primarily on leaves, control the passage of water vapor and other gases from plants to the atmosphere and vice versa. The size of the stomatal openings is negatively correlated with the atmospheric concentration of CO_2. That is, the higher the level of CO_2, the smaller the stomatal openings and the slower the rate of transpiration (the loss of water vapor from the plant). Hence, elevated CO_2 increases water use efficiency of plants per unit of leaf area, which tends to reduce water requirements and yield loss due to water stress. Water use efficiency per unit of ground area, however, is much less affected and may even increase if leaf area sufficiently increases (Reilly et al., 1996).

Photosynthesis is the process whereby plants combine solar energy with water (generally from the soil) and CO_2 from the air to produce glucose, a simple sugar. When classified by photosynthetic pathways, crops are generally divided into two groups—C3 or C4—depending on the number of carbon atoms in the first compound into which CO_2 is incorporated during photosynthesis. Experimental yield responses for C3 crops (e.g., wheat, rice, barley, oats, potatoes, and most other crops) to 700 parts per million by volume (ppmv) of atmospheric CO_2 (approximately double the 1995 concentration) average 30 percent higher, with a range of −10 to +80 percent. The yield response of C4 crops (corn, millet, sorghum, and sugar cane) to increases in atmospheric CO_2 is lower (Reilly et al., 1996). A commonly used estimate for the yield response of C4 crops to 555 ppmv of atmospheric CO_2 (double the pre-industrial and 225 ppmv above the 1990 concentration) is 7 percent (Rosenzweig et al.). Estimates for other yield responses to 555 ppmv of atmospheric CO_2 are: wheat—22 percent, rice—19 percent, soybeans—34 percent, and all other C3 crops—25 percent (Rosenzweig et al.). Knowledge of the benefits of elevated CO_2 on many tropical crops is incomplete (Gitay et al.).

The size of the effect of CO_2 fertilization on yields of field crops under commercial production, however, is uncertain. It will be small in regions where low fertilizer use or other factors limit crop growth. Benefits associated with water use efficiency will also be smaller in regions where water stress is a minor problem. Some of the direct effects of CO_2 will also be offset by the direct detrimental effects on crops of other fossil fuel emissions such as sulfur dioxide and ozone. CO_2 fertilization also may have some detrimental impacts. Although crop quantities are likely to increase, grain and forage quality declines with CO_2 enrichment (Gitay et al.). Some forage crops, for example, contain lower concentrations of protein when grown under high concentrations of CO_2. In addition, the competitive advantage of C3 weeds may increase relative to C4 crops (Reilly et al., 1996). Finally, reduced transpiration and higher leaf temperatures could affect climate by raising air temperatures and reducing precipitation (Sellers et al.).

Climate and Agricultural Resources

Climate affects agricultural resources in a number of ways. The most important way that climate affects land resources is through its influence on *length of growing season* (Food and Agriculture Organization of the United Nations (FAO)). Length of growing season is the length of time during the year that soil temperature and moisture are continuously suitable for crop growth. Other important climate-related characteristics of land resources include *thermal regime*, the amount of heat available (measured in terms of either temperature or degree-days) during the growing season, and the *freeze-free period*, the time between the last spring and first fall frosts. Length of growing season depends primarily on local temperature and precipitation. Temperature defines the maximum length. When soil temperature falls below some required minimum, for example, crops cannot grow. In some arctic and alpine areas, soil temperatures are always too low to support crops, while in many tropical and subtropical areas soil temperatures are always high enough to allow continuous cropping. The length of growing season is zero days in the former and may be up to 365 days in the latter.

An adequate soil temperature by itself does not, however, ensure crop growth. There must be adequate soil moisture as well. The climatic variables that most affect soil moisture are precipitation and temperature. Precipitation patterns determine when and how much water is on hand to be absorbed by the soil. Temperature, through its affect on evapotranspiration, helps to determine how long water remains in the soil. Evapotranspiration is the combined loss of water from a given area in a specific time by evaporation from the soil surface and by transpiration from plants. Temperature influences both evaporation and transpiration through its effect on the water-holding capacity of air. Up to some saturation point, for example, increasing temperature generally results in an increase in the water-holding capacity of air. And, so long as soil moisture is readily available, evapotranspiration tends to increase as the water-holding capacity of air increases. Hence, the length of growing season is short in desert areas where precipitation is relatively low and infrequent and where temperature is relatively high. Length of growing season approaches its maximum length in areas where precipitation is relatively frequent and high enough to offset losses due to evapotranspiration rates.

Crops vary in their requirements for these variables. Length of growing season, among other factors, determines what crops can be grown in a particular area. Some crops, such as wheat, sorghum, and others, only require a growing season of 90 to 120 days. Other crops require longer growing seasons. Corn, for example, typically requires 120 or more days to reach maturity. Some crops, such as sugar cane, require a year-round growing season. On the other hand, thermal regime generally determines how well a given crop will grow. Some crops attain their highest yields when the thermal regime is relatively low. Wheat, for example, does best with a thermal regime between 17°C and 23°C. Corn and rice, on the other hand, do best under higher thermal regimes, e.g., between 25°C and 30°C (Reilly et al., 1996). These characteristics also affect livestock. Length of growing season and thermal regime determine the availability of pasture or livestock feeds, such as hay or grain. In addition, high or low temperatures can directly generate stress that lowers livestock productivity.

Climate also governs the availability of water resources. In areas where the timing and intensity of precipitation limits soil moisture, irrigation can extend the length of the natural growing season. The source of the water used in such localities may depend on local precipitation, precipitation in some distant location, or past precipitation (i.e., supplies of ground water). Livestock also require a daily source of drinking water, which like irrigation water depends on precipitation. Precipitation is not always beneficial. Too much precipitation at the start or end of the typical growing season can delay planting or prevent harvesting. It can also produce overly saturated "water-logged" soils.

Extreme weather events have short-term impacts on land and water resources. Droughts, for example, shorten growing seasons by reducing soil moisture to levels below those required for crop growth. In addition to directly causing losses in production, droughts may also contribute to soil losses by wind erosion and reductions in livestock due either to deaths caused by a lack of forage and water or the active culling of herds by owners. Storms and floods also may reduce capital stocks important both to agriculture and other sectors of the economy. Flood waters released by the destruction of levies, for example, can demolish farm buildings, devastate livestock herds, and idle, or even damage, rich agricultural lands in river bottoms. Destruction of power lines and bridges may make it more difficult to produce and market agricultural commodities. Flooding also contributes to water-related soil erosion and offsite deposition of agricultural pollutants such as livestock wastes and chemicals leached from agricultural lands. Spring or fall floods shorten growing seasons by delaying planting or preventing harvesting. Lastly, both climate and extreme weather events govern the distribution and virulence of many pests and pathogens. The high risk of failure associated with frequent extreme weather events may even preclude agricultural production in locations otherwise suitable.

Given the importance of climate in characterizing land and water resources, one would expect global changes in climate to generate changes in land and water resources in many locations. Global warming will tend to increase agricultural productivity in regions where growing seasons and thermal regimes are currently constrained by low temperatures. Higher temperatures will tend to decrease agricultural productivity where growing seasons are constrained by soil moisture conditions or where thermal regimes are already high. The distribution of crop and livestock production will change as a result.

Global warming will probably be accompanied by greater amounts of precipitation, on average (Intergovernmental

Panel on Climate Change (IPCC), 1996). This occurs because higher surface temperatures increase the rate at which surface waters evaporate. Greater amounts of precipitation help to offset losses in soil moisture generated by higher temperatures. It may also make water resources more available for agricultural and other economic activities in some locations. Higher rates of evaporation, however, tend to reduce water resources by increasing the rate at which water levels in reservoirs decline.

In addition, regions that depend on snowpack for water may be adversely affected by warmer temperature in mountainous areas (Jacobs et al.). Snowpack is likely to decrease as climate warms—first because more precipitation falls as rain and second because snowpack develops later and melts earlier. Hence, peak stream flow is likely to come earlier in spring while summer flows are reduced. This could reduce the availability of water during hotter or drier periods of the growing season when irrigation water is needed most.

Changing temperature and precipitation patterns affect the distribution and virulence of many pests and pathogens. Some pests will simply follow their hosts (e.g., the crops and livestock upon which they prey) into new locations. Others, however, may become problems in localities where their activity would otherwise have been limited. Fungal diseases, for example, may become generally more prevalent because of milder winters and higher humidity in many locations (Reilly et al., 1996).

Climate change is likely to be accompanied by more extreme events, such as droughts and floods, in some areas (IPCC, Working Group II (WGII), 2001). Indeed, the frequency of great floods (i.e., floods with discharges greater than 100-year levels in basins larger than 200,000 km^2) already increased substantially during the 20th century (Milly et al.).

Finally, global warming will cause sea levels to rise (Church et al.). This is due to the thermal expansion of the oceans, melting of mountain glaciers, and changes in the extent and thickness of ice sheets in Antarctica and Greenland. Rising sea levels will reduce the amount of land available for all economic activities, including agriculture. Salt-water intrusions may also affect groundwater supplies in some coastal areas, and thereby hamper irrigation.

Adaptations to Agricultural Impacts

To take advantage of the opportunities and lessen the damages that rising greenhouse gas concentrations pose for agriculture, farmers and others will have to adapt (see Fankhauser et al., and Mendelsohn, for an overview of adaptation to climate change). Some adaptations will likely occur naturally or spontaneously in response to climate change or CO_2 fertilization. Other adaptations will require some planning by and cooperation among individuals or groups. In either case, the effectiveness of adaptation in coping with the impacts of climate change will vary regionally and depend a great deal on regional resources and social institutions (IPCC, WGII).

Autonomous responses that farmers would likely make on their own include shifting planting dates, increasing or decreasing fertilizer, changing pest management programs, using more irrigation water where readily available, adding or improving drainage systems for waterlogged soils, switching crop or livestock varieties, shifting from crops to grazing, etc. Previous research shows that estimated damages decline (and estimated benefits increase) as the number of autonomous responses simulated in a given study increase (Rosenzweig and Parry; Darwin et al., 1995). The amount of damage prevented demonstrates that farmer adaptations could be an important mechanism for reducing any negative impacts directly attributable to global climate change.

Farmers' adaptations would generate additional autonomous responses from producers in other sectors as well as from domestic and foreign consumers. As these responses filter throughout the world economy, international trade will tend to transfer agricultural products from regions where agricultural productivity improves to regions where agricultural productivity declines. Such interregional adjustments in production, trade, and consumption would buffer some of the losses in economic welfare generated by climate change on world agriculture (Kane, Reilly, and Tobey).

Breeding new crop and livestock varieties that are better suited to new climatic conditions, either publicly or privately, is an example of a planned response. Developing crops adapted to warmer temperatures through traditional breeding and genetic modification appears promising (Gitay et al.). Climate change itself could hamper development of some crops, however, if it adversely affects the availability of wild genetic stocks in some locations. The development of crops better adapted to elevated CO_2 remains very uncertain (Gitay et al.). Prospects of adapting livestock to increased air temperature through traditional breeding and genetic modification also are uncertain (Gitay et al.).

Adaptations that require planning and cooperation with other farmers or with other members of society over a relatively long time period include building large-scale irrigation facilities, maintaining or initiating flood control, or expanding access to markets. The first two adaptations would help to maintain agricultural production in an area, while the last would help spread risk from poor local harvests (and subsequent low local food supplies) over larger areas. Farmers would also likely respond by expanding agricultural lands either in areas currently suitable for agricultural production or into areas that are currently unsuitable but that become productive under global climate change. Construction of the infrastructure to support such endeavors also would require some planning. Land-use changes that accompany climate-induced shifts in cropland and permanent pasture, however, are likely to raise additional social and environmental issues in some locations. This could increase concerns over the environmental consequences of agriculture in some areas.

Finally, adaptation does not guarantee that farming will continue in an area or, if it does, that farm incomes will remain unchanged. In fact, climate change could reduce agricultural productivity to such an extent in some areas that the only viable adaptation would be to abandon farming. CO_2 fertilization could exacerbate such local problems. By effectively increasing productivity everywhere, CO_2 fertilization may help to reduce commodity prices, which in turn means lower incomes in the agricultural sector. This too would encourage people to leave farming.

Estimated Impacts of Rising Concentrations

There is a large body of literature on the impacts of rising concentrations of greenhouse gases on agriculture. Much of it has been reviewed elsewhere (see Reilly et al., 1996 and 2002; Schimmelpfennig et al.; Adams et al.; Lewandrowski and Schimmelpfennig; and Gitay et al.). For information on the impacts of rising greenhouse gas concentrations generally on the world as a whole see IPCC (1991, 1996, and 2001). For general information on the impacts of rising greenhouse gas concentrations on the United States see U.S. Global Change Research Program (USGCRP), National Assessment Synthesis Team (2000, 2001). For a summary of research pertaining to the impacts of sea level rise on the United States see Neumann et al.

This section presents estimates of the impacts of rising greenhouse gas concentrations on agricultural land and water resources. First, direct impacts of climate change on the characteristics and/or the availability of land and water resources are presented. Then, impacts of these climate-induced changes as well as the secondary impacts of CO_2 fertilization on resource use and value are presented. Finally, impacts on general economic welfare of these and other changes related to rising greenhouse gas concentrations are presented. This includes impacts based on direct estimates of climate change's effects on agricultural land values and impacts of sea level rise.

Results are from a number of studies (Darwin et al., 1995; Darwin, 1999a; Darwin and Tol; Fischer et al.; Gleick et al.; Jacobs et al.; Mendelsohn et al., 1999; Reilly et al., 2001, 2002; Reilly, 2002; Yohe et al.). These studies vary by modeling approach, spatial and sector coverage, and economic estimates. (See box, "Estimating Agricultural Economic Impacts of Rising Concentrations of Greenhouse Gases".) Results of these studies are supplemented with additional research by ERS in order to show a complete and consistent set of interactions from immediate impacts on resource characteristics, through changes in resource use and value, to changes in economic welfare. The large number of studies also helps to indicate the level of uncertainty surrounding the agricultural effects of rising concentrations of greenhouse gases. It also enables some of the uncertainty to be quantified. Still, all of the estimated impacts on land and water resources presented here are limited in a number of important ways. (See box, "Estimating Agricultural Economic Impacts of Rising Concentrations of Greenhouse Gases".) Eliminating these limitations is the task of future research. Results of such research may require a reevaluation of the estimates presented here.

Scenarios

Climatic changes in most of the scenarios in the studies summarized here are based on results from general circulation models (GCMs). A few studies rely on uniform changes in temperature or precipitation. In ERS analyses, climate change is simulated with GCM-based projections of temperature and precipitation (Darwin et al., 1995; Darwin, 1999a). Increases in global mean temperature projected by these models in these analyses range from 1°C to 5.2°C (table 7.2.1), which is somewhat lower than the 1.4°C to 5.8°C range of temperatures currently projected by the IPCC for the end of the 21st century (IPCC, 2001). Increases in global mean precipitation range from 1.3 percent to 15 percent—approximately 2.4 percent per 1°C-increase in mean global temperature on average (figure 7.2.1). The confidence limits indicate that (for this set of GCM results) the confidence that global mean precipitation increases as global mean temperature increases is very high.

In ERS analyses, increases in U.S. mean temperature range from 1.1°C to 6.7°C (table 7.2.2); changes in precipitation range from –1 percent to 14 percent (table 7.2.3). Precipitation increases approximately 2 percent per 1°C-increase in mean U.S. temperature on average (figure 7.2.2). The confidence limits of precipitation changes with respect to temperature changes in the U.S., however, are very broad and in the case of the lower limit even negative. This indicates that the confidence that U.S. mean precipitation increases as U.S. mean temperature increases is not very high. Consistent with the cautions enunciated by the National Research Council (NRC) regarding GCM-based projections of regional and local climate (NRC, 2001), changes in temperature and particularly precipitation in agricultural production regions are highly variable and hence uncertain. (See box, "Greenhouse Gas Concentrations and Climate Changes".)

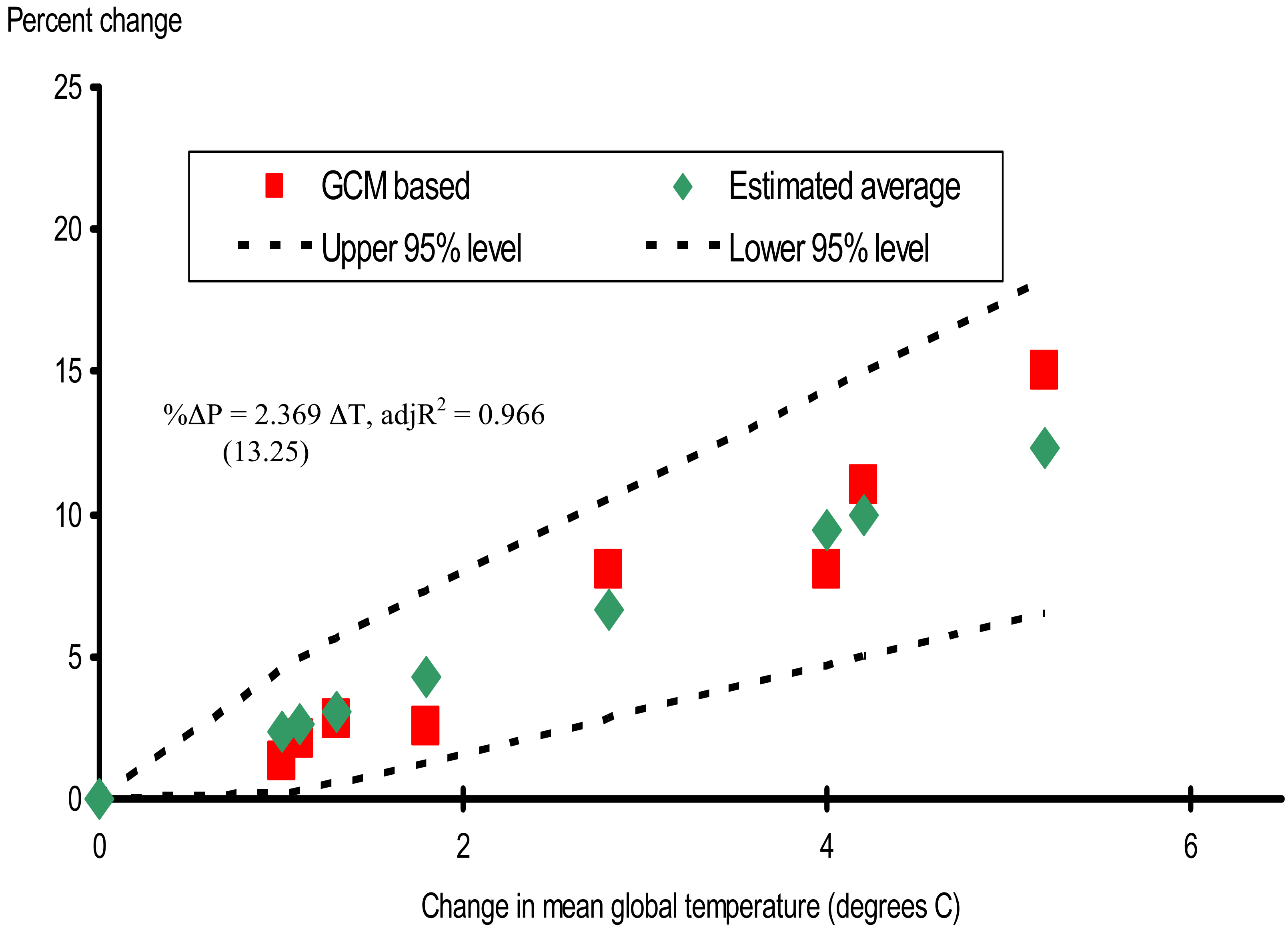
Table 7.2.1—Changes in mean global temperature and precipitation derived from results projected by general circulation models

General circulation model	Year calculated	Temperature change (°C)	Precipitation change (percent)
University of Illinois at Urbana-Champaign (UIUC)[1]	1996-1997	1	1.3
Max Planck Institute (MPI)[2]	1990-1991	1.1	2.1
Geophysical Fluid Dynamics Laboratory (GFDL89)[3]	1989	1.3	2.8
Hadley Centre (HC)[4]	1995	1.8	2.5
Oregon State University (OSU)[5]	1985	2.8	8
Geophysical Fluid Dynamics Laboratory (GFDL88)[6]	1988	4	8
Goddard Institute for Space Studies (GISS)[7]	1982	4.2	11
United Kingdom Meteorological Office (UKMO)[8]	1986	5.2	15

[1]Schlesinger et al. (1997, 2000).
[2]Cubasch et al. (1992) and Greco et al.
[3] Manabe and Wetherald.
[4]Johns et al.
[5]Schlesinger and Zhao.
[6]Manabe et al. (1991,1992), and Greco et al.
[7]Hansen et al.
[8] Wilson and Mitchell (1987).

Projected results from the UIUC GCM were supplied directly from the Climate Research Group, Department of Atmospheric Sciences, University of Illinois at Urbana-Champaign; Projected results from the MPI and GFDL89 GCMs are from Greco et al. (1994); Projected results from the Hadley Centre HC GCM were supplied by the Climate Impacts LINK Project (UK Department of the Environment Contract EPG 1/1/16) on behalf of the Climate Research Unit, University of East Anglia; Projected results from the OSU, GFDL88, GISS, and UKMO GCMs were provided by the National Center for Atmospheric Research, Boulder, CO.

Figure 7.2.1 - Change in mean global precipitation



Sources: USDA, ERS, derived from results of general circulation models (GCMs) described in Schlesinger et al. (1997, 2000), Cubash et al. (1992), Greco et al., Manabe and Wetherald, Johns et al., Schlesinger and Zhao, Manabe et al. (1991, 1992), Hansen et al., and Wilson and Mitchell.

Table 7.2.2—Changes in mean annual surface temperature in the U.S. and in U.S. agricultural production regions associated with changes in mean global temperature: derived from results projected by general circulation models[1]

	Change in mean global temperature (^oC)							
Region	1.0	1.1	1.3	1.8	2.8	4.0	4.2	5.2
	Change in mean annual surface temperature (^oC)							
United States	1.1	1.8	1.6	2.3	3.2	4.4	4.6	6.7
Northeast	1.1	2.4	1.7	1.8	3.2	4.6	3.9	7.6
Lake States	0.8	2.7	1.8	2.1	3.5	4.7	4.7	8.3
Corn Belt	0.9	2.4	2.0	1.6	3.5	4.3	4.8	7.2
Northern Plains	0.8	2.5	1.8	2.3	3.2	4.4	4.8	6.7
Appalachia	1.1	1.9	1.9	1.4	3.5	4	4.2	6.6
Southeast	1.2	1.6	1.7	1.3	3.4	3.7	3.7	5.5
Delta States	1.1	1.8	1.7	1.4	3.4	3.9	4.4	5.8
Southern Plains	0.9	1.6	1.3	1.9	3.3	4.0	4.4	5.9
Mountain States	1.0	2.2	1.7	2.6	2.7	4.4	4.8	6.3
Pacific States	1.0	1.4	1.6	2.5	2.3	3.9	4.6	6.2
Alaska	1.1	0.4	1.2	3.1	3.7	5.1	4.8	7.9
Hawaii	1.1	1.0	1.4	2.2	2.5	2.9	3.3	3.7

[1]The general circulation models (GCM) used to project the changes in temperature are (in ascending order by change in mean global temperature): the University of Illinois at Urbana-Champaign, the Max Planck Institute, the Geophysical Fluid Dynamics Laboratory (GFDL89), the Hadley Centre, Oregon State University, GFDL88, Goddard Institute for Space Studies, and the United Kingdom Meteorological Office. See box, "Greenhouse Gas Concentrations and Climate Change" for more information about GCMs.

Source: USDA, ERS.

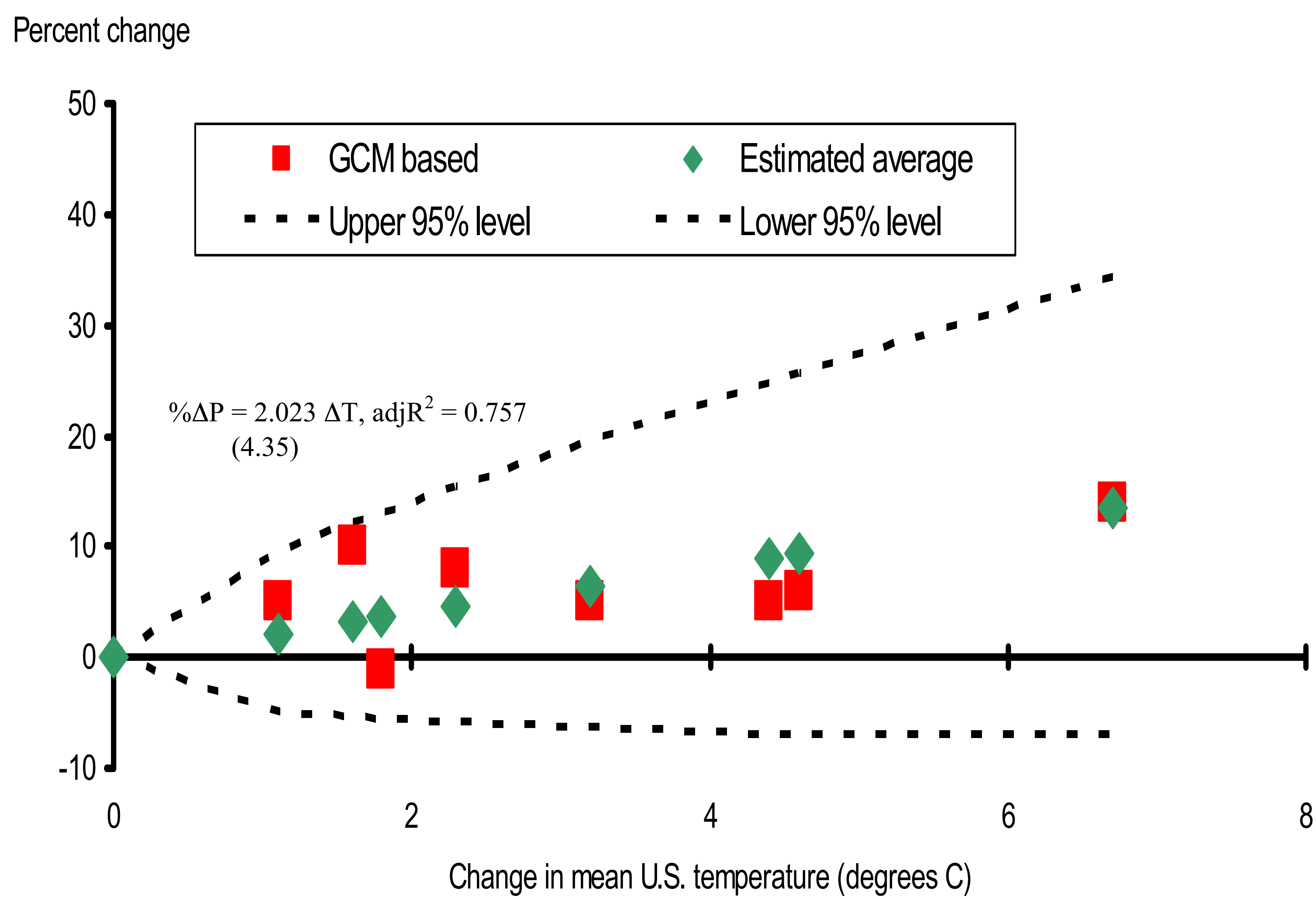
Table 7.2.3—Changes in annual average precipitation in the U.S. and in U.S. agricultural production regions associated with changes in mean global temperature: derived from results projected by general circulation models[1]

Region	Change in mean global temperature (C) 1	1.1	1.3	1.8	2.8	4	4.2	5.2
	Change in annual average precipitation (percent)							
United States	5	-1	10	8	5	5	6	14
Northeast	3	2	1	10	11	-2	0	16
Lake States	5	-10	4	11	5	12	6	11
Corn Belt	4	-4	5	8	2	6	4	8
Northern Plains	7	-18	8	7	6	6	2	12
Appalachia	3	0	2	7	7	3	9	7
Southeast	1	1	1	8	11	6	-1	6
Delta States	0	-1	6	4	2	6	-2	-1
Southern Plains	6	10	25	4	-2	-4	-6	-4
Mountain States	8	-13	16	-1	-1	-1	11	19
Pacific States	2	0	11	10	-1	7	15	20
Alaska	11	7	21	3	24	20	14	37
Hawaii	9	2	8	18	2	1	2	31

[1]The general circulation models (GCM) used to project the changes in precipitation are (in ascending order by change in mean global temperature): the University of Illinois at Urbana-Champaign, the Max Planck Institute, the Geophysical Fluid Dynamics Laboratory (GFDL89), the Hadley Centre, Oregon State University, GFDL88, Goddard Institute for Space Studies, and the United Kingdom Meteorological Office. See box, "Greenhouse Gas Concentrations and Climate Change" for more information about GCMs.

Source: USDA, ERS.

Figure 7.2.2 - Change in mean U.S. precipitation



Sources: USDA, ERS, derived from results of general circulation models (GCMs) described in Schlesinger et al. (1997, 2000), Cubash et al. (1992), Greco et al., Manabe and Wetherald, Johns et al., Schlesinger and Zhao, Manabe et al. (1991, 1992), Hansen et al., and Wilson and Mitchell.

Climate change also is simulated with GCM-based projections of temperature and precipitation in the recent studies conducted by the Agriculture Sector Assessment (ASA) Team of the National Assessment of Climate Variability and Change (Reilly et al., 2001, 2002; Reilly, 2002). Increases in mean annual temperature for the coterminous U.S. States range from 1.4°C to 5.8°C (table 7.2.4); changes in precipitation range from –4 to 23 percent (table 7.2.5). Again, the confidence that U.S. mean precipitation increases as U.S. mean temperature increases is not very high and changes in both temperature and precipitation at the regional level are highly variable and hence uncertain.

ERS analyses of CO_2 fertilization assume that the atmospheric concentration of CO_2 increases by 150 or 225 ppmv. The CO_2 fertilization scenarios are independent of ERS climate change scenarios. That is, the impacts of climate change and CO_2 fertilization are estimated separately. In the ASA studies, CO_2 fertilization is based on 95- and 310-ppmv increases in atmospheric CO_2. These concentrations are explicitly related to ASA climate change scenarios and the impacts of both CO_2 fertilization and climate change are estimated together.

Land and Water Resources

Changes in climate would affect land and water resources worldwide. Estimated impacts on land resources are mainly indicated by changes in growing season length (Darwin et al., 1995; Darwin, 1999a; Fischer et al., 2001). Estimated impacts on water resources are mainly measured by changes in runoff, e.g., the portion of precipitation that is not evapotranspirated back to the atmosphere (Darwin et al., 1995; Darwin, 1999a; Gleick et al.). Because of its potential impacts on plant water-use efficiency, CO_2 fertilization also may affect growing seasons and runoff. This direct effect on resources is highly uncertain and relatively small, however, and not explicitly simulated in most studies.

Land Resources—In ERS analyses, changes in climate affect land classes that are defined by length of growing seasons (table 7.2.6, figure 7.2.3). These land classes are similar to what the Food and Agriculture Organization (FAO) of the United Nations calls "agro-ecological zones." Length of growing season is calculated from observed mean monthly temperature and precipitation using a soil temperature and moisture algorithm (Leemans and Cramer; Eswaran et al.). Land class 1 (LC1) occurs where cold temperatures limit growing seasons to 100 days or less, primarily in polar and alpine areas. Land class 2 (LC2) occurs where dryness limits growing seasons to 100 days or less, mainly semi-desert and desert areas. Growing seasons in land class 3 (LC3), located primarily in northern latitudes, range from 101 to 165 days. Growing seasons in land class 4 (LC4), located throughout temperate and tropical areas, range from 166 to 250 days. Land class 5 (LC5) is located in lower latitudes and equatorial areas and has growing seasons ranging from 251 to 300 days. Land class 6 (LC6) has growing seasons longer than 300 days and is mostly located in tropical areas.

Land-class boundaries generally reflect thresholds in crop production possibilities. Crop production in LC1 and rain-fed LC2 is marginal and restricted to areas where growing seasons approach 100 days. LC1 and LC2 (without irrigation) are limited to one crop per year. Principal crops on LC3 are wheat, other short-season crops, and forage. LC3 is also limited to one crop per year. The growing season on LC4 is long enough to produce corn as well as allow for some double cropping. Major crops on LC5 are millet, sorghum, peanuts, tobacco, cotton, and rice; double cropping is common. Year-round growing seasons characterize LC6, which enables these areas to provide citrus fruits, sugar cane, cocoa bean, and coffee. In developed regions (e.g., United States, Canada, Europe, Japan, Australia, New Zealand, and the former Soviet Union), most cropland occurs on LC2, 3, and 4. In developing regions (e.g., Africa, Latin America, and all Asia except Japan), most cropland occurs on LC2, LC5, and LC6 (figure 7.2.4).

Table 7.2.4—Changes in mean annual surface temperature in the coterminous U.S. and in U.S. regions: derived from results projected by general circulation models[1]

Region	Hadley 2030	Canadian 2030	Hadley 2095	Canadian 2095
	GCM and projected year			
	Change in mean annual surface temperature (°C)			
United States	1.4	2.1	3.3	5.8
Northeast	1.0	1.8	2.7	5.6
Great Lakes/Midwest	1.1	2.4	2.7	6.1
Great Plains	1.6	2.2	3.6	6.3
Southeast	1.0	1.8	2.3	5.5
Southwest/California /Rockies	1.8	2.0	4.0	5.5
Northwest	1.7	1.8	4.1	4.9

[1]The general circulation models (GCM) used to project the changes in temperature are from the Hadley Centre and the Canadian Climate Centre. See box, "Greenhouse Gas Concentrations and Climate Change" for more information about GCMs.
Source: Gleick et al.

Table 7.2.5—Changes in annual average precipitation in the coterminous U.S. and in U.S. regions: derived from results projected by general circulation models[1]

Region	Hadley 2030	Canadian 2030	Hadley 2095	Canadian 2095
	GCM and Projected Year			
	Change in annual average precipitation (percent)			
United States	6	–4	23	17
Northeast	8	–6	24	0
Great Lakes/Midwest	9	–2	27	20
Great Plains	6	–2	16	13
Southeast	3	–19	22	–13
Southwest/California/Rockies	8	16	27	67
Northwest	11	8	13	31

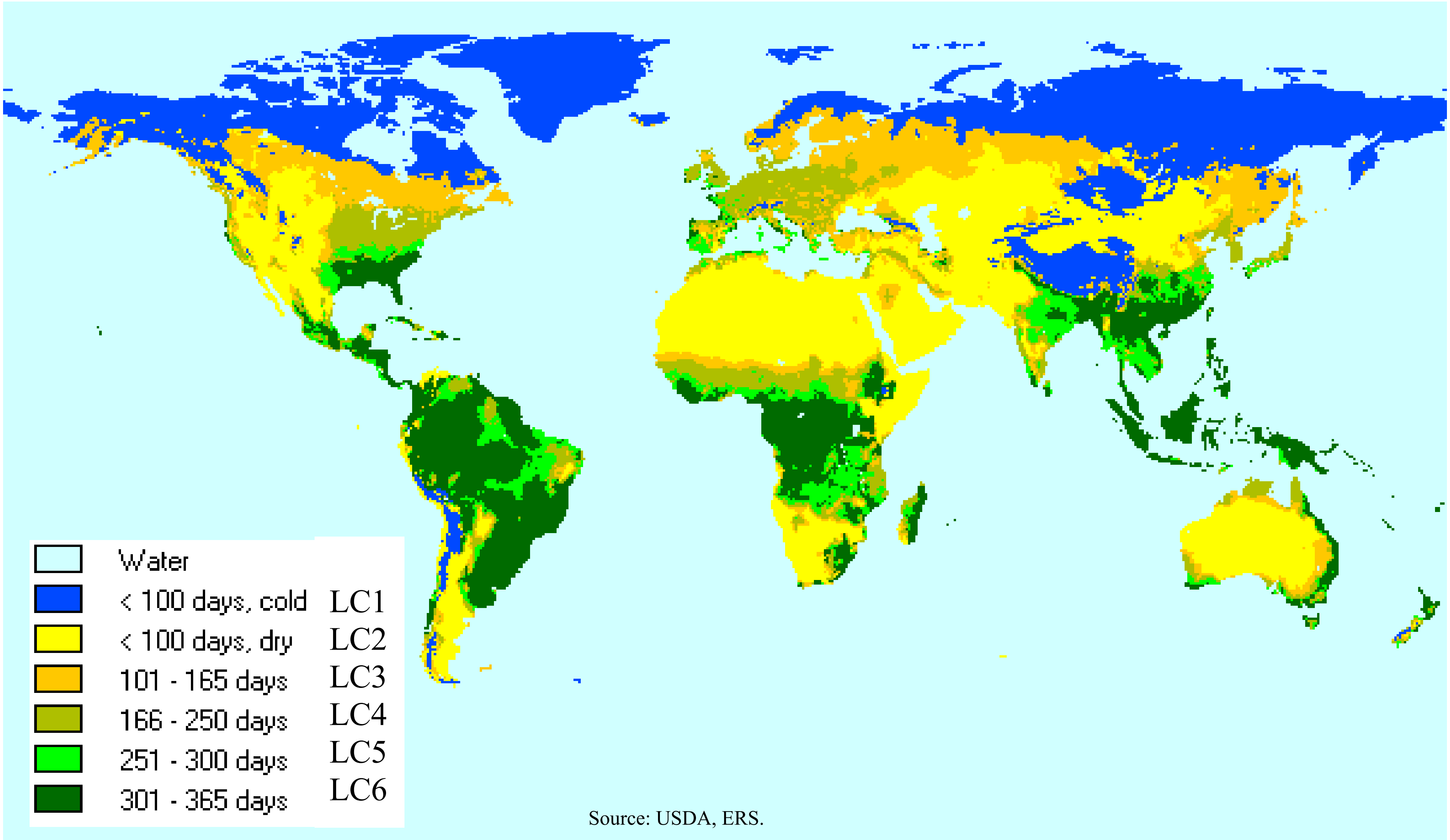
[1]The general circulation models (GCM) used to project the changes in temperature are from the Hadley Centre and the Canadian Climate Centre. See box, "Greenhouse Gas Concentrations and Climate Change" for more information about GCMs.
Source: Gleick et al.

Table 7.2.6—Land-class boundaries in the Future Agricultural Resources Model (FARM)[1]

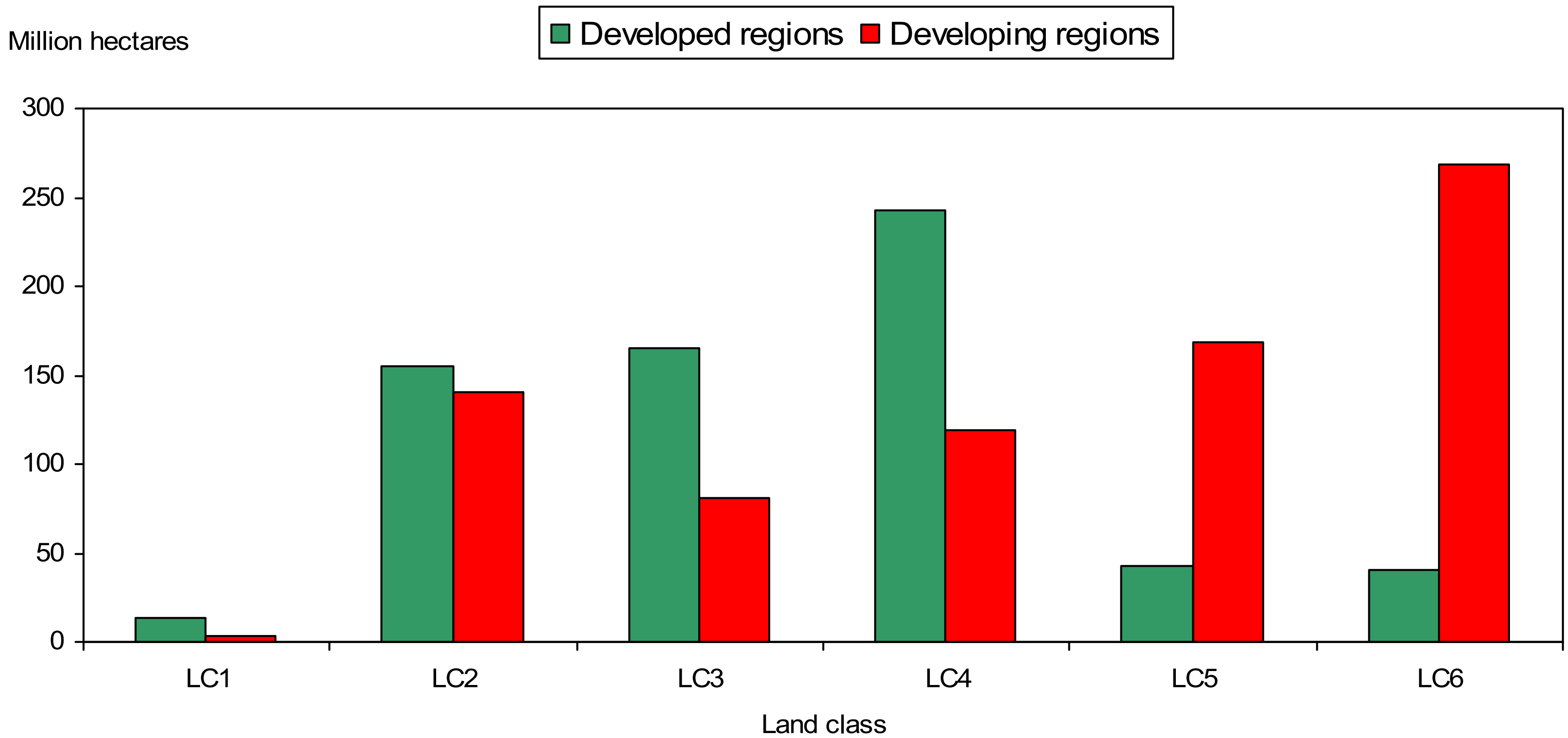
Land class	Length of growing season (days)	Time soil temperature above 5° (days)	Principal crops and cropping patterns	Sample regions
1	0 -100	≤125	Sparse forage for rough grazing	United States: northern Alaska World: Greenland
2	0 -100	≥125	Millets, pulses, sparse forage for rough grazing	United States: Mojave Desert World: Sahara Desert
3	101 - 165	≥125	Short-season grains; forage: one crop per year	United States: Palouse River area, western Nebraska World: southern Manitoba
4	166 - 250	≥125	Corn: some double-cropping possible	United States: Corn Belt World: France, Germany
5	251 - 300	≥125	Cotton and rice: double-cropping common	United States: Tennessee World: nonpeninsular Thailand
6	301 - 365	≥125	Rubber and sugar cane: double-cropping common	United States: Florida, southeast coast World: Indonesia

Source: Darwin et al., 1995.
[1]Future Agricultural Resources Model

Figure 7.2.3-Land classes under current climate conditions



7.2.4 - Estimated distribution of cropland by land class (LC) in developed and developing regions



Developed regions include the United States, Canada, Europe, Japan, Australia, New Zealand, and the former Soviet Union. Developing regions include Africa, Latin America, and all Asia except Japan. The length of growing season for the land classes are as follows: LC1 is ≤ 100 days and cold, LC2 is ≤ 100 days and dry, LC3 is 101 to 165 days, LC4 is 166 to 250 days, LC5 is 251 to 300 days, and LC6 is 301 to 365 days.
Source: USDA, ERS.

World Land Resources—Early ERS analyses indicated that 29 to 46 percent of the world's land (outside Antarctica) could be shifted to a new land class by projected changes in temperature and precipitation patterns that would accompany increases in mean global temperature ranging from 2.8°C to 5.2°C (Darwin et al., 1995). Growing seasons would lengthen in polar and alpine regions and shorten in tropical and relatively dry regions. More recent ERS analyses indicate that similar changes in growing seasons would occur under scenarios derived from increases in mean global temperature ranging from 1°C to 1.8° (e.g., the UIUC, MPI, GFDL89, and HC scenarios in figure 7.2.5). Climate change is generally associated with a reduction of land constrained by low temperature (LC1) and an increase in land constrained by low moisture (LC2). In some areas, increases in LC2 are due to reductions in precipitation, while in other areas soil moisture declines because increases in precipitation are more than offset by higher rates of evapotranspiration generated by higher temperatures. Land with no climatic constraints through most of the year (LC6) would decline, while land with some climatic constraints in part of the year (LC3, 4, and 5) would increase.

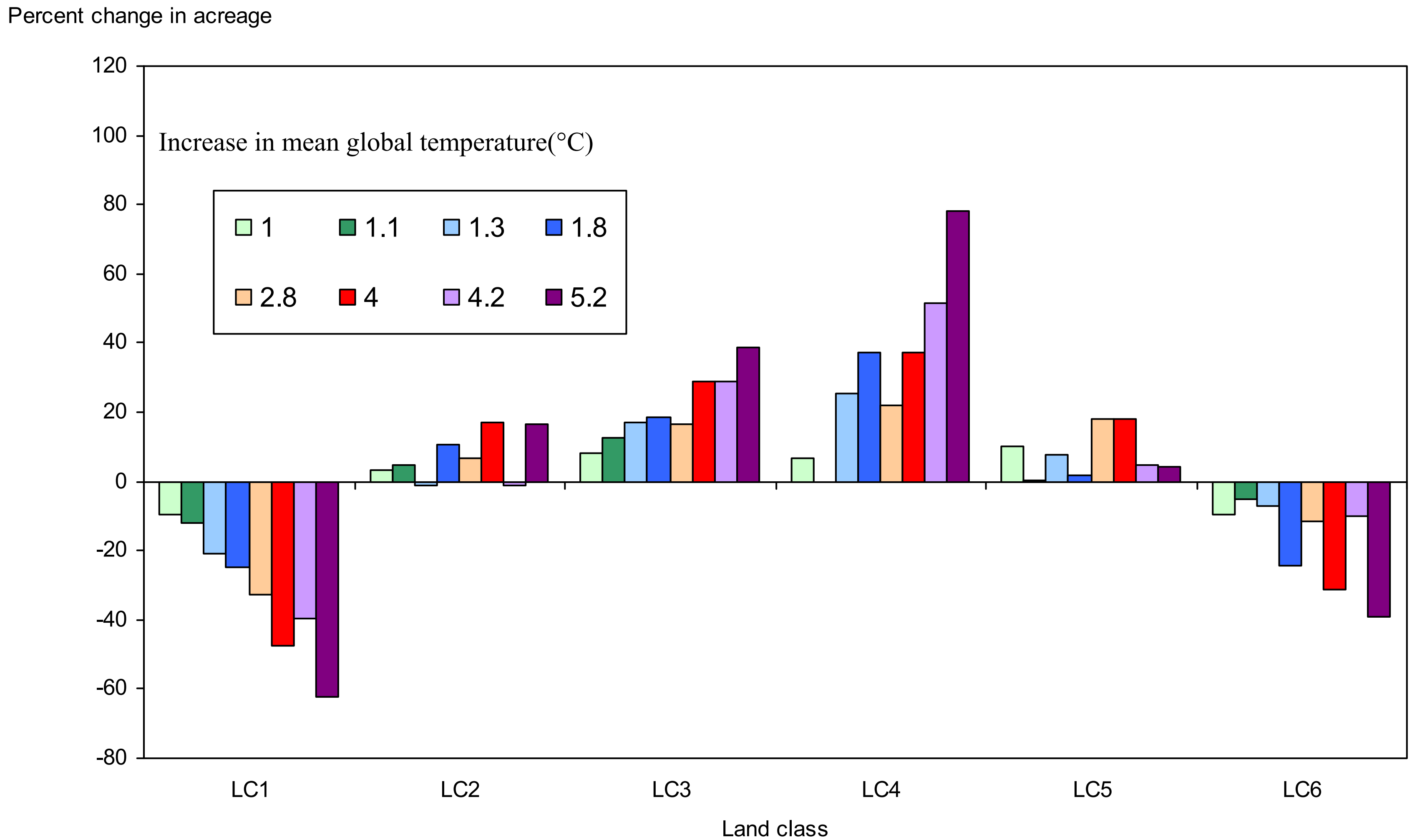
Estimated reductions in LC1 are consistent with observed changes in arctic and alpine regions (Gitay et al.). These findings are also consistent with a sensitivity analysis of temperature on the amount of cultivable land conducted by Fischer et al. They found that if temperatures were to uniformly increase worldwide, the amount of cultivable rain-fed land would increase on average in developed countries (which are located primarily in temperate zones), but decrease on average in developing countries (which are located mainly in tropical and subtropical zones). They also found that uniformly increasing precipitation as well would not alter this basic pattern. The total amount of cultivable rain-fed land initially would increase if temperature (and precipitation) were to uniformly increase, but at a decreasing rate and eventually would begin to decline.

ERS analyses, however, also indicate some important changes on existing cropland (figure 7.2.6). In developed regions, LC4 cropland is estimated to decrease, while LC5 and LC6 cropland is estimated to increase. The opposite would occur in developing regions. The magnitude of these shifts generally increases as global temperature increases. Projected declines in both regions of the cropland types most prevalent at present indicate that fairly extensive adaptations might be required in order to maximize agricultural efficiency under the new climatic conditions.

U.S. Land Resources—Early ERS analyses indicated that 39 to 55 percent of U.S. land could be shifted to a new land class by projected changes in temperature and precipitation patterns that accompany increases in mean global temperature ranging from 2.8°C to 5.2°C (Darwin et al., 1995). Estimated reductions in LC1, where cold temperatures limit growing seasons, indicate that total land suitable for agricultural production would increase under global climate change. The impact of climate change on the overall average productivity of land, however, is uncertain.

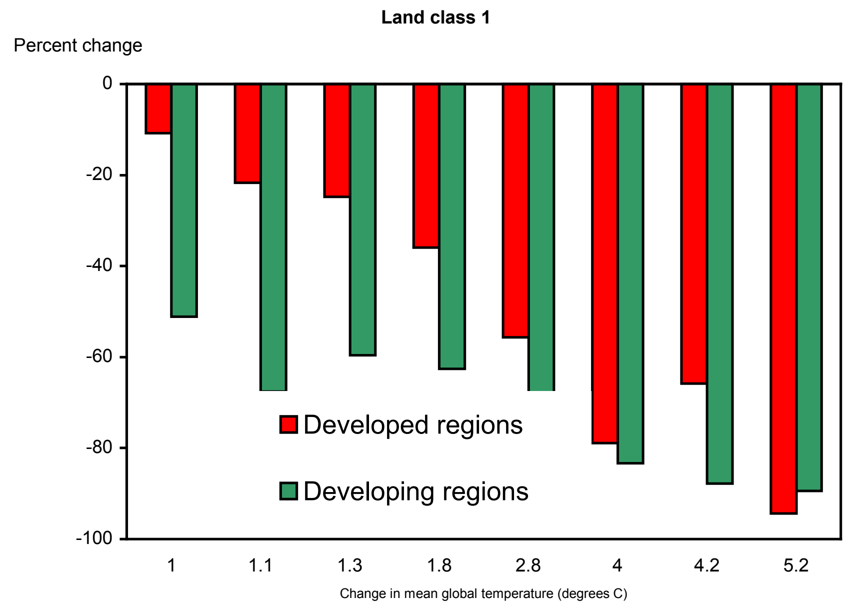
Recent ERS analyses of scenarios derived from increases in mean global temperature ranging from 1°C to 1.8° provide additional information (e.g., the UIUC, MPI, GFDL89, and HC scenarios in figure 7.2.7). As in the earlier analysis, LC1 and LC4 acreage is generally estimated to decrease, LC3 acreage to generally increase, and LC2 acreage may either increase or decrease. Estimated changes in LC5 and LC6 acreage differ somewhat from the earlier analysis. Additional data are required, however, to assess changes in the overall average productivity of land. Estimated changes in the length of U.S. growing season range from –3 to +14 days (table 7.2.7). They are more closely related to estimated changes in mean U.S. precipitation than to estimated changes in mean U.S. temperature (tables 7.2.3 and 7.2.2).

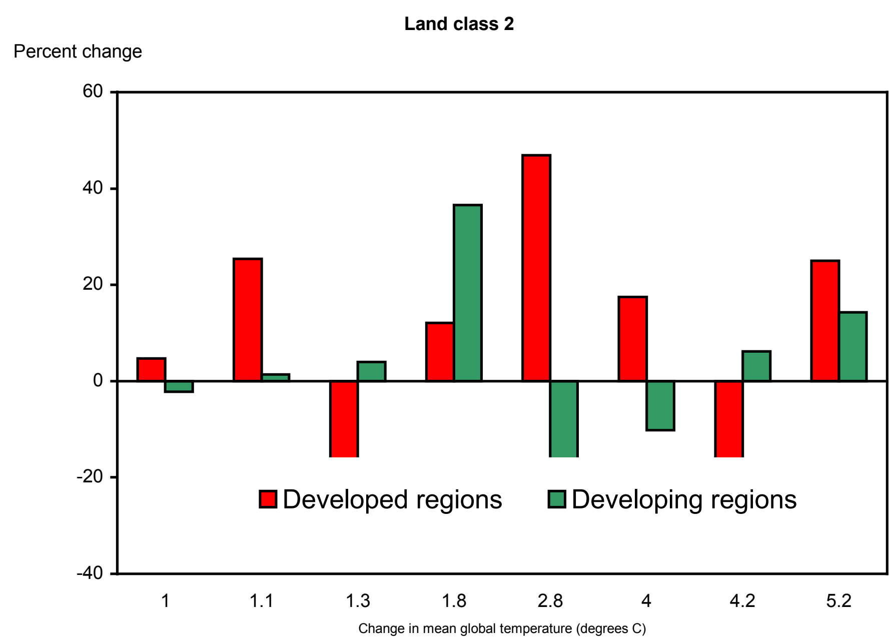
Figure 7.2.5 - Estimated effect of climate change on the global distribution of land among land classes (LC)



The length of growing season for the land classes are as follows: LC1 is ≤100 days and cold, LC2 is ≤100 days and dry, LC3 is 101 to 165 days, LC4 is 166 to 250 days, LC5 is 251 to 300 days, and LC6 is 301 to 365 days.
Source: USDA, ERS.

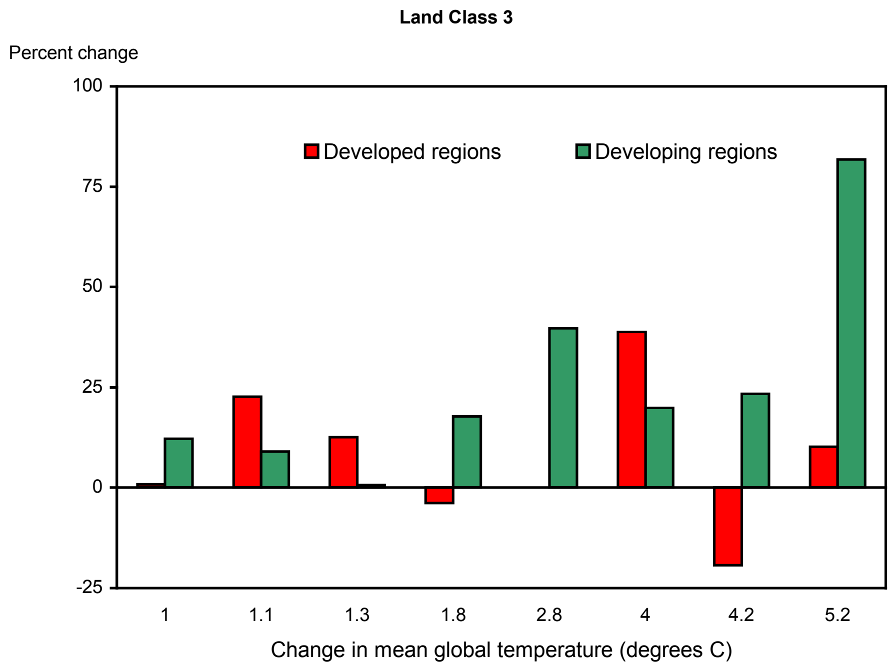
Figure 7.2.6—Climate change in land class area, by land class

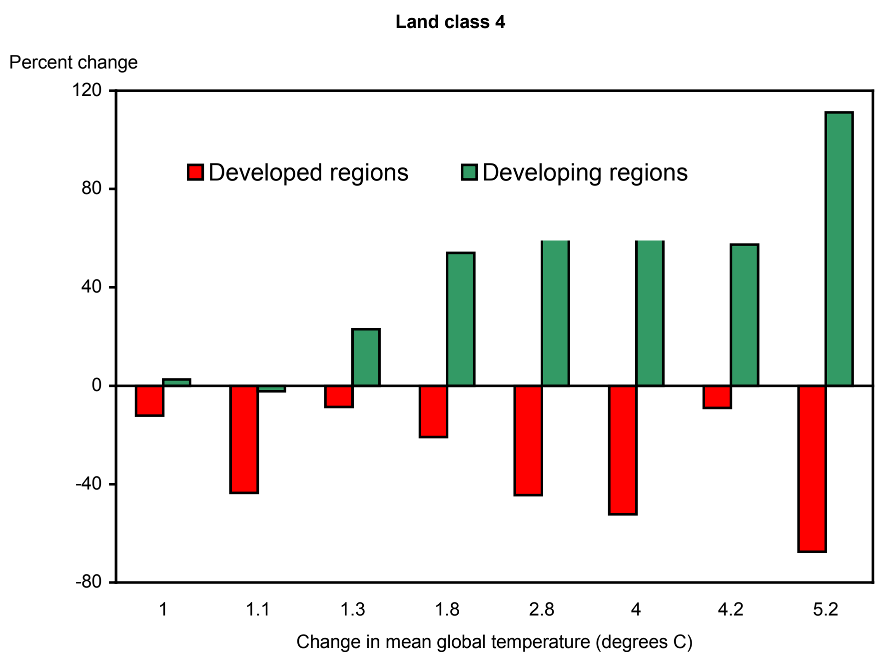




continued

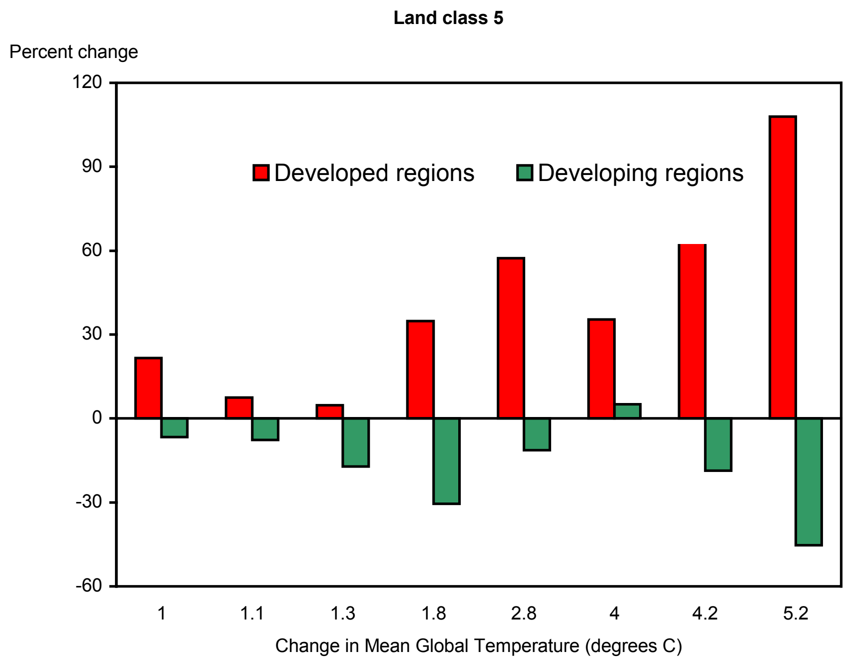
Figure 7.2.6—Climate change in land class area, by land class (continued)





continued

Figure 7.2.6—Climate change in land class area, by land class (continued)



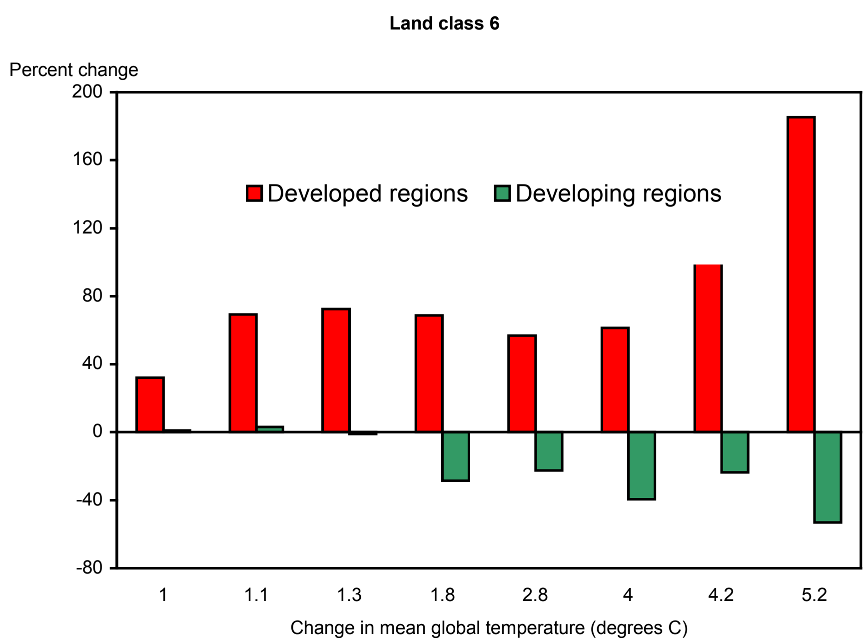
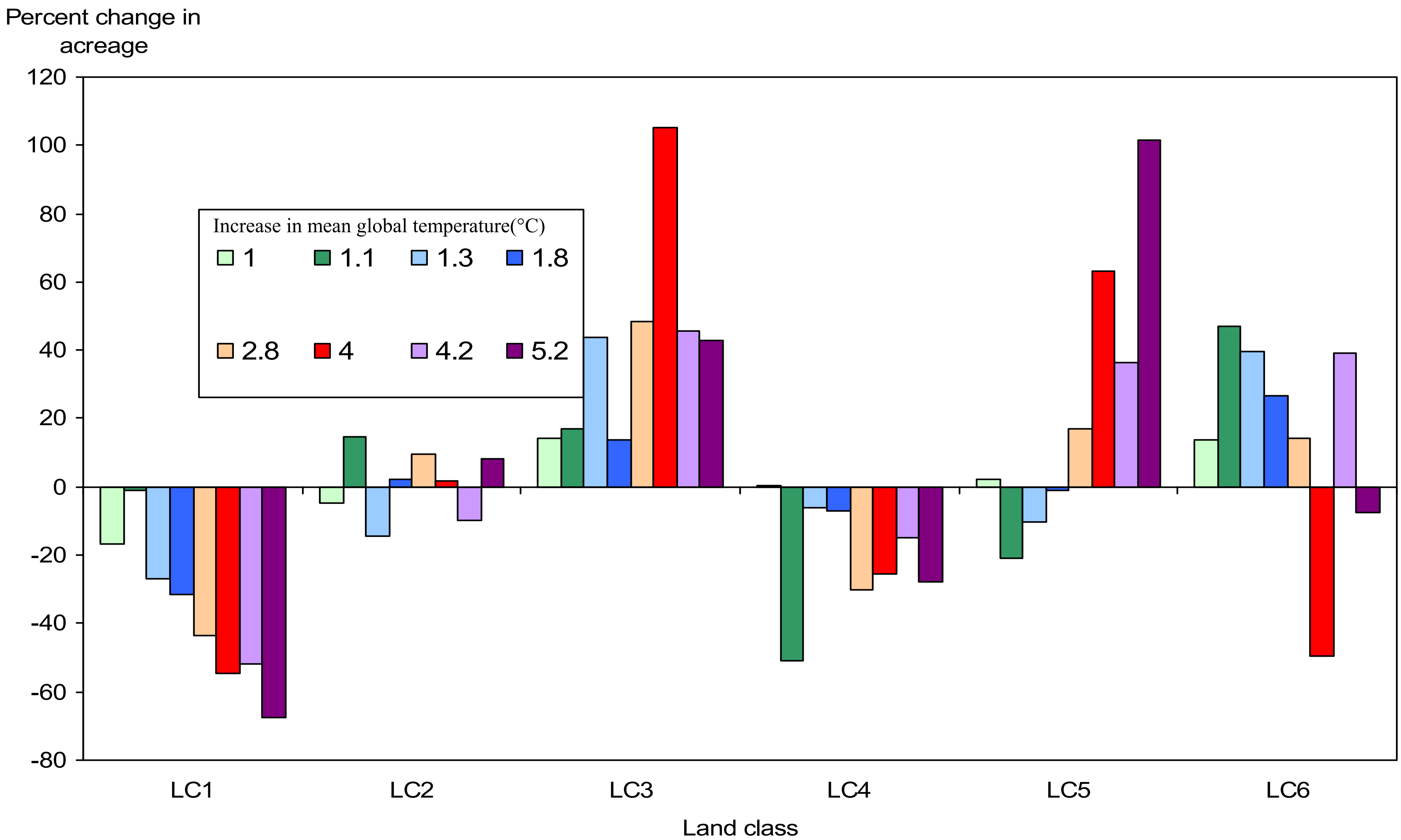


Figure 7.2.7 - Estimated effect of climate change on the distribution of land among land classes (LC) in the United States



The length of growing season for the land classes are as follows: LC1 is ≤100 days and cold, LC2 is ≤100 days and dry, LC3 is 101 to 165 days, LC4 is 166 to 250 days, LC5 is 251 to 300 days, and LC6 is 301 to 365 days.
Source: USDA, ERS.

Table 7.2.7—Estimated impacts of global climate change on average length of growing season in U.S. agricultural production regions

	Change in mean global temperature (^oC)[1]							
Agricultural Production Region	1	1.1	1.3	1.8	2.8	4	4.2	5.2
	Percent change							
United States	6.6	-3	13.6	8.6	3	-1.9	13.3	8.9
Northeast	4.6	5.2	6.1	8.8	13.6	-18.5	22.9	57.3
Lake States	2.7	-27.8	9.8	8.4	-6.1	5.3	20.1	2.8
Corn Belt	1.8	-10.1	-1.8	7.9	-5.8	-27.5	17.9	18.5
Northern Plains	9.5	-30.3	13.8	9.4	-6.6	2.2	-4.7	4.1
Appalachia	4.5	17.5	2	9	18.5	-6.4	19.3	6.4
Southeast	-0.4	0.2	-4	0	-4.1	-11	-1	-24.9
Delta States	0.4	10.3	1	9	-8.4	-16.9	-5.8	-23.5
Southern Plains	10.7	5.2	38.1	-15.2	1.2	0.4	-11.9	-26.7
Mountain States	17.7	-23.5	42.2	21.4	0.7	12	29.1	26
Pacific States	4.3	2.9	10.2	24.9	-3.4	9	32.2	30.1
Alaska	26.4	4.6	46.1	38	56.2	67.4	67.3	107.6
Hawaii	0	0	0	0	0	0	0	0

[1]The general circulation models (GCM) used to project the changes in temperature and precipitation from which the length of growing season is calculated are (in ascending order by change in mean global temperature): the University of Illinois at Urbana-Champaign, the Max Planck Institute, the Geophysical Fluid Dynamics Laboratory (GFDL89), the Hadley Centre, Oregon State University, GFDL88, Goddard Institute for Space Studies, and the United Kingdom Meteorological Office. See box, "Greenhouse Gas Concentrations and Climate Change," for more information about GCMs.

Source: USDA, ERS.

Estimated changes in length of growing season in U.S. agricultural production regions are highly variable. Negative values indicate, for example, that projected growing seasons shorten in about 25 percent of the hypothetical cases. Eleven of the shorter projections are associated with decreases in precipitation. Twelve of the remaining 15 shorter projections are associated with crop production regions such as the Southeast, Delta States, Southern Plains, and Corn Belt where initial temperatures are relatively high, especially during the growing season. Conversely, estimated growing seasons generally lengthen at high latitudes or in alpine areas such as Alaska, the Northeast, the Mountain States, and the Pacific States where initial temperatures are relatively low. These projections are consistent with expectations of shorter growing seasons in regions where climate change reduces precipitation or where temperatures are already relatively high and longer growing seasons in regions where temperatures are already relatively low. In any event, the uncertainty associated with these regional growing season lengths is a direct consequence of the uncertainty associated with regional climatic projections. (see box, "Greenhouse Gas Concentrations and Climate Change".)

Water Resources—In ERS analyses, changes in climate affect water resources by changing the amount of available runoff. Runoff is the portion of precipitation that is not evapotranspirated back to the atmosphere.
Runoff is calculated simultaneously with length of growing season from observed mean monthly temperature and precipitation using a soil temperature and moisture algorithm (Leemans and Cramer; Eswaran et al.). Runoff calculations for the base year in ERS analyses are calibrated to total internal renewable freshwater resources, which are approximately 41,000 km^3 per year for the world and approximately 2,500 km^3 per year for the U.S. (table 7.2.8). The Water Sector Assessment Team of the U.S. National Assessment also provides estimated changes in runoff (Gleick et al.).

Table 7.2.8—World freshwater resources in 1990

Region	Total internal renewable resource	Total withdrawals	Sector withdrawals Domestic	Industry	Agriculture
			Km^3		
United States	2,478.00	467.00	56	215	196
Canada	2,901.00	42.20	5	34	4
European Community	818.25	254.26	34	129	92
Japan	547.00	107.80	18	36	53
Other East Asia	2,863.00	470.70	29	34	408
Southeast Asia	3,419.60	87.60	11	13	64
Australia and New Zealand	740.00	19.00	12	0	6
Former Soviet Union and Mongolia	4,408.60	353.55	21	103	230
Other Europe	1,502.75	104.74	13	65	27
Other Asia	4,901.80	868.35	36	40	792
Latin America	11,943.00	320.80	26	75	220
Africa	4,184.00	144.00	10	7	127
World	40,707.00	3,240.00	271	750	2,219

Source: World Resources Institute.

World Water Resources—Early research indicated that impacts of climate change on water runoff were highly uncertain (Kaczmarek et al.). Some research showed that at increases in mean global temperature of 2.8°C or higher, annual water runoff would likely increase for the world as a whole, but shortages could occur in some regions (Darwin et al., 1995). More recent research suggests that changes in annual runoff (as indicated by changes in annual streamflow) would be broadly correlated with changes in precipitation (Folland et al.). However, estimated runoff declines in some regions even when precipitation increases because evapotranspiration increases as well (Arnell). If increases in evapotranspiration are larger than increases in precipitation, then water runoff decreases.

Recent ERS research estimated that annual freshwater runoff for the world decreases with relatively small increases in mean global temperature (e.g., less than 2°C), but increases with relatively large increases in mean global temperature (e.g., greater than 2.5° C) (table 7.2.9). This is due in part because precipitation is predicted to continually increase at about the same rate, e.g., by about 2.4 percent on average with each 1°C-increase in mean global temperature (figure 7.2.1). In the algorithm used to estimate water runoff (Eswaran et al.), however, potential evapotranspiration increases relatively rapidly at temperatures below 26.5°C, but begins to increase at a slower rate once temperature rises above 26.5°C and eventually reaches a maximum at about 30°C (Thornthwaite). As temperature increases, therefore, global runoff would tend to decrease initially, but then begin to increase. Impacts vary across regions. Runoff decreases in 50 percent or more of the scenarios in the European Union, Japan, and Southeast Asia. Runoff increases in 75 percent or more of the scenarios in the United States, Canada, and other East Asia.

U.S. Water Resources—In analyses based on GCM model runs (table 7.2.1), ERS estimates changes in U.S. annual runoff ranging from −9.5 to +8.8 percent (table 7.2.10). These changes are more closely related to changes in U.S. precipitation than to changes in U.S. temperature (tables 7.2.2 and 7.2.3). Regional runoff is highly variable. Runoff increases in most regions in one-half the scenarios and declines in most regions in the other half. About two-thirds of the estimated decreases are associated with either projected decreases or relatively small increases (4 percent or less) in annual precipitation. Many of the remaining estimated decreases are associated with relatively high projected increases in mean annual temperature. The seasonal pattern of precipitation also is important. Runoff will be greater for precipitation increases in winter, spring, or fall than for precipitation increases in summer.

Table 7.2.9—Estimated impacts of global climate change on water runoff

	Change in mean global temperature (°C)[1]							
Region	1	1.1	1.3	1.8	2.8	4	4.2	5.2
	Percent change							
World	-6.3	-0.4	-2.4	-8.9	25.7	19.1	31.5	17.6
United States	2.4	-9.5	8.8	3.3	0.5	7.5	-6.7	4.2
Canada	7.6	2.9	15.9	22.1	7.6	10.1	12.5	23.3
European Community	-7.4	-14.9	-5.9	-7.7	1.3	5	0	8.6
Japan	-2.7	-0.9	11.1	-3.6	0.5	10.2	-1.8	-9.4
Other East Asia	-13.8	2.5	0.4	-6.7	17.7	36.7	48.2	12.1
Southeast Asia	-2.4	-3.5	-3.9	-10.5	-2.2	6	8.4	10.3
Australia/New Zealand	1.2	-19.8	-10.1	-20.5	59.3	64.7	68.5	19.8
Rest of world	-8.5	1.1	-5.4	-13.2	28.8	14.6	38.8	17.1

[1]The general circulation models (GCM) used to project the changes in temperature and precipitation from which water runoff is calculated are (in ascending order by change in mean global temperature): the University of Illinois at Urbana-Champaign, the Max Planck Institute, the Geophysical Fluid Dynamics Laboratory (GFDL89), the Hadley Centre, Oregon State University, GFDL88, Goddard Institute for Space Studies, and the United Kingdom Meteorological Office. See box, "Greenhouse Gas Concentrations and Climate Change" for more information about GCMs.

Source: USDA, ERS.

Table 7.2.10—Estimated impacts of global climate change on average annual water runoff in U.S. agricultural production regions

	Change in mean global temperature (°C)[1]							
Agricultural Production Region	1	1.1	1.3	1.8	2.8	4	4.2	5.2
	Percent change							
United States	2.4	-9.5	8.8	3.3	0.5	7.5	-6.7	4.2
Northeast	1.2	-2	-2.1	8.7	3.3	-11.9	-20.4	-2.2
Lake States	10.8	-27.2	2.3	16.9	4.9	23.4	-1.2	-10.3
Corn Belt	4.2	-22.3	2	3.4	-11.2	4.3	-8.6	-4.9
Northern Plains	32.8	-58.8	-4.3	-19.9	3.1	8.8	-15.4	-3.7
Appalachia	-0.3	-15.2	-0.4	4.7	-13.6	3.8	-16.3	-4.9
Southeast	-10.3	-20	-2.8	-5.5	-16.4	19.4	-27.4	-39.6
Delta States	-8.7	-23.9	7	-9	-21.9	8.5	-30.1	-6
Southern Plains	-2.4	-38.6	49.3	-39.6	-16.9	-2.5	-37.8	-29.4
Mountain States	1.2	-25.2	18.1	33.4	-5.8	-0.5	3	9.9
Pacific States	-1.6	-1.9	11.8	38	-2.8	2.2	17.8	21
Alaska	11.6	9.6	19.5	-5.6	30.4	16.9	7.9	32.8
Hawaii	12	-0.5	8.8	21.1	13.8	26.5	-3.3	23.5

[1]The general circulation models (GCM) used to project the changes in temperature and precipitation from which water runoff is calculated are (in ascending order by change in mean global temperature): the University of Illinois at Urbana-Champaign, the Max Planck Institute, the Geophysical Fluid Dynamics Laboratory (GFDL89), the Hadley Centre, Oregon State University, GFDL88, Goddard Institute for Space Studies, and the United Kingdom Meteorological Office. See box, "Greenhouse Gas Concentrations and Climate Change" for more information about GCMs.

Source: USDA, ERS.

The production regions where estimated runoff declines in 50 percent or more of the scenarios are the Southeast, Southern Plains, Delta States, Appalachia, the Northern Plains, and the Corn Belt. Sometimes both water runoff and length of growing season are estimated to decline simultaneously. This would make it difficult for farmers to offset shorter growing seasons by expanding irrigation. These dual declines would be more likely to occur in the Southeast, Southern Plains, and Delta regions.

The Water Sector Assessment (WSA) Team of the U.S. National Assessment (Gleick et al.) also reports a broad range of runoff changes in U.S. hydrologic regions (table 7.2.11). As in the ERS analyses, runoff increases in most regions in one-half the scenarios and declines in most regions in the other half. The hydrologic regions where estimated runoff declines in 75 percent or more scenarios are the Lower Mississippi (Delta States), the Souris-Red-Rainy (Northern Plains), the Texas-Gulf (Southern Plains), and the Rio Grande (Southern Plains). Estimated changes in runoff generated by both ERS and WSA analyses are indicative of the high level of uncertainty associated with regional climate projections.

Climate change also affects irrigation water through its impact on snowpack in mountainous areas. Snowpack is likely to decrease as climate warms, first because more precipitation would fall as rain and, second, because snowpack would develop later and melt earlier. Hence, peak stream flow is likely to come earlier in spring while summer flows are reduced. With only one exception, snowpack in major western mountain regions would decrease 50 to 100 percent by the end of the 21st century under greenhouse gas scenarios in the National Assessment (Jacobs).

Land and Water Use

Climate-induced modifications of the world's land and water resources will affect how humans use them. Increases in agricultural productivity due to CO_2 fertilization also will affect the use of land and water resources. Some of the adaptations made by humans may have secondary impacts on the extent and productivity of important ecosystems.

Land Use—ERS analyses provide estimated changes for four basic land covers—cropland, grassland, forestland, and other land. Cropland and grassland are used to produce crops and livestock, respectively. Climate change causes the suitability of land for agricultural production to shift (see "Land Resources" section above). An average decline in the suitability of land for agriculture, for example, means that more land (albeit of lower average quality) would be required to produce the same level of output. Hence the demand for land (even land of relatively low quality) in agricultural production would rise. On the other hand, increases in the agricultural productivity of land resources, due either to climate change or CO_2 fertilization, reduce the amount of land required to obtain a given level of commodity output. This, in turn, would reduce the demand for agricultural land. In ASA studies, climate change and CO_2 fertilization would generate yield changes that affect agricultural production. Farmers and other economic agents would respond to these changes in part by increasing or reducing the amount of land and other resources in agriculture.

World Land Use—Climate-induced changes in land resources are expected to trigger changes in land use and cover (Gitay et al.). The most likely are poleward shifts of cold-limited vegetation types such as boreal forests and increases in the area of tropical and temperate forests. Research at ERS generates results that are consistent with these expectations (figure 7.2.8). Grassland, which at the poles includes tundra, is estimated to decrease under climate change, while woodland would tend to increase. Estimated impacts of climate change on world cropland and other land are uncertain. There is greater certainty about the impacts of CO_2 fertilization on world cropland. ERS analyses estimate that world cropland would decline by 4.6 and 5.9 percent on average under the fertilization effects of 150-ppmv and 225-ppmv increases in atmospheric CO_2 (table 7.2.12), respectively. These decreases would offset ERS estimated climate-induced increases in cropland in all but the most severe climate change scenario, e.g., a 5.2°C-increase in mean global temperature (figure 7.2.8).

Table 7.2.11—Percent changes in annual runoff in U.S. river basins and hydrologic regions: derived from results projected by general circulation models[1]

River basin/Hydrologic region	Hadley 2030	Canadian 2030	Hadley 2095	Canadian 2095
	GCM and projected year			
	Percent change			
New England	9	–8	28	–19
Mid-Atlantic	10	–13	33	–25
South Atlantic-Gulf	0	–61	31	–73
Great Lakes	20	–12	55	–10
Ohio	7	–16	43	–18
Tennessee	4	–33	40	–37
Upper Mississippi	21	–22	68	0
Lower Mississippi	–10	–65	16	–59
Souris-Red-Rainy	–18	–24	79	–80
Missouri	18	–25	45	48
Arkansas-White-Red	–1	–39	43	6
Texas-Gulf	–10	–87	–8	–34
Rio Grande	–3	–63	60	–56
Upper Colorado	7	–36	66	5
Lower Colorado	245	–67	1,361	–29
Great Basin	21	–7	138	75
Pacific Northwest	15	–2	12	18
California	30	29	134	161

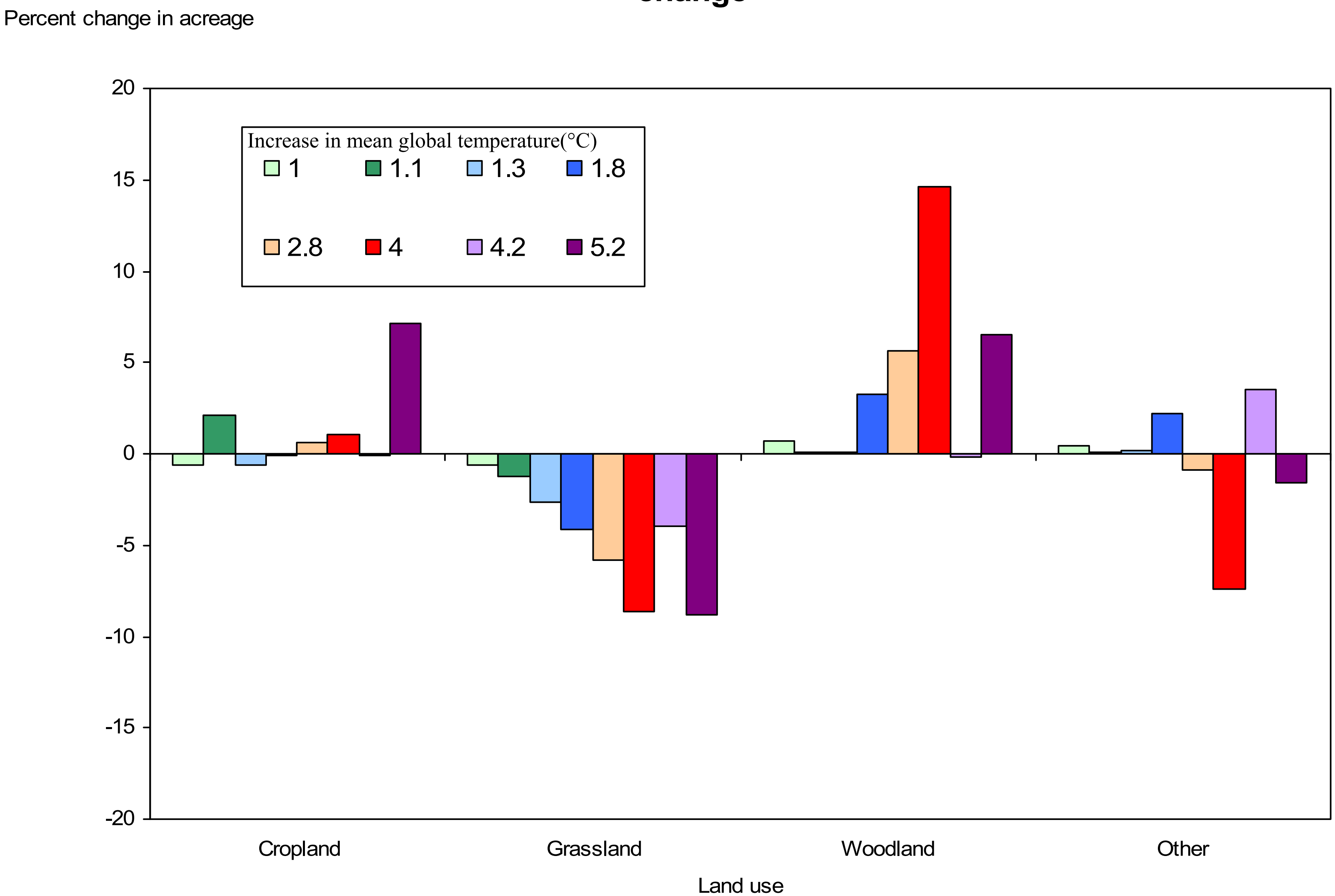
[1]The general circulation models (GCM) used to project the changes in temperature are from the Hadley Centre and the Canadian Climate Centre. See box, "Greenhouse Gas Concentrations and Climate Change" for more information about GCMs.
Source: Wolock and McCabe.

Table 7.2.12—Estimated impacts of the direct effects of increasing concentrations of atmospheric CO_2 on land and water resources

	Increase in atmospheric CO_2	
	150 ppmv	225 ppmv
	Percent change	
World		
Cropland	-4.6	-5.9
Forestland in moist tropical areas	1.1	1.7
Agricultural water	-4.4	-5.7
Total value of agricultural land	-6.8	-9.8
Price of water	-5.1	-5.3
United States		
Cropland	-5.6	-8.7
Agricultural water	-10.8	-23.3
Total value of agricultural land	-9.9	-12.6
Price of water	-5.2	-10.5
Income from agriculture	-7.7	-10.8

Source: USDA, ERS.

Figure 7.2.8 - Estimated effect of climate change on net global land-use change



Source: USDA, ERS.

The composition of tropical forests also may change under global climate change. In tropical Asia, for example, the area of tropical rain forests is estimated to decline (McLean et al.). Results from ERS indicate similar declines (figure 7.2.9). Early ERS analyses also show, however, that direct climate-induced decreases of tropical rainforests in Southeast Asia could be further aggravated by competition from crop production when mean global temperature increases by 2.8°C to 5.2°C (Darwin et al., 1995, 1996). Recent research reinforces the earlier results, but also indicates that competition from crop production may not contribute to further losses in tropical rainforests when mean global temperature increases by 1.1°C to 1.8°C. Results in figure 7.2.9, for example, show that the amount of cropland in areas classified as moist and tropical would not decline as much as the total amount of such land. This would occur because farmers would expand their cropland acreage on what moist tropical land remains. When mean global temperature increases by 2.8°C to 5.2°C, this expansion would come at the expense of forestland, which would decline by more than the total amount of all moist tropical land. When mean global temperature increases by 1°C to 1.8°C, however, expansion of cropland on moist tropical land would come at the expense of forestland in only one of four scenarios.

Some destruction of habitat that climate change could generate in some locations might be offset by decreases in cropland generated by CO_2 fertilization. The fertilization effects of 150-ppmv and 225-ppmv increases in atmospheric CO_2, for example, would be associated with 1.1 and 1.7 percent, respectively, projected increases of forestland on LC6 in moist tropical regions (table 7.2.12). These estimated increases would be large enough to offset the potential secondary impacts generated by the expansion of cropland in some scenarios, e.g., when mean global temperature increases by 2.8°C and 4°C (figure 7.2.9). However, these increases would not be large enough to reverse the total potential declines that increases in mean global temperature might generate in these forests.

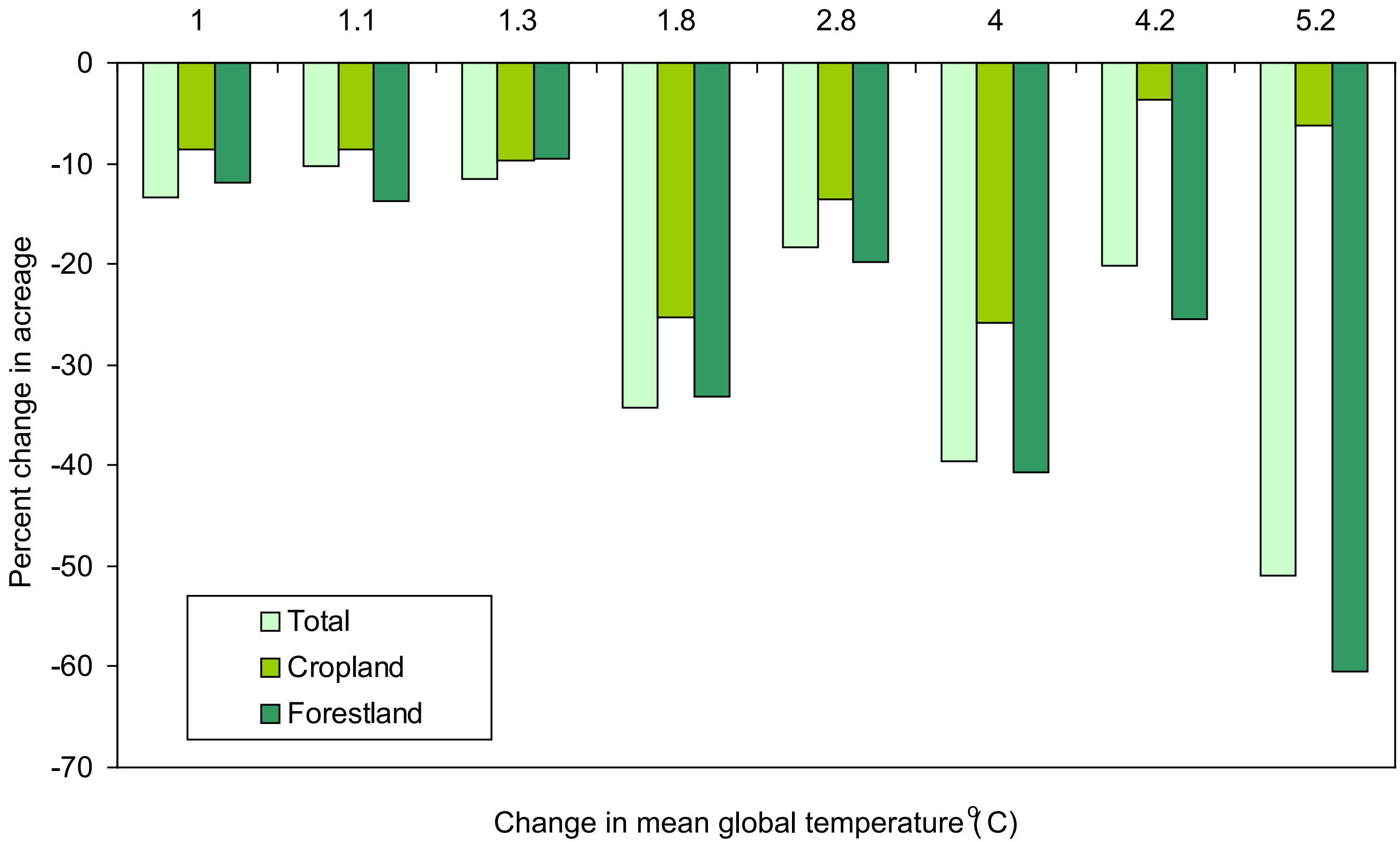
U.S. Land Use—ERS research shows that, in the U.S., cropland would generally increase, while grassland and forestland would generally decrease under global warming (figure 7.2.10). Estimated changes in other land are mixed. Estimated increases in cropland would range from 1 to 16 percent. CO_2 fertilization is estimated to reduce the amount of land required for a given level of commodity production in the United States, just as it would for the world as a whole. The fertilization effect of 150-ppmv and 225-ppmv increases in atmospheric CO_2 would be associated with 5.6- and 8.7-percent decreases of U.S. cropland, respectively (table 7.2.12). These estimated decreases would be large enough to offset some, but not all, ERS estimated increases in cropland area generated by increases in mean global temperature.

In the ASA core greenhouse gas scenarios (Reilly et al., 2002), which jointly simulate climate change and CO_2 fertilization, U.S. cropland area is always estimated to decline by 5 to 10 percent. This indicates that CO_2-fertilization effects would be moving in the same direction of, or completely offsetting, any climate-change effects. One reason why impacts of CO_2 fertilization would completely offset impacts of climate change on cropland in the ASA core scenarios may be that some of the ASA scenarios assume a 310-ppmv increase in atmospheric CO_2.

Water Withdrawals and Use

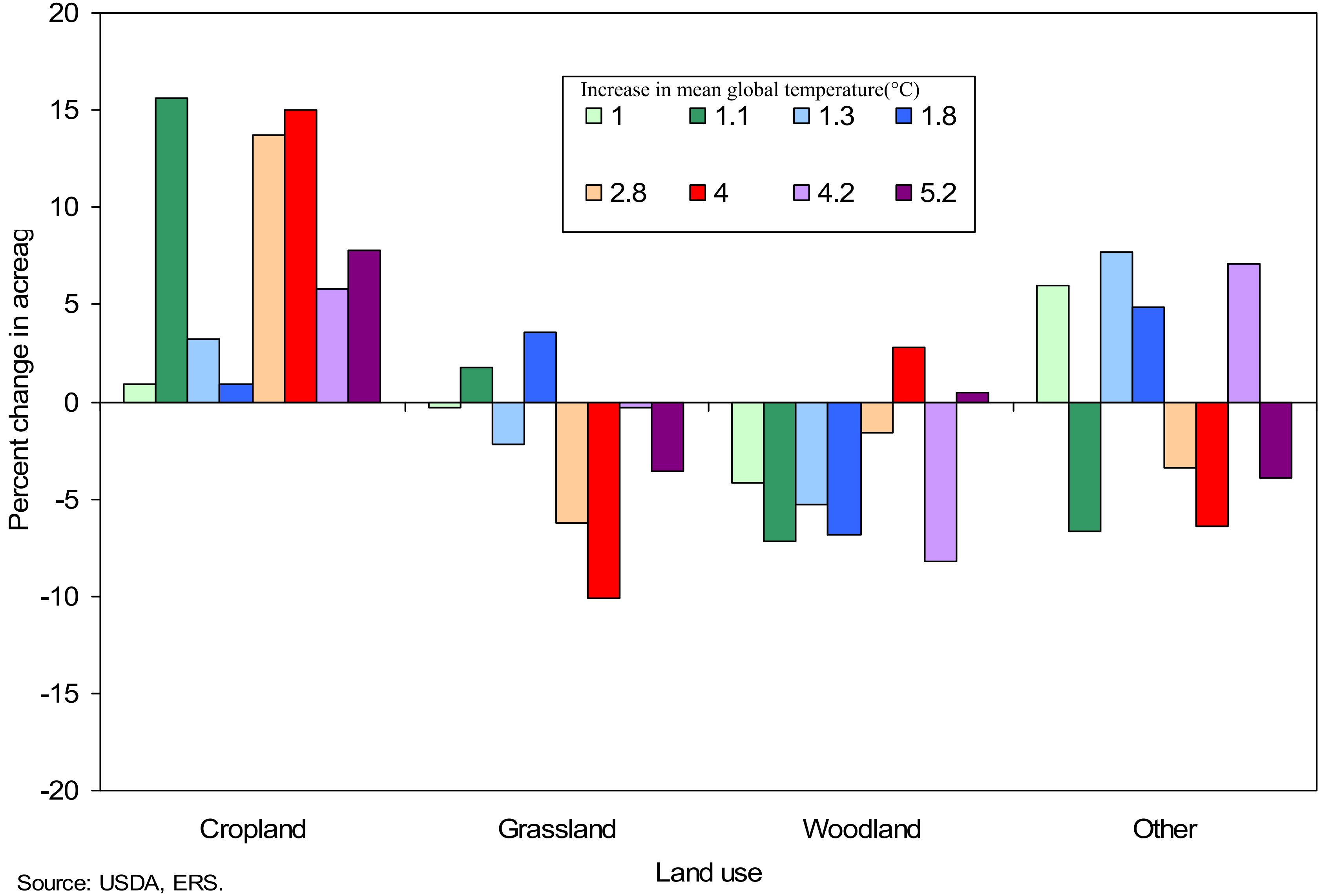
In ERS analyses, estimated changes in water supplies due to climate change are calculated directly from changes in runoff with supply elasticities (see table 4 in Darwin et al., 1995). Water supplies for the base year in ERS analyses are calibrated to total withdrawals of water, which are approximately 3,240 km^3 per year for the world and approximately 470 km^3 per year for the U.S. (table 7.2.8). Note that total withdrawals account for multiple use of the same water, e.g., water withdrawn twice is counted twice. Changes in runoff, therefore, lead to changes in total withdrawals. ERS analyses take the new total withdrawals as given. Responses are limited to changes in the allocation of total withdrawals between agricultural and non-agricultural sectors and to changes in price. All else

Figure 7.2.9 - Estimated effect of climate change on net change in total land, cropland, and forestland characterized as moist and tropical (LC6) in Africa, Latin America, Southern Asia, and Southeast Asia



Source: USDA, ERS.

Figure 7.2.10 - Estimated effect of climate change on net land-use change in the United States



Source: USDA, ERS.

equal, shorter, drier growing seasons, for example, would cause the demand for irrigation water to increase. As a result, the share of water used by the agricultural sector would increase. Non-agricultural sectors would offset their smaller shares of water by increasing capital and/or labor.

As expected, estimated changes in water supply generally have the same signs as estimated changes in runoff, but are smaller in absolute magnitude (table 7.2.13). The two exceptions occur for the aggregate "rest-of-world" region, where increased supply in the former Soviet Union is projected to more than offset decreased supplies in Other Asia, Latin America, or Africa. In one instance, this would lead to a projected increase in world water supply, rather than a decrease.

World Agricultural Water—About 69 percent of world water withdrawals are used in agricultural production (table 7.2.8). Agricultural water is generally projected to increase for the world as a whole in ERS analyses (table 7.2.14). Projected increases in world agricultural water withdrawals are associated with estimated increases in water supplies (table 7.2.13) as well as estimated increases in arid lands as depicted by projections of LC2 (figure 7.2.5). World agricultural water use would increase less than total withdrawals, for example, only when arid land decreases, e.g., scenarios where mean global temperature increases by 1.3°C and 4.2°C. Estimated impacts on regional use of agricultural water are quite variable. Some regional changes are due to changes in the amount of arid land. In Japan, the increases would be due to significant expansions in the production of rice, an irrigated crop. Changes in Canada and Australia and New Zealand appear relatively large simply because the current amount of water used in agriculture is relatively small.

Just as it does for land, CO_2 fertilization also has an indirect impact on agricultural water. By reducing the total amount of land (both rainfed and irrigated) required to obtain a given level of commodity output, it reduces the total amount of irrigation water required as well. ERS estimated that agricultural water declines by 4.4 and 5.7 percent on average under the fertilization effects of 150-ppmv and 225-ppmv increases in atmospheric CO_2 (table 7.2.12), respectively. Under some circumstances, these estimated decreases are large enough to completely offset ERS projected increases in total agricultural water induced by rising mean global temperatures.

U.S. Agricultural Water—About 42 percent of U.S. water withdrawals are used in agricultural production (table 7.2.8). ERS estimated changes in U.S. agricultural water range from –17.1 to +48.1 percent and are projected to increase in six of the scenarios (table 7.2.14). In four scenarios, increases in agricultural water would be larger than the corresponding increases in total withdrawals (table 7.2.13). In two scenarios, increases would occur even though total withdrawals decrease. The 48.1-percent increase presumes significant technological advances in the use of water by non-agricultural sectors and in the ability to move water from one location to another. (See box, "Estimating Agricultural Economic Impacts of Rising Concentrations of Greenhouse Gases".) In two scenarios, projected decreases in U.S. agricultural water would occur when arid lands (e.g., LC2) also decrease (figure 7.2.7).

As it does for the world, CO_2 fertilization reduces U.S. requirements for agricultural water. ERS analyses estimate decreases in U.S. agricultural water of 10.8 and 23.3 percent under the fertilization effects of 150-ppmv and 225-ppmv increases in atmospheric CO_2 (table 7.2.12), respectively. These estimated reductions would be large enough to offset most but not all of ERS estimated increases in agricultural water generated by rising mean global temperatures (table 7.2.14).

In the National Assessment, agricultural water decreases by approximately 5 to 40 percent (Reilly et al., 2002). These reductions are attributed to increasing precipitation in some areas and faster development of crops due to

Table 7.2.13—Estimated impacts of global climate change on water withdrawals

Region	Change in mean global temperature (°C)[1]							
	1.0	1.1	1.3	1.8	2.8	4.0	4.2	5.2
	Percent change							
World	-1.8	-0.1	0.7	-2.3	6.5	12.3	8.9	6.4
United States	1.1	-4.5	4.1	1.6	0.3	3.5	-3.2	2.0
Canada	3.4	1.3	7.1	9.9	3.4	4.5	5.6	10.4
European Community	-2.5	-5.1	-2.0	-2.6	0.4	1.7	0.0	2.9
Japan	-1.2	-0.4	4.7	-1.5	0.2	4.3	-0.8	-4.0
Other East Asia	-5.7	1.0	0.2	-2.8	7.3	15.1	19.9	5.0
Southeast Asia	-0.7	-1.0	-1.1	-2.9	-0.6	1.7	2.4	2.9
Australia and New Zealand	0.4	-6.8	-3.5	-7.0	20.3	22.1	23.4	6.8
Rest of world	-1.7	1.6	0.1	-3.5	9.5	16.5	11.3	9.1

[1]The general circulation models (GCM) used to project the changes in mean global temperature are (in ascending order by change in mean global temperature): the University of Illinois at Urbana-Champaign, the Max Planck Institute, the Geophysical Fluid Dynamics Laboratory (GFDL89), the Hadley Centre, Oregon State University, GFDL88, Goddard Institute for Space Studies, and the United Kingdom Meteorological Office. See box, "Greenhouse Gas Concentrations and Climate Change" for more information about GCMs.
Source: USDA, ERS.

Table 7.2.14—Estimated impacts of global climate change on water used in agriculture

Region	Change in mean global temperature (°C)[1]							
	1.0	1.1	1.3	1.8	2.8	4.0	4.2	5.2
	Percent change							
World	-0.3	10.3	0.3	5.5	12.8	15.8	5.7	13.5
United States	-9.7	48.1	-17.1	4.7	16.6	5.5	3.9	6.4
Canada	4.6	98.7	-87.5	-19.7	19.9	40.5	17.5	37.5
European Community	-15.6	13.5	-15.5	-40.1	-42.3	-17.4	-32.0	-11.4
Japan	22.7	27.0	48.4	36.2	65.6	73.5	63.2	62.4
Other East Asia	-4.9	0.2	1.0	-2.4	2.2	15.1	16.3	11.6
Southeast Asia	-3.0	3.4	-2.2	-0.8	4.1	3.7	-11.8	8.1
Australia and New Zealand	20.0	69.8	-35.9	77.3	86.0	131.9	35.3	97.5
Rest of world	2.6	7.0	2.3	9.8	17.0	17.4	3.8	14.6

[1]The general circulation models (GCM) used to project the changes in mean global temperature are (in ascending order by change in mean global temperature): the University of Illinois at Urbana-Champaign, the Max Planck Institute, the Geophysical Fluid Dynamics Laboratory (GFDL89), the Hadley Centre, Oregon State University, GFDL88, Goddard Institute for Space Studies, and the United Kingdom Meteorological Office. See box, "Greenhouse Gas Concentrations and Climate Change" for more information about GCMs.
Source: USDA, ERS.

higher temperatures. In addition to increases in temperature, however, Reilly et al.'s scenarios also simulate the CO_2-fertilization effects of 95- and 310-ppmv increases in atmospheric CO_2, and this probably contributes to reductions in agricultural water as well. The two largest decreases in agricultural water use (e.g., 30 to 40 percent) in the ASA, however, would be associated with the substantial declines in water supplies generated by the Canadian-GCM-based scenarios (table 7.2.11).

Value of Land and Water Resources
This section focuses on projections of the potential monetary impacts of rising greenhouse gas concentrations on land and water resources. Four impacts are evaluated—the value of agricultural land, water prices, economic welfare, and U.S. agricultural income, e.g., income from land, labor, and capital employed in the agricultural sector. The section ends with a few projected impacts of sea level rise on economic welfare.

Value of Agricultural Land—The value of agricultural land measures returns to agricultural landowners. Land is also an important source of wealth in rural areas. Changes in the value of agricultural land incorporate changes in both returns per acre and the number of acres used to produce crops and livestock. Both climate change and CO_2 fertilization can affect the demand for agricultural land. As outlined in the "Land Use" section, a decline in land's average agricultural productivity means that more land is required to produce the same level of agricultural output (and vice versa). Hence, reductions in land's agricultural productivity are associated with greater demand for agricultural land, while increases in land's agricultural productivity are associated with decreases in the demand for agricultural land. Prices per acre tend to move in the same direction as demand, e.g., increases in demand are associated with higher prices per acre and decreases in demand are associated with lower prices per acre. Because both quantity and price tend to move in the same direction, the value of agricultural land (e.g., price times quantity) also tends to increase or decrease as demand for agricultural land increases or decreases (or to increase or decrease as average agricultural productivity decreases or increases).

International trade can cause further adjustments by spreading changes in land values among regions. Climate change, for example, would enhance land's agricultural productivity in some regions but reduce it in other regions. The tendency will be for land values to decline in the former and increase in the latter. International trade, however, allows the increased demand for agricultural land in the latter to also be felt in the former. Hence, land values may not fall as much in the former and may not rise as much in the latter as they would without trade. If conditions were right, potential declines in a region's agricultural land value could even be completely offset. CO_2 fertilization, on the other hand, enhances land's agricultural productivity and would thereby reduce land values everywhere. Hence, the ability of international trade to offset declines in a region's land values is limited.

As reported by Darwin (1999a), estimated impacts of increases in mean global temperature of 2.8°C to 5.2°C on the average total value of the world's agricultural land (e.g., cropland and permanent pasture) would range from –3.1 to 1.5 percent (table 7.2.15). Impacts vary, however, by region. Projected values would increase in Southeast Asia (by 6.5 to 21.3 percent), for example, but decrease in Japan (by 27.1 to 34.7 percent). Recently estimated impacts of increases in mean global temperature from 1°C to 1.8°C on the average total value of the world's agricultural land range from –1.1 to 0.7 percent. Again, projected impacts vary by region, increasing in Europe (by 2.2 to 5.1 percent), for example, but decreasing in Japan (by 3.7 to 11.6 percent). Projected changes in U.S. agricultural land values would range from –1.7 to +6.7 percent (from –\$0.5 to +\$2.1 billion per year). Whether climate change will enhance or reduce the value of U.S. agricultural land is very uncertain. Projected increases and decreases would occur with equal frequency (four scenarios each).

In ERS analyses, the fertilization effect of 150-ppmv and 225-ppmv increases in atmospheric CO_2 are predicted to cause 6.8 and 9.8 percent declines, respectively, in the value of the world's agricultural land, on average. Under similar conditions, the value of U.S. agricultural land would be estimated to decline by 9.9 and 12.6 percent, respectively, or about \$3.1 to \$4 billion per year (table 7.2.12). In the U.S., the losses in value attributable to CO_2 fertilization would be larger than ERS estimated potential gains in value attributable to climate change.

Table 7.2.15—Estimated impacts of global climate change on the total value of agricultural land

Region	Change in mean global temperature (°C)[1]							
	1.0	1.1	1.3	1.8	2.8	4.0	4.2	5.2
	Percent change							
World	0.4	-1.1	-1.1	0.7	-3.1	1.5	-0.9	0.2
United States	-0.7	-0.8	-1.7	0.1	2.6	6.7	-3.0	0.9
Canada	-2.2	6.3	-10.8	-6.6	0.8	2.5	-3.1	7.8
European Community	2.7	2.2	2.5	5.1	1.1	3.6	5.7	6.1
Japan	-4.4	-3.7	-11.6	-11.1	-27.1	-29.4	-28.1	-34.7
Other East Asia	0.9	-6.0	-2.0	1.0	-1.2	-2.8	-5.2	-2.3
Southeast Asia	2.6	-0.4	-1.2	12.2	6.5	14.3	12.1	21.3
Australia and New Zealand	-1.5	-0.7	-0.5	7.0	-13.0	-2.9	3.4	-3.5
Rest of world	0.7	-0.8	-0.9	-0.5	-3.2	1.7	-1.1	0.0

[1]The general circulation models (GCM) used to project the changes in mean global temperature are (in ascending order by change in mean global temperature): the University of Illinois at Urbana-Champaign, the Max Planck Institute, the Geophysical Fluid Dynamics Laboratory (GFDL89), the Hadley Centre, Oregon State University, GFDL88, Goddard Institute for Space Studies, and the United Kingdom Meteorological Office. See box, "Greenhouse Gas Concentrations and Climate Change" for more information about GCMs.
Source: USDA, ERS.

Water Prices—In ERS analyses, changes in water prices reflect changes in the supply of and demand for water. Climate change affects water supplies through its impact on water withdrawals and water demand through its impacts on the soil moisture conditions of agricultural land. CO_2 fertilization would reduce demand for agricultural water because it would reduce the amount of land (both rainfed and irrigated) required to obtain a given level of commodity output (see "Water Withdrawals and Use" section). In general, increases (decreases) in water withdrawals would be associated with decreases (increases) in water prices. On the other hand, increases (decreases) in water demand would be associated with increases (decreases) in water prices. Changes in water demand, therefore, could offset or even reverse price changes generated by changes in water supply.

ERS analyses show that the price of world water is projected to increase on average in six (75 percent) of the climate-change scenarios evaluated here (table 7.2.16). In three scenarios, price increases would be associated with decreases in total water withdrawals. In another three scenarios, water prices would increase even when total water withdrawals increase. In two scenarios, decreases in the price of water would be associated with increases in total water withdrawals. There would be significant region-specific differences. Projections of water prices would tend to decrease in Canada and the European Community, for example, but would increase in Japan. In the U.S., projected changes in the price of water would range from –12 to +49 percent, increasing in five scenarios and decreasing in three. In five scenarios, U.S. water prices and withdrawals would move in opposite directions. In three scenarios, however, the price of water would increase even when water withdrawals increase.

In ERS analyses, the fertilization effects of 150-ppmv and 225-ppmv increases in atmospheric CO_2 are projected to cause 5.1- and 5.3-percent declines, respectively, in average world water prices, and 5.2- and 10.5-percent declines in average U.S. water prices (table 7.2.12). These estimated declines would be large enough to offset some but not all of ERS estimated potential increases in water prices generated by rising mean global temperatures.

Economic Welfare

Changes in economic welfare capture the complete economic impacts of changes in land and water resources generated by increasing concentrations of greenhouse gas emissions. This section focuses on world economic

Table 7.2.16—Estimated impacts of global climate change on the price of water

Region	Change in mean global temperature (°C)[1]							
	1.0	1.1	1.3	1.8	2.8	4.0	4.2	5.2
	Percent change							
World	5.3	12.9	1.5	17.8	3.5	-3.4	-8.8	11.5
United States	-5.9	48.7	-11.9	0.6	9.2	-1.6	6.5	1.0
Canada	-2.2	5.3	-9.5	-7.8	-1.4	-1.1	-2.9	-5.4
European Community	-3.4	12.8	-3.8	-11.5	-14.6	-8.2	-11.3	-7.4
Japan	23.1	26.5	42.9	43.3	114.7	113.2	112.9	141.3
Other East Asia	8.6	-4.2	3.8	3.9	-21.8	-9.2	-22.5	42.1
Southeast Asia	-3.9	10.2	-1.3	6.1	10.0	2.4	-21.9	7.8
Australia and New Zealand	7.7	55.3	-8.2	64.5	11.4	34.7	-11.7	43.9
Rest of world	8.1	7.1	3.1	29.3	4.2	-9.4	-15.6	1.3

[1]The general circulation models (GCM) used to project the changes in mean global temperature are (in ascending order by change in mean global temperature): the University of Illinois at Urbana-Champaign, the Max Planck Institute, the Geophysical Fluid Dynamics Laboratory (GFDL89), the Hadley Centre, Oregon State University, GFDL88, Goddard Institute for Space Studies, and the United Kingdom Meteorological Office. See box, "Greenhouse Gas Concentrations and Climate Change" for more information about GCMs.
Source: USDA, ERS.

welfare, U.S. economic welfare, and economic welfare in the U.S. agriculture sector. This section also reports changes in economic welfare due to potential rises in sea level.

World Economic Welfare—In ERS analyses, changes in economic welfare are annual percent changes in real expenditures (e.g., expenditures adjusted for price changes) on all goods and services plus savings. Changes in world economic welfare are population-weighted sums of percent changes in regional economic welfare. These measures are comparable to annual rates of economic growth. Early estimates of the impacts of changing temperature and precipitation patterns on world welfare were relatively small (±0.1 percent), even when global mean temperature was projected to increase by 2.8°C to 5.2°C (Darwin et al., 1995). Darwin's (1999a) revised estimates were less optimistic (declining by 0.003 to 0.110 percent) but still relatively small (table 7.2.17). Recent analyses of temperature increases ranging from 1° to 1.8°C imply estimated changes in annual welfare ranging from –0.050 to +0.004 percent. Hence, except in one scenario, ERS estimates that world welfare would decline by 0.003 to 0.110 percent. The estimates are highly uncertain, however, because their 95-percent confidence limits are relatively broad and encompass both positive and negative values over the range of temperature increases analyzed (figure 7.2.11).

This is not too surprising. The impact on world welfare would be an aggregate of opposing impacts on regional welfare (table 7.2.17 and figure 7.2.12). Economic welfare is estimated to increase in Japan by up to 0.11 percent, for example, but to decrease in Southeast Asia by as much as 1 percent, which would be a substantial reduction in economic growth. Declines in Southeast Asia's economic welfare would stem from its location in the Tropics, where initial temperatures are already relatively high. Because the "rest-of-world" combines areas at high and middle latitudes with areas in tropical zones, results for this region are not very revealing. A partial-equilibrium analysis of temperature increases ranging from 2.8°C to 5.2°C, however, estimates that economic welfare would increase in the Former Soviet Union and decrease in Latin America and Africa (Darwin, 1999a). Estimated impacts on economic welfare in Eastern and Northern Europe and in Western and Southern Asia would be mixed.

Table 7.2.17—Estimated impacts of global climate change on economic welfare

Region	Change in mean global temperature (°C)[1]							
	1.0	1.1	1.3	1.8	2.8	4.0	4.2	5.2
	Percent change							
World	0.00	-0.05	-0.05	-0.05	-0.06	0.00	-0.01	-0.11
United States	0.01	-0.05	0.04	0.03	-0.04	-0.08	0.03	0.03
Canada	0.06	-0.03	0.16	0.15	0.03	-0.01	0.19	0.10
European Community	-0.01	0.00	0.00	-0.06	-0.02	-0.08	-0.07	-0.12
Japan	0.03	-0.01	0.06	0.06	0.07	0.04	0.11	0.03
Other East Asia	0.02	-0.13	-0.15	0.09	-0.03	0.09	0.11	-0.07
Southeast Asia	-0.13	-0.07	-0.08	-0.54	-0.42	-0.53	-0.60	-1.00
Australia and New Zealand	0.07	-0.01	0.10	-0.02	0.18	-0.03	0.12	0.08
Rest of world	0.01	-0.02	-0.03	-0.05	-0.05	0.03	-0.01	-0.05

[1]The general circulation models (GCM) used to project the changes in mean global temperature are (in ascending order by change in mean global temperature): the University of Illinois at Urbana-Champaign, the Max Planck Institute, the Geophysical Fluid Dynamics Laboratory (GFDL89), the Hadley Centre, Oregon State University, GFDL88, Goddard Institute for Space Studies, and the United Kingdom Meteorological Office. See box, "Greenhouse Gas Concentrations and Climate Change" for more information about GCMs.
Source: USDA, ERS.

ERS regional estimates of economic welfare are consistent with many estimated climate-induced reductions in crop yields reported for Africa, Southern and Southeast Asia, and Latin America (Smith et al.; Singh and El Mayaar; Amien et al.; Saseendran et al.; Buan et al.; and Karim et al.). They are also consistent with estimates of changes in agricultural production in Africa, Asia, and Latin America (Winters). In a global study of climate change projected for 2080 (Fischer et al.), rainfed cereal production is projected to increase in high-latitude regions like Canada and Russia and to either increase or decrease in temperate and tropical regions, depending on local conditions. Equatorial South America, South and Southeast Asia, and Africa, however, are projected to be particularly hard hit, which would cause the estimated number of undernourished people to increase substantially in some 40 countries (Fischer et al.).

Because of its beneficial effects on crop growth, CO_2 fertilization is projected to increase economic welfare (Reilly and Hohmann; Tsigas et al.; Darwin and Kennedy). Early global estimates of the value of CO_2 fertilization were relatively high, ranging from $666 million to $1,952 million (measured in 1990 dollars) per ppmv of CO_2 per year. These estimates are upwardly biased, however, because they were based on an incorrect assumption about the relationship between percent changes in supply and percent changes in yield. (See box, "Estimating Agricultural Economic Impacts of Rising Concentrations of Greenhouse Gases".) Estimates are smaller without that bias. Based on a 225-ppmv increase in atmospheric CO_2, ERS estimates that world economic welfare would increase by about $348 million (measured in 2000 dollars) per ppmv. The total impact on world economic welfare would be about 0.67 percent (Darwin and Kennedy). In recent ERS analyses the beneficial effects of a 150-ppmv increase in atmospheric CO_2 on crop growth are associated with an increase in world economic welfare of about 0.48 percent (table 7.2.18).

These estimated gains in global welfare are consistent with estimated increases in agricultural production due to

CO_2 fertilization (Rosenzweig and Parry). They also more than offset global climate-induced welfare losses estimated directly by ERS. In addition, conservatively estimated regional benefits of fertilization generated by a 150-ppmv increase in atmospheric CO_2 would more than offset most of the estimated worst-case regional damages induced by climate change (table 7.2.18). The only exceptions are the U.S. and Southeast Asia. The worst-case damages in the U.S. would be more than offset by the conservatively estimated benefits of a 225-ppmv increase in atmospheric CO_2. Another recent study, however, estimated that world cereal production would decrease as early as 2020 under global climate change even when the direct effects of CO_2 on crop growth were included. Declines were most prevalent in Africa, Southeast Asia, and Latin America (Parry et al.).

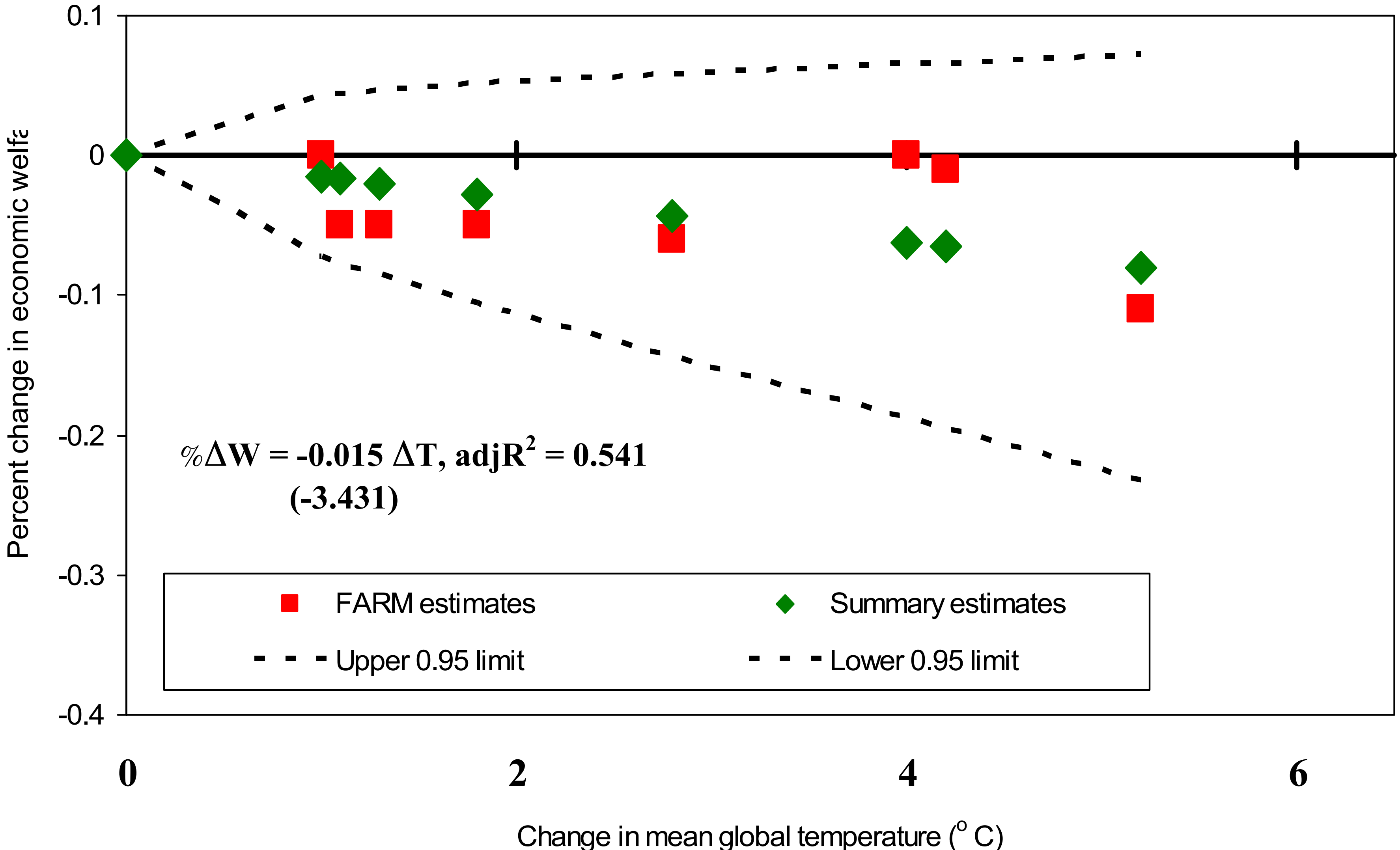
U.S. Economic Welfare—A number of recent studies have estimated changes in U.S. economic welfare due to potential agricultural impacts of rising concentrations of greenhouse gases (table 7.2.19). For details of these studies, see "Estimating Agricultural Economic Impacts of Rising Concentrations of Greenhouse Gases." Estimates provided by Mendelsohn et al. (1999) are very broad, ranging from –\$6 to +\$46 billion per year. Much of this variability, however, is due to the use of different models. In ERS analyses, the range of estimated impacts derived from a global economic model is much narrower, e.g., ranging from –\$5.4 to +\$2.2 billion per year (–0.08 to +0.03 percent) when mean global temperature increases by 2.8°C to 5.2°C (Darwin 1999a). When mean global temperature increases by 1°C to 1.8°C, estimated impacts on U.S. economic welfare range from –\$3.4 to +\$2.5 billion per year (–0.05 to +0.04 percent). There is no discernible trend in these results and the 95-percent confidence limits are fairly broad, encompassing positive and negative impacts over the range of temperatures investigated (figure 7.2.13).

Early estimates of annual U.S. welfare generated by CO_2 fertilization ranged from \$26.6 to \$61.1 billion per year for a 225-ppmv increase in CO_2 (Adams et al.). This works out to \$118 to \$272 million per ppmv CO_2 per year. These estimates include benefits from current export demand in non-U.S. markets. In recent ERS analyses, the direct annual impacts of a 225-ppmv increase in atmospheric CO_2 were estimated to range from \$9.1 to \$12.3 billion, or from \$40 to \$55 million per ppmv atmospheric CO_2 (Darwin and Kennedy). These estimates do not include benefits in non-U.S. markets. They do include changes in international trade, specifically a smaller demand for U.S. exports and greater supply of imports into the U.S. which one would expect from increases in agricultural production overseas. The direct annual impact of a 150-ppmv increase in atmospheric CO_2 on U.S. welfare is conservatively estimated to be \$4.9 billion, or about \$33 million per ppmv atmospheric CO_2.

Some studies evaluate scenarios that simultaneously combine the effects of climate-change and CO_2-fertilization. Annual impacts on U.S. welfare of a 4.3°C- to 4.4°C-increase in global mean temperature coupled with a 225-ppmv increase in atmospheric CO_2, for example, were estimated to range from –\$20.0 to +\$14.8 billion (Adams et al.). The estimates include benefits from current export demand in non-U.S. markets. The ASA estimates increases in U.S. welfare ranging from –\$0.3 to +\$11.8 billion under increases in mean global temperature ranging from 1.4°C to 5.8°C coupled with either a 95-ppmv or 310-ppmv increase in atmospheric CO_2 (McCarl; Reilly et al., 2002). These estimates do not include benefits in non-U.S. markets.

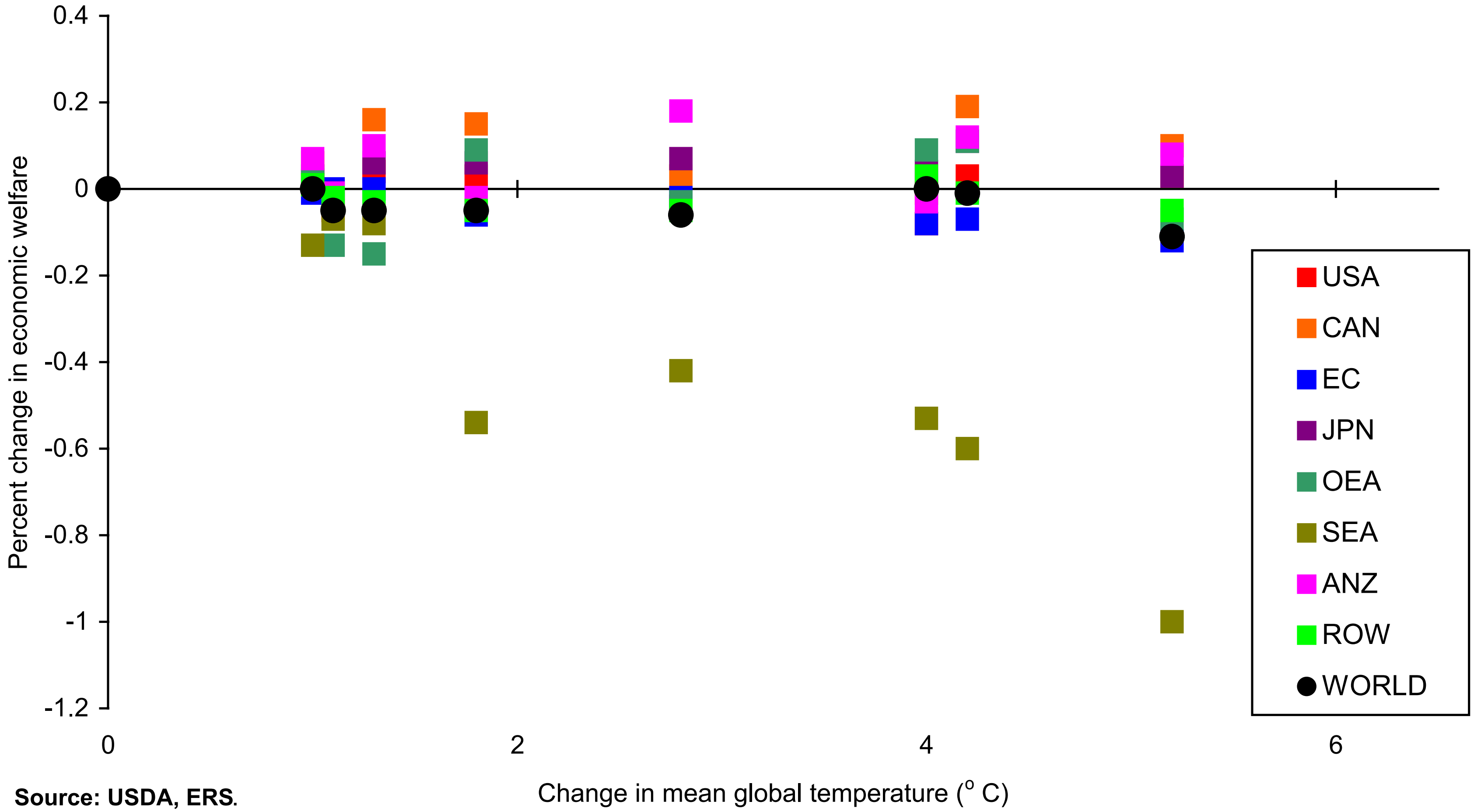
U.S. Agriculture Sector—In ERS analyses, welfare impacts on the U.S. agricultural sector are measured by changes in real income obtained from primary factors (e.g., land, labor, and capital) utilized in agricultural

Figure 7.2.11 - Estimated effect of climate change on world economic welfare



Source: USDA, ERS.

Figure 7.2.12 - Estimated effect of climate change on regional economic welfare



Source: USDA, ERS.

Table 7.2.18—Regional impacts of CO_2 fertilization and the worst-case impacts of global climate change

Region	Worst-case global climate change scenario[1]	150-ppmv increase in atmospheric CO_2	225-ppmv increase in atmospheric CO_2[2]
	Percent change in economic welfare		
United States	-0.08	0.07	0.13
Canada	-0.03	0.08	0.17
European Community	-0.12	0.13	0.15
Japan	-0.01	0.20	0.18
Other East Asia	-0.15	0.80	0.96
Southeast Asia	-1.00	0.61	0.98
Australia and New Zealand	-0.03	0.03	0.05
Rest of world	-0.05	0.44	0.66
World	-0.11	0.48	0.67

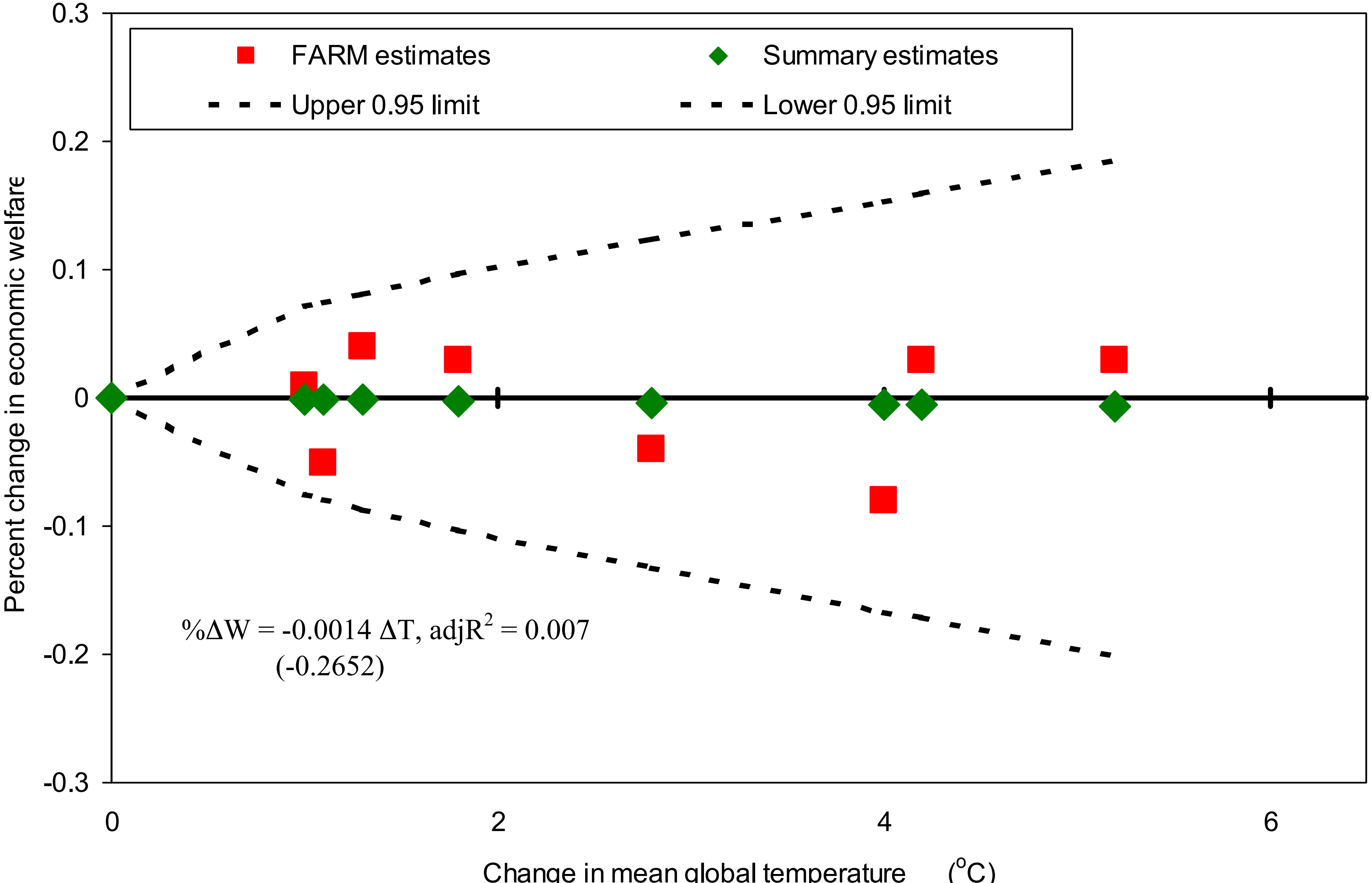
[1]Worst-case refers to impacts directly estimated with ERS models (see Table 7.2.17). The value for the world does not include potential losses derived from lower bounds of 95-percent confidence limits of model results.
[2]Darwin and Kennedy
Source: USDA, ERS.

Table 7.2.19—Estimated annual impacts (billion 2000 dollars per year) of rising concentrations of greenhouse gases on U.S. economic welfare[1]

Study	Changes in temperature or atmospheric CO_2	Measure	Value
		Billion 2000 $	
Mendelsohn, Nordhaus, and Shaw (1999)	Uniform increase of 5°C with increases in precipitation of 0 to 15 percent over U.S.	Ricardian rent on farmland[2]	–$6.0 to +$45.9
Darwin (1999a)	Increases of 2.8°C to 5.2°C globally from four GCMs	Total welfare[3]	–$5.4 to +$2.2
Darwin and Kennedy (2000)	An increase of 225 ppmv atmospheric CO_2	Total welfare	+$9.1 to +$12.3
Adams et al. (1999)	Increases of 4.4°C and 4.3°C globally from two GCMs and 225 ppmv atmospheric CO_2	Total surplus (TS)[4], Agricultural producer surplus (PS)	TS: –$20.0 and +$14.8 PS: –$2.4 and +$11.6
McCarl (2000)	Increases of 1.4°C to 5.8°C over U.S. from two GCMs and 95 and 310 ppmv atmospheric CO_2	Total U.S. surplus (USTS)[5], agricultural producer surplus (PS)	USTS: –$0.3 to +$11.8 PS: –$5.1 to –$0.4

[1]Units were annualized where appropriate and converted to 2000 dollars in order to facilitate comparisons across studies. Correction factors for converting 1982 and 1990 dollars to 2000 dollars are, respectively, 1.615 and 1.237. Derived from data in *Economic Report of the President: Transmitted to Congress, February 2001*.
[2] Ricardian rents implicitly assume that the value of land with a given set of climatic conditions is fixed even though climate change may cause the total amount of land with those characteristics to change. Despite their association with farmland, Ricardian rents measure changes in overall economic welfare. Changes in Ricardian rents, however, simply provide a monetary measure of climate-induced changes in the agricultural suitability of farmland. The monetary changes are not actually retained by landowners, but passed on to consumers. In fact, increases in Ricardian rents are correlated with decreases in income from agricultural land (Darwin, 1999a).
[3]Total welfare is total real expenditures (e.g., expenditures adjusted for price changes) on all goods and services plus savings.
[4]Total surplus is the sum of U.S. consumer surplus, foreign consumer surplus, U.S. agricultural producer surplus, and foreign agricultural producer surplus.
[5]Total U.S. surplus is the sum of U.S. consumer surplus and U.S. agricultural producer surplus.

Figure 7.2.13 - Estimated effect of climate change on U.S. economic welfare



Source: USDA, ERS.

production. Estimated impacts of climate change on U.S. agricultural income would range from –\$0.2 to +\$5.9 billion per year, or from –0.2 to +6.1 percent. There would be a slight upward trend as mean global temperature increases, e.g., for every 1°C-increase in mean global temperature, annual U.S. agricultural income would increase by 1.1 percent or \$1.1 billion (figure 7.2.14). The trend is associated with increases in the price of agricultural commodities, which are associated with a decline in world welfare. The 95-percent confidence limits are fairly broad, however, encompassing positive and negative impacts over the range of temperatures investigated.

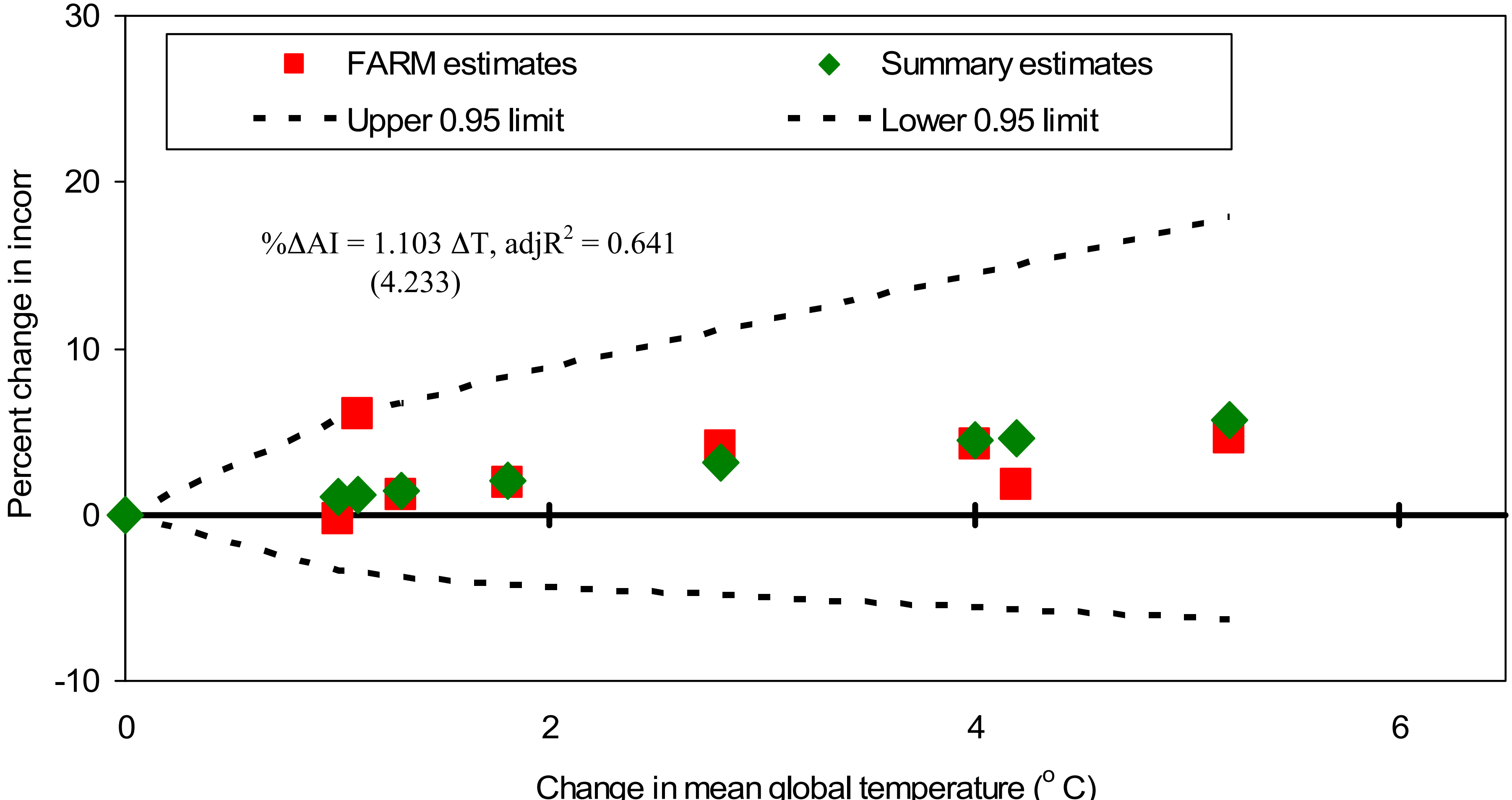
Early estimated annual impacts of CO_2 fertilization on U.S. agricultural producers ranged from –\$90.9 to +\$2.4 billion, or from –\$404 to +\$11 million per ppmv CO_2, for a 225-ppmv increase in CO_2 (Adams et al., 1995). More recently, ERS conservatively estimated the direct annual impacts of 150-ppmv and 225-ppmv increases in atmospheric CO_2 on U.S. agricultural income to be, respectively, –\$7.6 and –\$10.6 billion (–7.7 and –10.8 percent) on average, or losses of \$51 and \$47 million per ppmv atmospheric CO_2 (table 7.2.12). These losses in agricultural income would be attributed to declines in agricultural prices that would, in turn, be driven by the increase in agricultural productivity generated by the fertilization effect. The flip side of these falling prices, however, is the expected increase in consumer welfare.

In three studies that evaluate climate change and CO_2 fertilization simultaneously, impacts on U.S. agricultural producers were projected to range from –\$2.4 to +\$11.6 billion per year (Adams et al., 1999) and from –\$5.1 to –\$0.4 billion per year (McCarl, 2000; Reilly et al., 2002). Both the gains to consumers and losses to producers are attributed to lower commodity prices (Reilly et al., 2002). These studies hold constant the demand for U.S. exports and the supply of imports into the U.S. Because it stimulates crop growth worldwide, however, CO_2 fertilization would reduce demand for U.S. agricultural commodities and increase the supply of imports into the U.S. Hence, U.S. farmers would likely sell less and at lower prices, which would in turn mean more negative or less positive estimates of producer surplus than those reported in these studies (Darwin, 2000).

There is little explicit information on how greenhouse gas concentrations will affect economic welfare in U.S. production regions. It will depend primarily on the specific shifts in temperature and precipitation patterns that climate change generates as well as on the regional responses to changes in comparative economic advantage that the shifting climatic patterns will induce. The former is uncertain. At present, the different climatic patterns generated by various GCMs produce widely varying impacts on land and water resources (see tables 7.2.7, 7.2.10, and 7.2.11). With regard to the latter, however, one would expect that agricultural production (and the surplus or income that such production provides) would shift from relatively less favored to relatively more favored regions. The overall impact on regional economic welfare would, in turn, depend on the importance of agriculture in the regional economy. That is, it would be larger in regions where agriculture is a major source of income.

For example, producer surplus would decline by \$3.2 billion per year in a 2030 scenario based on the Hadley Centre's GCM (McCarl). Aggregate production would increase by 25 to 60 percent in the most-favored regions, but only by 6 to 18 percent in least-favored regions. One would expect that producer surplus would decline more in the least-favored regions than in the most-favored regions. In fact, producer surplus may even increase in some most-favored regions. The regions least favored in the climate change scenarios used by the National Assessment are the Southeast, Southern Plains, Northeast, Delta States, and Appalachia (McCarl). The regions least favored in the climate change scenarios used in ERS analyses are the Southeast, Corn Belt, Delta States, Lake States, and Northern Plains (see table 7.2.7).

Figure 7.2.14 - Estimated effect of climate change on U.S. income from agricultural land, labor, and capital



Source: USDA, ERS.

Sea Level Rise and Economic Welfare—The midpoint of sea-level-rise projections for the end of the 21st century is approximately 0.5 meters (Church et al.). (See box, "Greenhouse Gas Concentrations and Climate Change".) For the world as a whole, the estimated direct annuitized cost of a 0.5-meter rise in sea level by the end of the 21st century ranges from $11.0 to $16.7 billion (measured in 2000 U.S. dollars)(Darwin and Tol). Direct costs include the value of dry land lost to sea level rise, the cost of coastal protection, the value of wetland lost to coastal protection, and the value of wetland lost to sea level rise. The range of projections stems from assuming different initial land values in the analysis. As a worldwide phenomenon, however, climate-induced sea level rise would likely cause significant losses in land and capital endowments in many regions simultaneously. The size and scope of these losses would induce a general increase in consumer prices that would generate economic costs over and above any direct costs. Darwin and Tol estimate that including these price effects would increase annual costs by about 13 percent. Darwin and Tol also found that the response of international traders to differential changes in regional prices tends to redistribute losses from regions with relatively high damages from sea level rise to regions with relatively low damages. This means that sea level rise would be likely to reduce economic welfare even in landlocked regions.

Darwin and Tol estimate the direct annuitized cost to the U.S. of a 0.5-meter rise in sea level by the end of the 21st century would range from $1.2 to $2 billion per year (Darwin and Tol). Again, the range of projections stems from assuming different initial land values in the analysis. Including price effects would increase annual costs by about 43 percent, e.g., from $1.7 to $2.8 billion. These estimates are much higher than estimates provided by Yohe, Neumann, and Marshall, who report annual direct annuitized costs of $33, $104, and $203 million (measured in 2000 U.S. dollars) for sea level rises of 0.33, 0.67, and 1 meter, respectively, by the end of the 21st century. Darwin and Tol's direct annuitized costs are larger primarily because they assume that the coastline subject to inundation is longer (29,000 kilometers versus 20,000 kilometers or less), the cost of protection is higher ($3.3 million versus $2.5 million per kilometer against a 1-meter rise in sea level), and the discount rate is lower (1 percent versus 3 percent). The last difference is particularly important. The present value of $1,000,000 spent in 2100 is about $368,000 and $50,000, respectively, under discount rates of 1 and 3 percent. Resolving these issues will help to reduce the uncertainty surrounding estimates of the impacts of sea level rise.

Policies That Aid Adaptation

Analyses clearly indicate that climate change caused by rising concentrations of greenhouse gases could affect the location and level of agricultural production in many areas. As a result, the long-term productivity and competitiveness of agriculture in some regions may be at risk and climate change may thereby disrupt farm communities. Concerns over environmental impacts of agriculture on land and water resources could increase in some regions as well. It is also likely, however, that some potential losses would be at least partially offset by gains in other regions. CO_2 fertilization, on the other hand, would cause the price of agricultural commodities to fall. This, in turn, would reduce the amount of income obtained in the agricultural sector. The extent to which losses are avoided and gains obtained, however, will depend on how farmers adapt their production processes to the new climatic and other conditions (Rosenzweig and Parry; Darwin et al., 1995; Schimmelpfennig et al.). This section focuses on public policies that could affect the ability of farmers to effectively respond to the challenges posed by global climate change and other potential impacts of rising greenhouse gas emissions.

There are a number of public policies that would encourage appropriate adaptations. Some adaptations, such as switching crop varieties, introducing more suitable crops, or shifting from crops to grazing, can often be undertaken by individual farmers on their own. Such autonomous responses, however, require adequate detection, which is difficult given the year-to-year variability of weather events. Nevertheless, government policies that support reliable 6- to 8-month weather projections or information about suitable alternative crop and livestock possibilities would help farmers make efficient choices about what to produce in a given year. Government policies that support reliable longrun information about potential changes in climate in specific locations would facilitate autonomous responses that require adjustments over time. Obtaining such information is one of the objectives of the Climate Change Research Initiative (see box, “Governmental Response to Climate Change”). Government policies that encourage the development of new varieties that can better withstand episodes of low soil moisture or high air temperatures during the growing season also would be helpful in some areas. The characteristics of such new crop varieties will eventually spread to other areas, however, and thereby put downward pressure on agricultural prices.

Other adaptations, such as increasing irrigation, maintaining flood control, or preserving soil and water resources, require cooperation with other farmers or with other members of society over a longer timeframe. To increase irrigation or maintain flood control, for example, storage capacity behind dams may have to be adjusted. USDA’s Natural Resources Conservation Service is already “updating the climate components of its primary erosion prediction and conservation planning tool using precipitation and temperature data covering the period 1971-1999” (Soil and Water Conservation Society). Such adaptations would benefit from government policies that provide reliable longrun information about potential changes in climate and their effects on land and water resources in specific locations.

Another adaptation that requires long-term cooperation with other members of society would be to expand agricultural markets. Expanding markets primarily involves increasing the ability to trade agricultural commodities both within and between countries. Increasing the ability to trade would enable regions where the suitability of agricultural production declines to obtain agricultural commodities from regions where the suitability of agricultural production increases. Government policies that provide the necessary roads or other physical infrastructure as well as those that reduce international trade barriers would help to expand agricultural markets.

Finally, adaptation does not guarantee that farming will continue in an area or, if it does, that farm incomes will remain unchanged. Some adaptation, therefore, will involve shifting agricultural production from one location to another. This adaptation, too, would benefit from government policies that support reliable longrun information about where agriculture will and will not be economically feasible under climate change. It may be difficult in some locations to determine when a safety net is no longer justified to ease the pain of normal year-to-year variability in weather and becomes a hindrance to necessary adaptations (Lewandrowski and Brazee). As illustrated by estimated forestland changes in moist tropical regions (see Land and Water Use section above), however, expanding agriculture into new areas may conflict with ecological objectives. Government policies that encourage changes in land use may have to be tempered with constraints in ecologically sensitive areas. Similar problems are likely to arise when expanding irrigation systems, particularly in areas where climate change reduces water resources. Government policies that facilitate the migration of people from one location to another, or the transition from one profession to another, may be useful. The latter would include policies that stimulate economic growth and development and thereby encourage more alternatives to agriculture as a source of livelihood.

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Glossary of Special Terms

CO_2 fertilization—The beneficial effect on plant growth that rising concentrations of atmospheric carbon dioxide (CO_2) generate through its ability to increase water-use efficiency and the rate of photosynthesis in most plants.

Climate—The average meteorological conditions—temperature, precipitation, wind, etc.—that prevail in a region.

Climate change—An overall trend toward global warming and increased amounts of precipitation.

Climate change scenarios—Projections of climatic variables used in analyses of global climate change. Some studies rely on uniform increases in temperature and precipitation. Other studies rely on results from general circulation models (GCM).

Evapotranspiration—The combined loss of water from a given area in a specific time period by evaporation from the soil surface and by transpiration from plants.

General circulation model (GCM)—Large, complex mathematical models that simulate changes in global meteorological conditions.

Greenhouse gas—The term "greenhouse" refers to the ability of some gases to absorb energy radiated from Earth to space and to thus warm the atmosphere. The most important greenhouse gas is water vapor (H_20). The most important greenhouse gases associated with human activities are carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O).

Greenhouse gas intensity—Measures the ratio of greenhouse gas emissions to economic output.

Length of growing season—Length of time during the year that soil temperature and soil moisture are continuously suitable to crop growth.

Ppmv—Parts per million by volume.

Thermal regime— Average temperature during the growing season.

Trends in Greenhouse Gas Concentrations

Concentrations of carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O), and other greenhouse gases have increased in the Earth's atmosphere since the Industrial Revolution. The term "greenhouse" refers to the ability of these gases to absorb energy radiated from Earth to space and to thus warm the atmosphere. The atmospheric concentration of CO_2, for example, has increased by 31 percent since 1750 (Intergovernmental Panel on Climate Change, 2001). It has increased by 17 percent (from 315 ppmv to about 370 ppmv) since 1958 (National Research Council, 2001). Atmospheric concentrations of CH_4 and N_2O have grown by about 145 percent and 15 percent, respectively, since 1750. (See table 7.2.20 and figure 7.2.15 for additional information on past concentrations of greenhouse and other gases.) Some of these increases are due to human activities that emit greenhouse gases into the atmosphere. Major human sources include combustion of fossil fuels, deforestation, and production of some agricultural commodities such as rice and livestock. Concentrations are expected to increase in the future. The rate of increase depends on the rate of world economic growth and the technologies utilized in production of energy (Nakicenovic and Swart, 2000). (See box, "Greenhouse Gas Concentrations and Climate Change".)

Table 7.2.20—Examples of greenhouse gases associated with human activities

	Carbon dioxide (CO_2)	Methane (CH_4)	Nitrous oxide (N_2O)
Pre-industrial concentration	280 ppmv	700 ppbv	275 ppbv
Concentration in 1994[1]	358 ppmv	1,720 ppbv	312 ppbv
Rate of concentration change[2]	1.5 ppmv/yr	10 ppbv/yr	0.8 ppbv/yr
Atmospheric lifetime (years)[3]	50 – 200	12	120

ppmv = parts per million by volume; ppbv = parts per billion by volume

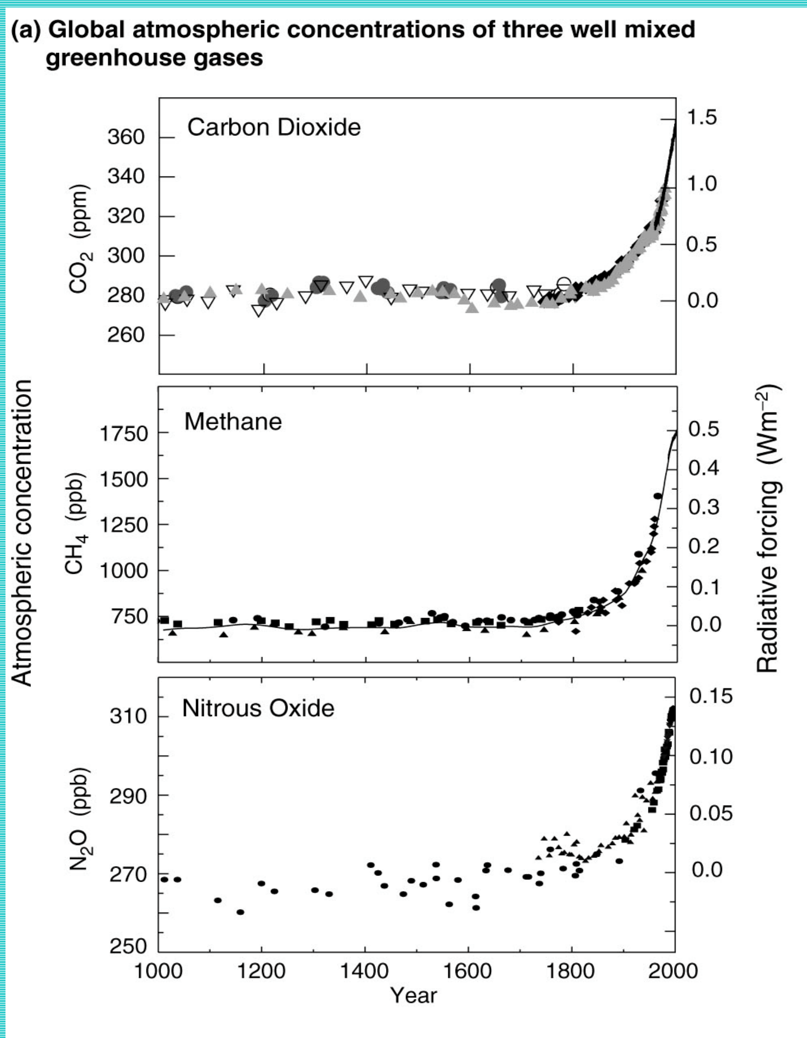
[1] N_2O concentration estimated from 1992-1993 data.

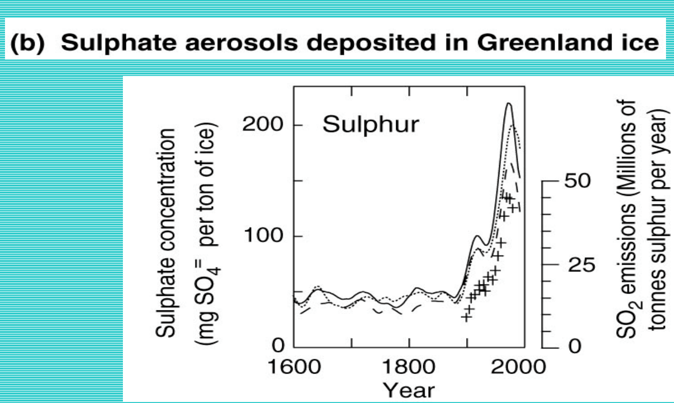
[2] Growth rates are averaged over the decade beginning in 1984.

[3] No single lifetime for CO_2 can be defined because of the different rates of uptake by different processes. Adjustment time for CH_4 takes account of the indirect effects of CH_4 on its own lifetime.

Source: Intergovernmental Panel on Climate Change (1996)

Figure 7.2.15—Greenhouse gas concentrations during the industrial era.





Source: Intergovernmental Panel on Climate Change (2001)

Greenhouse Gas Concentrations and Climate Change

Climate refers to average meteorological conditions—temperature, precipitation, wind, etc.—that prevail in a region. Climate change may refer to any change in climate over time whether due to natural variability or human activity. Three major sources of natural variability affect climate: changes in the Earth's orbit, changes in ocean currents due to shifting continents or large-scale melting of continental ice, and changes in the composition of the global atmosphere—especially water vapor and "greenhouse" gases such as carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O)—due to volcanic or other tectonic activities. The term "greenhouse" refers to the ability of these gases to absorb energy radiated from Earth to space and to thus warm the atmosphere. Other gases, particularly sulfur dioxide (SO_2), form aerosols that cool the atmosphere by reflecting sunlight.

Emissions from human activity may also influence the composition of the global atmosphere. According to the Third Assessment Report by Working Group I to of the Intergovernmental Panel on Climate Change (IPCC), which organizes, summarizes, and reports the work of several hundred scientists, increases in the emission of these gases have been associated with a rise in mean global temperature of from 0.3°C to 0.6°C since the late 19th century (IPCC, WGI). The IPCC also concluded that the balance of evidence suggests that there is a discernible influence on global climate by human emissions of greenhouse gases into the atmosphere (IPCC, 1996). (See figure 7.2.16 for simulations of natural and anthropogenic influences on global mean surface temperatures.)

Both the IPCC and the National Research Council (NRC) suggest that the Earth's climate probably will warm during the 21st century (IPCC, 2001; NRC). A substantial portion of this warming may occur even if global efforts are undertaken to reduce emissions of heat-trapping gases. As indicated in figure 7.2.17, panel d, estimates of the rise in mean global temperature range from 1.4°C to 5.8°C by the end of the century (IPCC, 2001). Precipitation is also projected to increase on average, but not uniformly. It is projected to increase in high latitudes and most tropical areas (particularly over oceans), but projected to decrease in most of the subtropics (Cubash et al., 2001). These projections are consistent with changes in precipitation patterns during the 20th century (Folland et al.). Sea level rise is an important consequence of climate change. As indicated in figure 7.2.17, panel e, estimates of the rise in mean global sea level range from 0.09 to 0.88 meters by the end of the century (Church et al.).

The broad range in projections is due to two major sources of uncertainty. First, as shown in figure 7.2.17, panels a-c, there is considerable uncertainty in projections of economic activity and associated changes in atmospheric concentrations of greenhouse and other gases. (For more information about the characteristics of the economic scenarios underlying figure 7.2.17, see IPCC (2001) or Nakicenovic and Swart). Second, there is considerable uncertainty in current understanding of how the climate system varies naturally and reacts to changes in atmospheric concentrations of greenhouse and other gases (NRC). Hence, current projections of concentrations as well as climatic and related responses should be regarded as tentative and subject to future adjustments (either upward or downward) (NRC).

The NRC suggests a number of specific areas of science that need to be studied further (in order of priority) to advance our understanding of climate change. They include: "(1) the future use of fossil fuels; (2) the future emissions of methane; (3) the fraction of the future fossil-fuel carbon that will remain in the atmosphere and provide radiative forcing versus exchange with the oceans or net exchange with the land biosphere; (4) the feedbacks in the climate system that determine both the magnitude of the change and the rate of energy uptake by the oceans, which together determine the magnitude and time history of the temperature increases for a given radiative forcing; (5) details of the regional and local climate change consequent to an overall level of global climate change; (6) the nature and causes of the natural variability of climate and its interactions with forced changes; and (7) the direct and indirect effects of the changing distributions of aerosols" (NRC).

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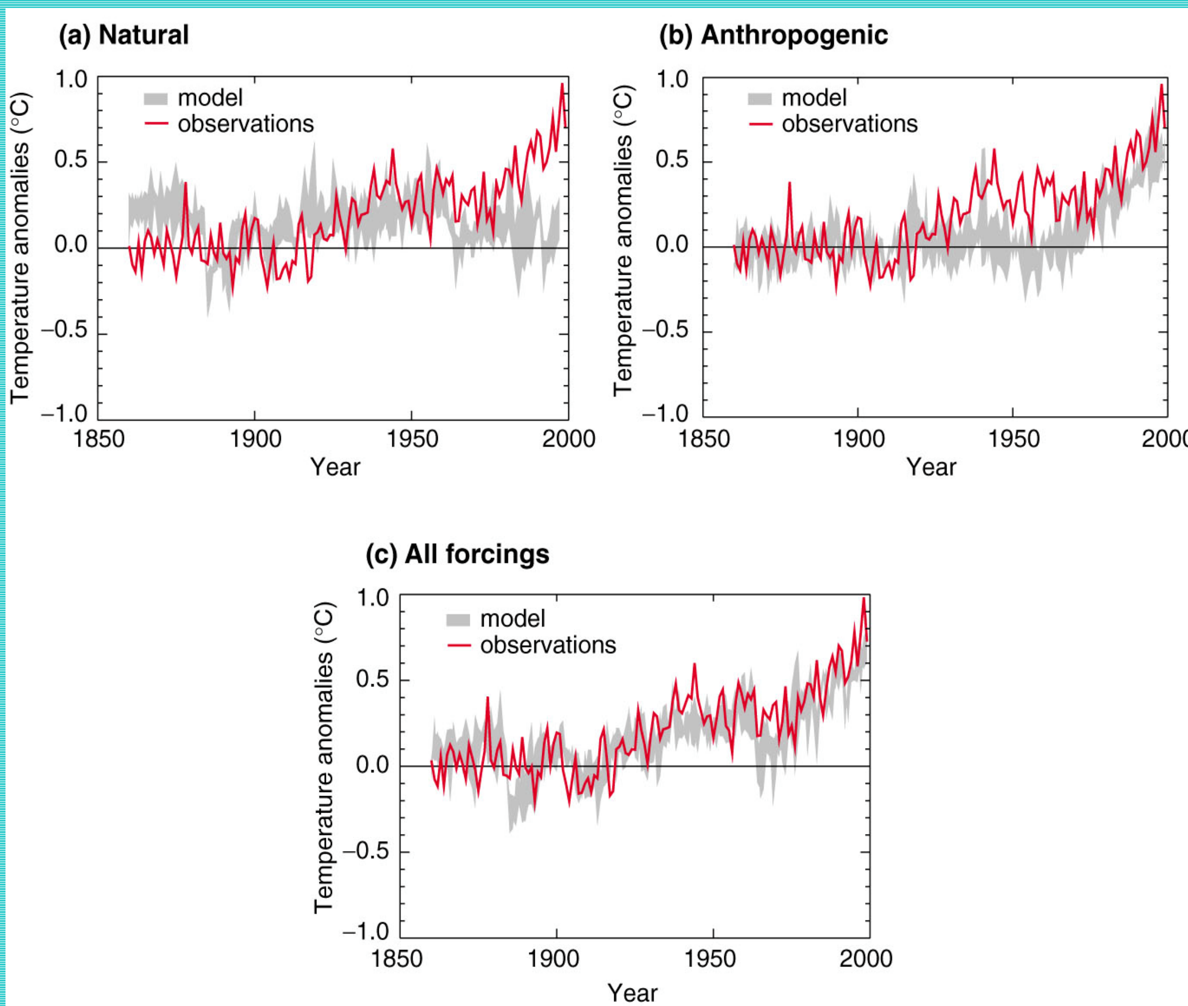
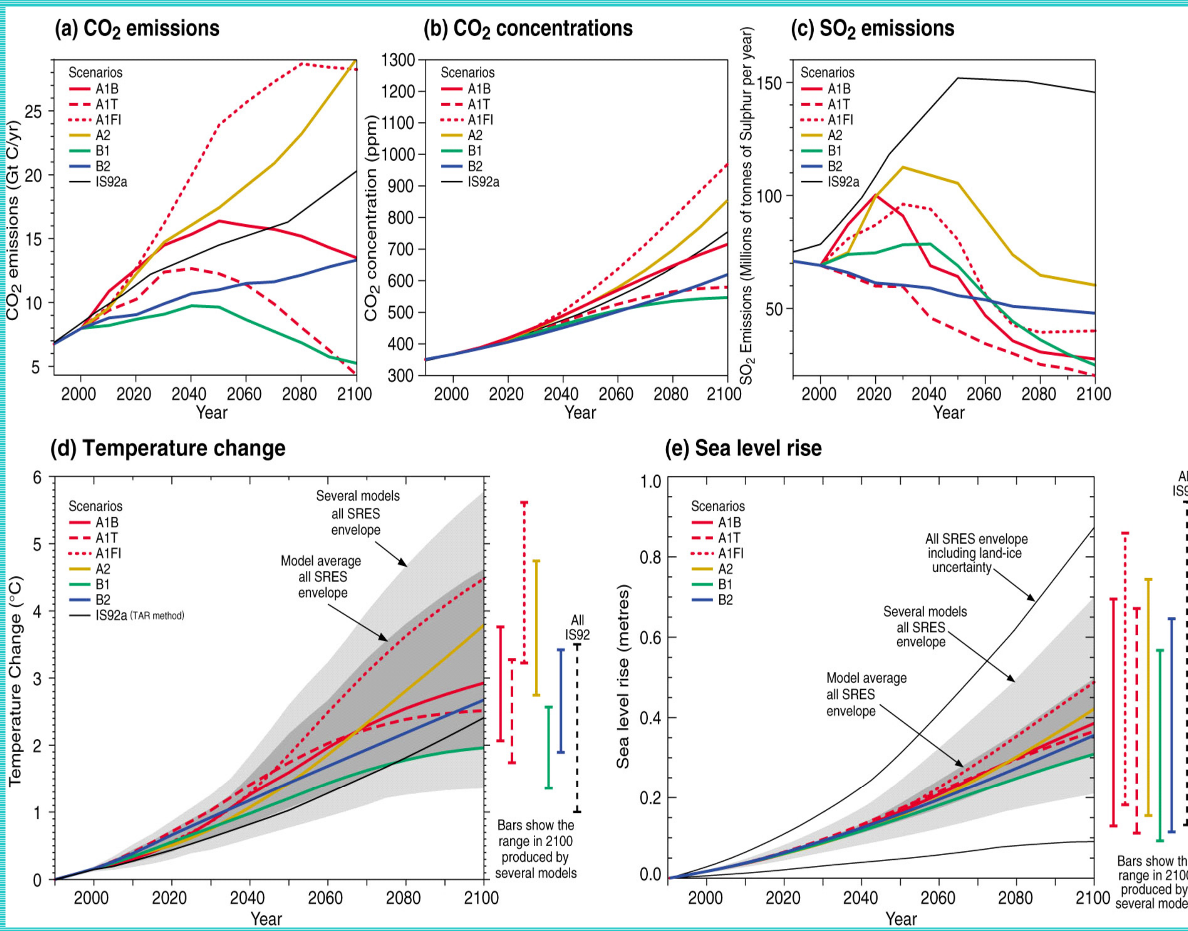
Figure 7.2.16—Simulated annual mean global surface temperatures



Source: IPCC (2001)

Figure 7.2.17—Emissions and climate in the 21st century.



Source: IPCC (2001)

Governmental Response to Climate Change

To address the challenges posed by global climate change, the international community developed the United Nations Framework Convention on Climate Change (FCCC). Ratified by the United States in 1992, it now has over 170 member countries. The Convention seeks to stabilize atmospheric concentrations of greenhouse gases at safe levels. Covered gases include carbon dioxide, methane, nitrous oxide, hydrofluorocarbons, perfluorocarbons, and sulfur hexafluoride. To respond to the challenge of global climate change, the U.S. plans to reduce the greenhouse gas intensity of the U.S. economy from today's 183 metric tons of emissions per million dollars gross domestic product (GDP) to 151 metric tons per million dollars GDP in 2012 (U.S. Global Climate Change Research Program, 2002). Greenhouse gas intensity measures the ratio of greenhouse gas emissions to economic output. A report by the U.S. Department of State (2002) provides background material and details of this plan.

To make sound decisions when implementing these agreements and plans, administrative and congressional policymakers require more information about the behavioral, economic, and ecological aspects of these problems than is currently available. Assessment of the research on greenhouse gas emissions is conducted periodically by the Intergovernmental Panel on Climate Change (IPCC). It has published three reports that summarize the state of current knowledge (IPCC, 1991, 1996, and 2001) and numerous technical and supplemental reports. The potential for emissions of greenhouse gases to change the Earth's climate has been subject to concerted Federal research since the late 1970s. To further such research, President George H. W. Bush established the U.S. Global Change Research Program (USGCRP) in 1989 (National Science and Technology Council). Under the USGCRP, global change research that relates to agriculture is the U.S. Department of Agriculture's responsibility, with the economic component under the purview of the Economic Research Service.

Since 2001, President George W. Bush has established the U.S. Climate Change Research Initiative (CCRI), the National Climate Change Technology Initiative (NCCTI), and the Committee on Climate Change Science and Technology Integration (CCCSTI). The CCRI "will improve the integration of scientific knowledge, including measures of uncertainty, into effective decision support systems and will adopt performance metrics and deliverable products useful to policymakers in a short timeframe (2-5 years)" (U.S. Global Change Research Program, 2002). The goal of the NCCTI is to "advance and bring focus to technologies that offer great promise to significantly reduce greenhouse gas emissions...." (U.S. Global Change Research Program, 2002). The CCCSTI's functions "include but are not limited to: 1) providing recommendations concerning climate science and technology to the President; 2) recommending the movement of funding and programs across agency boundaries; and 3) coordination with the Office of Management and Budget on the Committee's recommendations... Research will continue to be coordinated through the National Science and Technology Council in accordance with the Global Change Research Act of 1990" (U.S. Global Climate Research Program, 2002).

Estimating Agricultural Economic Impacts of Rising Concentrations of Greenhouse Gases

Estimating the agricultural economic impacts of rising concentrations of greenhouse gases requires a number of steps. They include devising scenarios related to rising concentrations of greenhouse gases, simulating the agronomic impacts of the scenarios, and estimating the agricultural economic effects of these impacts or of other scenario attributes. The science of estimating economic impacts of climate change, CO_2 fertilization, sea level rise, and related changes is in its infancy. There are many shortcomings at present (Gitay et al.; NRC). These shortcomings compound the uncertainty surrounding climatic and other impacts associated with rising concentrations of greenhouse gas emissions (see box, "Greenhouse Gas Concentrations and Climate Change").

Devising Scenarios

Scenarios typically consider one or more major effects of rising greenhouse gases concentrations—climate change, CO_2 fertilization, and sea level rise—obtained from various sources. Many effects are not considered. Climate change studies, for example, usually consider average changes in climatic variables and thereby exclude extreme events such as droughts, storms, or floods. Potential climatic surprises such as a shutdown of the Gulf Stream also are not captured. Likewise, studies of CO_2 fertilization ignore any detrimental effects on plant growth of non-CO_2 gases released by burning fossil fuels (particularly ozone, sulfur dioxide, and nitrogen dioxide). Comprehensive scenarios that simultaneously and consistently include all potential future impacts are not yet available.

With regard to climate change, some studies uniformly impose projected changes in climatic variables in all areas analyzed. Such projections do not accurately reflect local differences caused by atmospheric circulation patterns and the Earth's topography. Causal linkages between temperature and precipitation changes also are absent. The main advantage to this approach is that the underlying response of a modeling framework to changes in meteorological variables is readily observed. Other studies rely on projected changes in climatic variables derived from experimental and control runs of general circulation models (GCMs). GCMs simulate the causal linkages between changing concentrations of greenhouse gases and changes in temperature, precipitation, and other climatic variables. They also strive to reflect regional and local differences caused by atmospheric circulation patterns and the Earth's topography. Nevertheless, uncertainty still exists regarding projected changes in regional and local climate by GCMs (NRC).

This uncertainty can be compounded by the methods used to adjust current climate variables or to downscale local GCM results to even finer resolutions. Darwin (1997), for example, found that the ratio method (e.g., climate change results divided by base climate results) performs more poorly than the difference method (e.g., climate change results minus base climate results) for adjusting current precipitation levels with GCM projections of precipitation. Also, GCMs operate at relatively coarse scales (from 250 to 1,000 kilometers at the equator), whereas climatic projections at 50 or even 2-3 kilometers are required for some of the models used in economic estimations of impacts. Mearns et al. found that climate changes based on coarse and fine scales at a site in Iowa differed enough to generate yield changes with opposite signs when used in a crop growth model.

Scenarios of CO_2 fertilization assume one or more specific increases in concentrations. The most commonly used increase in the literature is 225 parts per million by volume (ppmv), approximately double the pre-industrial level. More recently, increases of 90, 150, and 310 ppmv have appeared. Some scenarios jointly consider CO_2 fertilization and climate change. Such scenarios implicitly assume that the particular relationships between the composition of atmospheric gases and climatic conditions projected by GCM runs are correct. Such scenarios may contribute to a false sense of consistency between climate change and CO_2 fertilization, however, when in fact the relationship between the gaseous composition of the atmosphere and climatic conditions is highly uncertain (see box, "Greenhouse Gas Concentrations and Climate Change"). Scenarios of sea level rise usually assume an increase of between 0.5 and 1 meters by 2100. Scenarios that jointly consider sea level rise with climate change or CO_2 fertilization have not yet appeared.

Simulating Agronomic Impacts

Once scenarios are obtained, the next step in most agricultural economic studies is to simulate the agronomic impacts of the changes specified by the scenarios. The most common method relies on crop-growth models to estimate changes in crop yields induced by changes in climate and/or CO_2 concentrations (see, for example, Rosenzweig and Iglesias). The major drawback of this method is that each farm-level adaptation (e.g., switching crop variety, changing planting or harvesting dates, etc.) has to be identified and assessed separately. In addition, results from a relatively few locations have to be interpolated over wide areas. Also, potential climate-induced increases in production possibilities in areas currently not suitable for agricultural production are typically ignored. Finally, different crop-growth models produce different changes in yield for the same crops (Mearns et al.). In some studies, changes in crop yields due to CO_2 fertilization are based on results from agronomic experiments. Studies that rely on crop yield changes for agronomic impacts usually exclude the direct effects of climate change on livestock production. One study, however, developed relationships between changes in temperature, livestock production, and feedstuff consumption (Adams et al., 1999a). continued

Estimating Agricultural Economic Impacts of Rising Concentrations of Greenhouse Gases (continued)

Another method relies on the analogous-regions concept, that is, the concept that similar climates mean similar production practices. It uses empirical methods to correlate climatic conditions with land and water resources used in agricultural production. Some studies (e.g., Darwin et al., 1994, 1995; Darwin, 1999a) implement an analogous-region approach by linking climate variables with land and water resources in a geographical information system (GIS) with a relatively fine resolution, e.g., 0.5-degree grids. Land and water resources in turn are empirically linked with production of agricultural commodities as well as other goods and services. Changes in climate, therefore, generate changes in land and water resources, which in turn affect crop and livestock production on existing agricultural lands. The major advantage of this approach is that it implicitly captures farm-level adaptations under the new climatic conditions. This approach also captures how climate change might affect the potential for agricultural production on land not currently used for agriculture.

Note, however, that the agronomic impacts are only indirectly linked with climate change. And the changes in yield implicit in results from analogous-regions models may not be consistent with yields derived from crop growth models. The method used to link climate with land resources in Darwin et al. (1994, 1995) and Darwin (1999a), for example, does not consider some seasonal phenomena important to U.S. agriculture. These include: 1) vernalization, a period of cold required by some plant species (e.g., winter wheat) before they will produce flowers and a harvestable crop; 2) potential detrimental effects of frost or precipitation on field operations, particularly during planting and harvesting seasons; and 3) thermal regime, the effects that average air temperatures during growing seasons have on plant growth. The method used to link climate with land resources in Darwin et al. (1994, 1995) and Darwin (1999a) also does not explicitly consider differences in day length and soil depth. Finally, different models of land and water resources may give different results to identical changes in climate. Gleick et al., for example, show that estimated changes in water runoff may differ from one water-balance model to another under the identical climate change scenario.

Sea level rise also can be simulated within some analogous region frameworks. GIS-based studies can estimate the amount and type of land at risk due to sea level rise using high-resolution altitude data (see for example Darwin and Tol). Here, too, the agronomic impacts are only indirect, consisting of lost production as cropland and pastureland is inundated. Most economic assessments of sea level rise, however, do not isolate its agricultural economic impacts from total economic impacts and, hence, do not distinguish cropland or pastureland from other land types. Analyses of sea level rise also use information about the length of coastline that may require protection. Some uncertainty is associated with determining the length of coastline and amount of land and capital threatened by a given increase in sea level.

Estimating Economic Effects

Agronomic or related impacts once obtained are then incorporated into a structural economic model, which explicitly simulates how landowners, farmers, households and other economic agents maximize profit and/or utility. They capture economic adaptations (e.g., switching crops, expanding or contracting acreage, or changing patterns of international trade and/or consumption) that economic agents, both domestic and foreign, might make in response to greenhouse-gas-induced agronomic changes. The extent to which economic adaptations are captured depends on the model. These models also estimate various economic impacts such as changes in resource use and value, commodity production and price, and economic welfare.

Studies that rely on yield changes as their greenhouse-gas impacts typically incorporate them by adjusting the production or supply functions in their economic models (Adams et al., 1988, 1990, 1995, 1999; Kane et al.; Rosenzweig et al.; Reilly and Hohmann; Rosenzweig and Parry; Tsigas et al.; Parry et al.; Darwin and Kennedy). Some of the earlier studies (Kane et al.; Rosenzweig et al.; Reilly and Hohmann; Rosenzweig and Parry; Tsigas et al.) assumed that percent changes in yield were equivalent to percent changes in supply. This assumption is not valid, however, and its use overestimates either gains or losses in supply (Darwin and Kennedy). The size of such overestimates can be substantial. Darwin and Kennedy demonstrate with an analysis of CO_2 fertilization that this invalid assumption would overestimate the economic benefits by 61 to 166 percent. Studies that rely on changes in land and water resources as their climate-induced agronomic impacts incorporate them by adjusting the quantities of these resources in their models (Darwin et al., 1995; Darwin, 1999a). The method of imposing changes in land resources in the earlier study did not fully take the current land-use pattern into account. This was corrected in the later study. Studies of sea level rise rely on economic models that calculate optimal levels of coastal protection and land loss, e.g., where the marginal cost of protection equals the marginal cost of the land and capital lost to sea level rise (Yohe et al.; Darwin and Tol). At a minimum, the economic estimates of the impacts of sea level rise provided by these models include both the costs of protection and the value of land and capital lost. Protection costs are derived by multiplying the length of coastline potentially at risk by the construction costs of coastal protection. Land and capital values are calculated by multiplying the amounts of land and capital lost by their respective prices.

continued

Estimating Agricultural Economic Impacts of Rising Concentrations of Greenhouse Gases (continued)

Price projections required for these calculations are just as uncertain as the projections of quantities. Also, these minimal estimates do not include the potential increase in consumer prices that the loss and diversion of productive resources would generate. These price effects can be captured by using the optimal levels of resource loss to adjust land and capital resources in another structural model that simulates the downstream changes in prices (Darwin and Tol). Darwin and Tol demonstrate that global economic losses attributable to sea level rise are 13 percent higher when these price effects are taken into account.

Some studies use the analogous-regions approach to bypass estimation of agronomic impacts and forego structural economic models altogether. Instead, they estimate economic impacts directly from changes in climatic variables (Mendelsohn, Nordhaus, and Shaw, 1994, 1996, 1999; Darwin, 1999a). Most of these studies rely on econometric models obtained by regressing county-level values of U.S. farm real estate on climatic and other variables (Mendelsohn et al., 1994, 1996, 1999). The approach is called "Ricardian" because it relies upon standard theory of land rent, which originated with David Ricardo (1772-1823), as a way of identifying the impacts of changes on net economic welfare. Changes in climate variables are simply incorporated into the econometric model and their economic impacts are calculated directly. Darwin (1999a) obtains similar measures of economic welfare by multiplying climate-induced changes in land resources (generated with a GIS) by the base prices of the land resources. This approach has not been used to estimate impacts of CO_2 fertilization.

Because it is based on the analogous-regions concept, this approach implicitly captures farm-level adaptations under the new climatic conditions. But because it foregoes a structural economic model, this approach fails to capture additional economic adaptations (e.g., adjusting labor or capital, or changing patterns of international trade and/or consumption) that moderate either gains or losses. There is also some confusion about whether the economic impacts estimated with this approach fall upon landowners, consumers, or both. Darwin (1999a) addresses both of these issues by comparing Ricardian estimates with estimates obtained from a structural economic model. With regard to the former, Darwin (1999a) shows that within a global framework Ricardian estimates systematically overestimate both benefits and losses and are on average upwardly biased because inflated benefits are larger than exaggerated losses. With regard to the latter, Darwin (1999a) shows that the economic impacts estimated with the Ricardian approach are not retained by landowners but passed on to consumers. In fact, increases in Ricardian values of agricultural land are correlated with decreases in income from agricultural land.

Various characteristics of the economic models also contribute to the uncertainty surrounding estimates of agricultural economic impacts. One of the most important is whether the economic model provides "partial equilibrium" or "general equilibrium" analyses (Mansfield). Analyses that assume that price can change in one or a few markets without causing significant price changes in other markets are called *partial equilibrium analyses*. Models for conducting such analyses often consider one sector within one country. If international trade causes significant market interactions between countries, a multi-country model with one sector may be used. These models are perfectly adequate in situations where prices in one sector are not correlated with or have little repercussion on prices in other sectors.

Analyses that take account of the interrelationships among prices in all markets are called *general equilibrium analyses*. Such analyses require models that capture the interactions between all economic sectors and consumers in one or more countries. They are necessary in cases where prices in one sector are correlated with or have major consequences for prices in other sectors. Global general equilibrium models are preferable for analyses of rising concentrations of greenhouse gases because they affect all economic sectors in all countries simultaneously. The role of international trade is particularly important. Kane, Reilly, and Toby, for example, suggest that international trade would help to offset agricultural economic losses in some regions by gains in other regions. And in Darwin and Tol's analysis of sea level rise, international trade is shown to redistribute losses from regions with relatively high damages to regions with relatively low damages. When international trade is simulated, all regions, even those with no direct losses to sea level rise, incur at least some economic losses.

Uncertainty also arises because estimated impacts of the same greenhouse gas scenarios vary significantly (e.g., have different magnitudes and/or opposite signs) when imposed on projections of 2060 economic conditions rather than on 1990 economic conditions (Adams et al., 1999b). The reasons for these differences, however, have not been explored. Certainly, assumptions about how technological advances in agriculture might affect relationships between climate change or CO_2 fertilization and crop growth could significantly affect economic impacts.

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Consider the following case: At present, CO_2 fertilization scenarios implicitly assume that the relationships between the atmospheric concentration of CO_2 and crop growth will remain constant over time. Interaction with technological change over time is precluded. It is entirely possible, however, that technological advances in agriculture could significantly alter the relationship between the atmospheric concentration of CO_2 and crop growth. If future crops were developed to use CO_2 as efficiently as corn does today, the beneficial effects of higher concentrations of CO_2 on crop growth might be considerably reduced. Similar issues are associated with technological advances that might generate crops more tolerant to heat or water stress. Systematic analyses comparing results of greenhouse gas scenarios imposed on both current and projections of future economic conditions would help to resolve these issues.

Estimating U.S. Impacts

The main structural economic models used to estimate U.S. agricultural economic impacts of rising concentrations of greenhouse gases are the Agriculture Sector Model (ASM) and the Future Agricultural Resources Model's (FARM) computable general equilibrium (CGE) model. There are some recent estimates from Ricardian models as well. ASM was recently used by the Agriculture Sector Assessment (ASA) Team of the National Assessment of Climate Variability and Change, which was conducted as part of the U.S. Global Change Research Program (McCarl; Reilly et al., 2002, 2001; Reilly). ASM combines a national U.S. model with a global trade model. The national model consists of separate regions, e.g., most of the coterminous 48 States plus subregions of Illinois, Indiana, Iowa, Louisiana, Ohio, and Texas. Crops include barley, corn, cotton, grapefruit, hay and pasture, oats, oranges, potato, rice, silage, sorghum, soybeans, sugar cane, sugar beet, tomato, and wheat. Livestock include beef cattle, dairy cattle, and sheep.

Greenhouse gas scenarios for the ASA combine results from two GCMs with atmospheric CO_2 concentrations 90 and 310 ppmv above current levels. The agronomic impacts of climate change and CO_2 fertilization are jointly estimated with crop growth models (mostly), and a livestock performance function. Estimated agronomic impacts of just climate change or just CO_2 fertilization are not available. Some farm-level adaptations (e.g., early planting and alternative cultivars) were included in the agronomic impacts. Crop yield changes are incorporated into the model such that a 1-percent increase in yield means a 1-percent increase in output accompanied by no increase in land, labor, capital, and water inputs and a 0.6-percent increase in other input use. Livestock performance changes are incorporated into the model in a similar manner, except that a 1-percent increase in output requires a 1-percent increase in feedstuff. Changes in pasture yields are incorporated such that a 1-percent increase in yield means 1-percent less pasture used per unit of output. Changes in water supply from the Water Sector Assessment (Gleick et al.) by ASM region are used to adjust initial supplies of irrigation water. Economic impacts (resource use, quantities and prices, producer and consumer surplus) are reported relative to the agricultural economy in 2000 for the U.S. as a whole (except Hawaii and Alaska) and for USDA production regions. The core scenarios assumed that foreign demand for U.S. agricultural commodities and foreign supply of agricultural commodities into the U.S. would remain constant. A sensitivity analysis was conducted to evaluate these trade assumptions.

FARM was developed by the Economic Research Service to estimate the agricultural economic impacts of global climate and other changes (see Darwin et al., 1994, 1995, 1996; Darwin, 1999a; Darwin and Kennedy; and Darwin and Tol). FARM's CGE model simulates production, international trade and consumption of 13 aggregate commodities (wheat, other grains, non-grains, livestock, forest products, coal-oil-gas, other minerals, fish-meat-milk, other processed foods, textiles-clothing-footwear, other nonmetallic manufactures, other manufactures, and services) in eight regions, including all of the U.S.

Climate-change scenarios are based on global results (e.g., all major land areas except Antarctica) from eight GCMs. Separate CO_2 fertilization scenarios assume atmospheric concentration of 150 ppmv and 225 ppmv. Agronomic impacts of climate change are implicitly captured by a GIS that links climate variables with six land classes and water withdrawals in the eight regions. The land classes are defined by length of growing season. Climate-induced changes in the distribution of land among land classes are incorporated by adjusting the quantity of land in each class and use by region. Where land class changes, farmers implicitly and automatically adapt the appropriate crop and livestock production systems for their region. Changes in regional water withdrawals are incorporated by increasing or decreasing the quantity of water withdrawn in each region. Water withdrawals are treated, however, as though they could occur anywhere within a given region; hence, water is considerably more mobile in the model than in reality. The agronomic impacts of CO_2 fertilization are based on crop yield changes in the literature (Rosenzweig et al.). These crop yield changes are incorporated into FARM CGE model such that a 1-percent increase in yield means a 1-percent increase in output accompanied by no increase in land, 0.5-percent increases in labor and capital, and 1-percent increases in other inputs. Major economic impacts for the U.S., other regions, and the world as a whole include changes (relative to 1990 economic conditions) in land use and value, irrigation water and price, commodity prices and quantities, income from agriculture, and total economic welfare. These can be directly compared with changes in climate variables as well as the direct effects on resources (e.g., changes in length of growing season, the distribution of land by land class, and water runoff) that are estimated with FARM's GIS..

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Estimating Agricultural Economic Impacts of Rising Concentrations of Greenhouse Gases (continued)

Recent Ricardian estimates of the agricultural economic impacts of climate change are provided by Mendelsohn, Nordhaus, and Shaw (1999). The estimates are from econometric models obtained by regressing county-level values of U.S. farm real estate for 1982 on climatic and other variables. Two models, one with and one without climate variation terms, are weighted to emphasize grain crops, like corn, wheat and soybean. Another two models are weighted to emphasize warm-weather crops and irrigated areas, e.g., the truck farms and citrus belt of U.S. coastal regions (Mendelsohn et al., 1994). Neither model fully accounts for the contributions of livestock production to U.S. farmland values (Darwin, 1999b; Mendelsohn and Nordhaus, 1999). The climate change scenarios are composed of uniform increases in temperature of 1.5, 2.5, and 5°C, combined with uniform changes in precipitation of 0, 7, and 15 percent. Total U.S. economic impacts of the climate changes are sums of estimated changes for each county in the coterminous 48 States.

ERS Reports Related to Greenhouse Gas Emissions and Concentrations

Agricultural Adaptation to Climate Change: Issues of Longrun Sustainability, AER-740, June 1996 (David Schimmelpfennig, Jan Lewandrowski, John Reilly, Marinos Tsigas, and Ian Parry). Summarizes results of a collection of ERS research projects that include more economic flexibility and adaptability than earlier analyses. Frames the discussion of economic adjustments within the context of global agricultural and environmental sustainability.

World Agriculture and Climate Change: Economic Adaptations, AER 703, June 1995 (Roy Darwin, Marinos Tsigas, Jan Lewandrowski, and Anton Raneses). Evaluates the potential impacts of global climate change on world and U.S. agriculture with a global economic model that links climatic conditions to land and water resources and to production, trade, and consumption of agricultural and other commodities throughout the world.