RFF REPORT

Agriculture and the Food System

Adaptation to Climate Change

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ADAPTATION | AN INITIATIVE OF THE CLIMATE POLICY PROGRAM AT RFF

JUNE 2009

RESOURCES FOR THE FUTURE

Table of Contents

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Summary

This paper discusses the capability of U.S. agriculture to adapt to climate change. After discussing key features of U.S. agriculture, findings of some recent modeling studies on the economic impacts of climate change are reviewed, and their limitations discussed. Next, critical biophysical and economic vulnerabilities of agriculture and the food system are identified, and the appropriate role for public policy in adaptation is discussed. The paper concludes by identifying areas for additional research on adaptation.

1. Introduction

One of the most important sectors of the economy, U.S. agriculture is highly dependent on climate. Farms and ranches are also the largest group of owners and managers of land that impacts ecosystem services, such as greenhouse gas (GHG) mitigation, water quality and quantity regulation, and wildlife habitat and biodiversity conservation. In addition, agriculture is playing an increasingly important role in the energy sector through biofuels production. Consequently, the impacts of climate change on agriculture, and agriculture's ability to adapt to and mitigate the impacts of climate change, are critical issues for agricultural households as well as the general public and public policy decision makers.

The importance of agriculture to the U.S. and global economies extends far beyond the farm gate. Whereas production agriculture represents less than 2 percent of U.S. gross domestic product (GDP), transportation, processing, and distribution of food represents more than 10 percent of GDP, and the food system is global, with agricultural commodities and processed foods representing about 10 percent of U.S. goods exports. Although most research to date has focused on agricultural production, climate change and GHG mitigation have implications for agricultural and food product transportation, processing, and distribution that remain largely unexplored. Potential impacts include the effects of sea level rise on transportation infrastructure, changes in the design and location of storage facilities, and changes in the range and type of food pathogens that must be managed.

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The economic importance of U.S. agriculture and the food system derives from the comparative advantage in the production of key food and feed grains, livestock, dairy, and horticulture and specialty crops. This comparative advantage is due to the favorable endowment of soils and climate, complemented by investments in transportation and market infrastructure, irrigation infrastructure in the arid West, research and development of suitable technology, investment in the skills and knowledge of farm managers and workers, and an enabling institutional and policy environment. As the climate changes, the productivity of the U.S. land endowment and the suitability of these complementary investments will also change.

My goal in this paper is to review the research on the adaptation of U.S. agriculture and the food system to climate change and to suggest directions for future research needed to address adaptation. In the next section I review basic facts about the agricultural and food sectors, and in the third section I review research on biophysical and economic impacts of climate change on the agricultural sector. I do not address the food processing and distribution sector in this review because no studies have been conducted to date regarding the impacts of climate change on the food sector. I discuss the vulnerabilities of the agricultural and food sectors to climate change in the fourth section. . In the fifth section I put the analysis of adaptation into institutional and policy contexts. I conclude with implications for climate change policy and directions for future research.

2. Some Facts about the U.S. Agricultural and Food Sectors

In this section, I briefly review some facts about the U.S. agricultural and food sectors. This is important, on one hand, because these sectors are dynamic and rapidly changing, and on the other hand, because, in our urbanized society, few people are familiar with the contemporary realities of these industries. The interested reader can find a great deal of information in the "Briefing Room" documents at the website of the Economic Research Service of U.S. Department of Agriculture (USDA) (www.ers.usda.gov/briefing/) from which the following facts were extracted.

Perhaps the most important fact about the agricultural sector is its transformation during the 20th century from the traditional family farm growing a mix of crops and livestock, to an array of much more diverse, specialized, and technologically advanced business enterprises. Likewise, the food processing and distribution sectors were transformed from small-scale, local enterprises to a globalized system of trade in generic commodities, such as corn and wheat as well as fresh meat, vegetables, and various forms of processed food products.

This transformation means that there is no such thing as a "typical" farm today. Although corn, soybeans, wheat, rice, cotton, livestock, poultry, and dairy remain major products and occupy a large land area, farms producing those commodities are highly specialized. Moreover, in value terms, many other products, ranging from horticultural crops to nursery plants to specialty crops, are far more important outside of the central U.S. corn and wheat belts. In value terms, the food processing and distribution sectors are more important than agricultural commodity production in the U.S. economy.

The USDA counts about 2.1 million enterprises as farms in the United States, but among farm households, only about 7 percent are commercially oriented with sales of more than $250,000, and these account for more than two-thirds of all production in value terms. In the 1930s, when modern agricultural policies were first put in place, the average income of farm household was about half of per capita nonfarm household income, but by the 1970s, farm incomes had overtaken nonfarm incomes. Since 1996, average income for farm households has exceeded the average U.S. household income by 5 to 17 percent. Whereas in the past, most farm households earned most of their income from farm activities, today off-farm sources of income (including employment earnings, other business activities, other investments, and transfer payments) provide more than 85 percent of household income. Very large commercial farms (sales greater than $500,000) have average household income about four times the U.S. household average, and this is the only size class that earns a large share of its income (80 percent) from farm sales.

Despite the public's perception that "corporate farms" have taken over U.S. agriculture, family-operated farms continue to account for most of agricultural production. The share of production held by nonfamily farms has grown over time, but accounted for only 14 percent of the value of production in 2003. Many family farms are incorporated businesses for legal purposes, but less than 2 percent of sales come from entities with more than 10 stockholders. A more important change in farm structure has been the shift toward very large family farms (sales of at least $500,000, in 2003 dollars), which accounted for nearly half of production in 2003, up from 32 percent in 1989. The number of those very large family farms also grew—from 39,700 in 1989 to 66,700 in 2003. Meanwhile, the share of production from smaller family farms ($10,000–$250,000 in sales) fell from 40 percent in 1989 to 26 percent in 2003. The trend toward larger farms is sector wide. The shift to larger livestock operations is well documented and pronounced. For example, family farms with at least $500,000 in production value held 61 percent of hog production and 75 percent of poultry and egg production in 2003, compared with 16 percent and 48 percent, respectively, in 1989. Very large family farms are also becoming increasingly dominant in cash grains and soybeans, tobacco, cotton, and peanuts—the crops that receive most of federal farm subsidies.

Government programs and policies have had a major impact on agriculture since the 19th century. One of the most important policies was the creation of the land grant universities beginning in 1865, along with the creation of the USDA's Agricultural Research Service. Together with the private sector, these institutions have been responsible for creating the revolution in agricultural science and technology that has made it possible for agricultural production growth to exceed the rapid global population growth of the 20th century. In addition, since the 1930s, the federal government has provided price supports, income subsidies, and trade protection to farmers growing major commodities. Also beginning in the 1930s, U.S. policies were designed to address soil conservation to combat the "dust bowl," and since the 1980s these policies have expanded to address broader conservation and environmental objectives.

As production of program crops shifted to very large farms, commodity subsidies, based on the amount of land in production of those crops, also shifted sharply. Farms with less than $250,000 in production value received 63 percent of commodity payments in 1989; by 2003, they received 43 percent of payments. In 2003, half of commodity payments went to households with income above $75,772. One-quarter went to households earning more than $160,142, and 10 percent of payments went to households earning more than $342,918. This shift in commodity payments to higher-income households is being driven by the shift of production to the largest class of farms (over $500,000 in sales), whose households have substantially higher incomes.

3. Adaptation and Impacts

Since the first assessment of climate change was published by the Intergovernmental Panel on Climate Change (IPCC 1990), substantial efforts have been directed toward understanding climate change impacts on agricultural systems. The resulting advances in our understanding of climate impacts have come from the collection of better data, the development of new methods and models, and the observation of actual changes in climate and its impacts.

Early impact studies largely ignored adaptation, but it was soon recognized that adaptation is a critical factor in determining impacts. However, quantifying adaptation is a major challenge for modeling studies. Most recent studies attempt to incorporate adaptation by simulating the effects of climate change without and with some form of adaptation, and comparing the results.

Agricultural adaptation can occur in many ways, from the individual field where a crop is grown; crop varieties are selected; and management decisions such as tillage, fertilization, and pesticide application are made to the farm level, where managers choose among crop, livestock, and other activities and capital investment decisions are made. Beyond the farm gate, many other decisions are made that affect the economic environment in which farms operate, including infrastructure investments, research and development, and policy. Many of these adaptations at the farm level and in the broader food system and economy are made without government involvement and are referred to as *autonomous adaptation* in the IPCC assessment reports (IPCC 2001, Parry et al. 2007). Other adaptations that involve government intervention are referred to as *planned adaptations*.

Quantitative modeling studies of agricultural adaptation have attempted to account for autonomous farm-level adaptations by adjusting planting dates and genetic characteristics of crop varieties, and by using models that reallocate land to crops according to changes in profitability. However, the models are not capable of representing adjustments in capital stocks that may be required to achieve these management adaptations. Some modeling studies also account for the market equilibrium effects of production changes. However, as I discuss further below, none of the modeling studies has attempted to model planned adaptations, such as changes in research and development, infrastructure investments, market institutions, or policies.

Impacts of climate change on agriculture can be quantified in physical and in economic terms. Physical impacts can be measured in terms of total production, productivity (e.g., crop yields or total factor productivity), and the spatial and temporal distribution of these physical outcomes. In economic terms, impacts can be measured in many ways, including (a) farm-level impacts, such as the gross value of production, cost of production, net value of production, and farm income and (b) aggregate or market impacts, including the value of production, consumption, and trade.

3.1 A Conceptual Framework

Climate change impacts agricultural production because climate is one of the key factors of production, providing essential inputs (water, solar radiation, and temperature) needed for plant and animal growth. Farmers make decisions at the extensive margin (what to produce at a site) and at the intensive margin (how to produce at a site) to maximize economic returns, and achieve other objectives, such as risk management, based in part on site-specific climate conditions. Many other factors also affect farmers' decisions, including transportation costs, access to labor and other inputs, and a wide array of public policies. Over time, these complex, interacting factors induce a spatial organization of agriculture that tends to be economically efficient, given the various constraints on the system.

When climate changes, the economically efficient spatial organization of agriculture changes. As with any economic decision, the rational response to climate change depends on balancing benefits and costs. However, these rational responses will depend on the ability of decision makers, from the farm level to the national policy level, to perceive changes in climate and to take action. The extent to which decision makers are able to perceive changes will depend on many things, including the fact that information is imperfect and costly, and that there are many complex and interacting factors causing observed outcomes in both biophysical and economic terms. The high degree of uncertainty about climate changes, particularly at specific sites where agricultural decisions must be made, means that the perceived effects of climate change, and thus the perceived gains from adaptation, are likely to be discounted for this uncertainty. Moreover, even when climate changes are perceived with some degree of certainty, decisionmakers' abilities to take action may also depend on many factors, including their individual attitudes toward risk and change, the ability to adapt to changes, and external factors constraining or supporting adaptation.

In summary, the economic analysis of adaptation to climate change can be viewed as a response by economic decisionmakers to incentives created by climate change:

Net expected benefits of adaptation =
perceived gains from adaptation – costs of adaptation.

When the net expected benefits of adaptation are positive, rational decision makers will take adaptive actions. This simple logic underlies the quantitative analysis of impact and adaptation.

3.2 Biophysical Impacts of Climate Change and Carbon Dioxide Concentrations on Agriculture

Agricultural production and productivity depend on the genetic characteristics of crops and livestock, soils, climate, and the availability of needed nutrients and energy. Researchers use crop and livestock growth simulation models to analyze the possible impacts of climate change and increases in atmospheric carbon dioxide (CO_2) concentrations (known as *CO_2 fertilization*) on crop and livestock productivity. Temperature and precipitation, key drivers of agricultural production, operate on the highly site-specific and time-specific basis of the microclimate in which a plant or animal is located. This fact presents a major challenge to modelers, because the general circulation models (GCMs) used to simulate climate change typically operate on spatial and temporal scales that are far coarser than what is needed to represent impacts on agriculture. The site-specific character of agriculture also makes modeling land-use and management decisions a challenge, because data covering the U.S. landscape are not available at the spatial and temporal resolution at which decisions are made (field and farm, within and across production cycles).

Impacts on Soil and Water Resources

Water availability is a key factor in crop and livestock productivity. Climate models predict an increase in precipitation for most regions of the United States, except for summer precipitation in the South and Southwest (Adams and Peck 2008). However, these increases in precipitation will be offset by a number of factors associated with higher temperatures, including more evaporation, increased precipitation in the form of rainfall in the winter, and earlier runoff of mountain snowpack. These changes will probably result in reduced soil moisture for crops, increased demands on groundwater resources, and greater competition among water users in the arid western United States.

Although climate does not directly impact soils, land-use changes in response to climate change can have important effects on soils, particularly in marginal environments, such as semiarid and arid regions. Drought can lead to overgrazing, which can, in turn, lead to increased erosion and the loss of soil organic matter and nutrients from topsoil. Increased rainfall intensity can also increase erosion and can result in a loss of productivity (Hatfield et al. 2008).

Impacts on Crop Yields

The most comprehensive study of U.S. agriculture to date was carried out by the U.S. Global Climate Research Program national agricultural assessment (Reilly et al. 2003). Simulations from four GCMs were used, together with assumptions about CO_2 concentrations, as inputs into a number of crop simulation models to evaluate impacts on rain-fed and irrigated systems. The simulations were carried out for existing management practices and for adaptation scenarios that included changes in planting dates and the use of cultivars adapted to warmer climates.

Table 1 presents a summary of the crop yield simulation results, by GCM and adaptation scenario, averaged over all crops. Two key results are apparent in these data. First, the general finding is that crop yields are expected to increase in the range of 3 to 25 percent by 2030, to as much as 50 percent by 2090; and second, the increases are larger under the adaptation scenarios. A closer examination of the data disaggregated by crop and region shows that these national averages obscure important differences, with the yields of some crops increasing much more than the yields of others (e.g., cotton, soybeans, and barley increase much more than corn, wheat, and some vegetable crops). Northern regions generally have larger, positive yield changes, whereas southern regions increase less and decline in some cases. The different climate models also produce substantially different results. The use of the Hadley model results in the largest yield gains; the Canadian and the Commonwealth Scientific and Industrial Research Organisation (CSIRO) models give positive, but smaller, gains; and the Regional Climate Model (RegCM) results in the smallest gains. The RegCM is a downscaled version of the CSIRO model, suggesting that disaggregation may lead to predicted impacts that are less positive than the predictions of aggregated models, a point considered further below.

Table 1. Impact of Climate Change on U.S. Crop Yields in 2030 and 2090, without and with Adaptation (% Change)

	Hadley			Canadian			CSIRO			REGCM		
	All	Dry	Irr	All	Dry	Irr	All	Dry	Irr	All	Dry	Irr
2030 without adaptation	16	17	11	8	8	4	4	3	9	4	4	88
2030 with adaptation	21	22	16	14	15	10	5	5	11	6	5	10
2090 without adaptation	35	37	20	14	14	12	19	20	16	7	5	16
2090 with adaptation	43	46	25	27	28	19	28	29	22	16	16	22

Notes: Dry = dryland crops, Irr = irrigated crops.
Source: McCarl 2008.

Impacts on Livestock

Livestock are sensitive to temperature, and studies show that climate change will have positive effects on livestock productivity by raising temperatures in winter; however, this effect will be outweighed by the negative effects of hotter summers. These effects increase at an increasing rate as temperatures rise. As with humans, the combination of high temperature and high humidity causes greater stress and discomfort in livestock, and thus a larger loss in productivity. Milk production declines in dairy operations, the number of days required for cows to reach their target weight grows longer in meat operations, conception rates in cattle fall, and swine growth rates decline. As a result, swine, beef, and milk production are all projected to decline with increases in average temperature and temperature extremes. The recent U.S. climate change assessment estimated that livestock productivity would decline 5–7 percent, on average, by midcentury under the climate model scenarios the authors used, although studies suggest that productivity losses in the southern United States could be on the order of 10 percent or more (Reilly et al. 2003).

3.3 Economic Impacts

Evaluating the economic impacts of climate change adds more layers of complexity to the analysis. At the farm level, changes in productivity, enterprise choice, and management decisions result in changes in economic returns, given prices of inputs and outputs. But when these changes in farm-level production are aggregated to the market level, they cause changes in prices, and these processes play out at regional, national, and international levels. Additionally, over the long periods of time relevant to climate change, changes in population and income lead to changes in demand. Thus, a great deal of data and many model assumptions are necessary to construct an economic analysis of climate change impacts. As with the analysis of crop yields and livestock productivity, decisions at the farm level and the market level are a part of the adaptation process. In most modeling exercises, the assumed adaptations in growing crops and livestock are incorporated into models that allow land-use and management changes. However, the models are not sophisticated enough to incorporate endogenous technology change or capital investment, so arbitrary assumptions must be imposed for these factors.

Several methodologies have been used to estimate possible impacts of climate change on agriculture. Most studies use *integrated assessment* models, which combine process-based crop and livestock models that simulate the impacts of climate change on productivity with economic models that simulate the impacts of productivity changes on land use, crop management, and farm income. Many of these models also link the farm management outcomes to environmental impact models to investigate impacts such as those on water use and quality, soil erosion, terrestrial carbon stocks, and biodiversity. The data presented here are derived from the recent U.S. assessment of climate change impacts on agriculture (Reilly et al. 2003), which used an integrated assessment model.

Research suggests that in highly productive regions, such as the U.S. corn belt, the most profitable production system may not change much; however, in transitional areas, such as the *ecotone* between the corn belt and the wheat belt, substantial shifts may occur in crop and livestock mix, in productivity, and in profitability. Such changes may be positive if, for example, higher temperatures in the northern Great Plains were accompanied by increased precipitation, so that corn and soybeans could replace the wheat and pasture that presently predominate. Such changes also could be negative if, for example, already marginal crop and pastureland in the southern Great Plains and southeast became warmer and drier. In addition to changes in temperature and precipitation, another key factor in agricultural productivity is the effect of elevated levels of atmospheric CO_2 on crop yields. Some studies suggest that higher CO_2 levels could increase the productivity of small-grain crops, hay, and pasture grasses by 50 percent or more in some areas (and much less so for corn), although these effects are likely to be constrained by other factors, such as water and soil nutrients.

Table 2 shows that the aggregate economic impacts of climate change on U.S. agriculture are estimated to be very small, on the order of a few billion dollars (compared to a total U.S. consumer and producer surplus of $1.2 trillion). This positive outcome is due to positive benefits to consumers that outweigh negative impacts on producers. Impacts on producers differ regionally (Table 3), and the regional distribution of producer losses tends to mirror the productivity impacts, with the corn belt, Northeast, South, and Southwest having the largest losses and the northern areas gaining. The overall producer impacts are estimated to range from –4 to –13 percent of producer returns, depending on which climate model is used. The statistical modeling studies mentioned earlier produce estimates of very small impacts on U.S. agriculture as well. For example, the more recent study by Deschenes and Greenstone (2007) finds impacts on the order of 3 to 6 percent of the value of agricultural land and cannot reject the hypothesis of a zero effect.

Table 2. Annual Changes in U.S. and Global Agricultural Economic Surplus Due to Climate Change in 2030 and 2050, without and with Adaptation ($$10^6$)

	Climate Model			
	Canadian	Hadley	REGCM	CSIRO
2030 without adaptation				
United States	424	2,953	–1,531	–1,603
Rest of the world	1,697	1,949	410	313
Total globally	2,121	4,902	–1,121	–1,290
2030 with adaptation				
United States	1,870	4,466	–224	–429
Rest of the world	2,720	2,959	621	634
Total globally	4,590	7,425	397	205
2090 without adaptation				
United States	457	5,432	–2,015	406
Rest of the world	1,981	3,614	–37	1,381
Total globally	2,439	9,047	–2,052	1,788
2090 with adaptation				
United States	2,948	8,048	1,760	3,749
Rest of the world	3,422	4,077	2,192	2,747
Total globally	6,370	12,125	3,952	6,496

Note: U.S. baseline is $1,200,000.
Source: McCarl 2008.

Table 3. Regional U.S. Producer Welfare Changes for 2030, with Adaptation ($\$10^6$ and %)

	Canadian	Hadley	REGCM	CSIRO
Corn belt	–1,745	–1,962	–1,218	–1,209
Great Plains	–370	–968	–72	–200
Lake States	1,357	352	–50	–94
Northeast	–91	–236	–21	–63
Rocky Mountains	721	307	878	885
Pacific Southwest	325	–97	134	132
Pacific Northwest, east side	112	9	274	264
South Central	–868	–448	–505	–518
Southeast	–419	–365	–223	–219
Southwest	–250	–483	–293	–297
Total	–1,228	–3,891	–1,096	–1,391
% of baseline	–5.1%	–13.0%	–3.7%	–4.4%

Source: McCarl 2008.

3.4 Impacts on Ecosystem Services

Changes in climate are expected to have significant impacts on ecosystem function, and thus on the ecosystem services valued by humans (Backlund et al. 2008). The changes in land use and management associated with agriculture are also likely to affect the ecosystem services associated with agricultural lands, such as the regulation of water quantity and quality and the global carbon cycle and conservation of biodiversity. Although both scientific understanding and comprehensive assessments of these impacts are lacking, case studies in the literature suggest some possible impacts.

The national climate models used in the U.S. assessment showed that pesticide use could increase, although the authors did not attempt to evaluate the potential environmental or health effects of such an increase (Reilly et al. 2003). This result is consistent with the observed greater use of pesticides in warmer regions of the United States. Considering that the crop models used in the U.S. assessment do not effectively represent possible impacts of pests and diseases on crops, it would be reasonable to assume that a warmer climate with elevated CO2 levels would increase pest and disease pressure and thus result in greater use of pesticides than the U.S. assessment models predict (Hatfield et al. 2008). Increased use of pesticides would be expected to have adverse effects on ecosystem services such as water quality, pollination and biodiversity.

Another likely major impact of climate change is on water availability and water resources. Reilly et al. (2003) presented results from case studies of groundwater quantity in the Edwards aquifer in Texas and the impact of agriculture on water quality in the Chesapeake Bay. The aquifer study indicated that a drier, warmer climate would result in greater depletion of the aquifer due to both agricultural and urban demands for water. The Chesapeake study indicated that increased corn production in the region would substantially increase nutrient loadings into the bay.

Land-use change is estimated to be an important source of GHG emissions, through the loss of carbon stored both in soils and in aboveground biomass. Antle et al. (2006a) found that the stock of soil carbon in the central United States could be reduced on the order of 20 percent if the effects of CO2 fertilization are negligible, but would be much less if CO2 fertilization effects on crop productivity are large. In addition, the study showed that the impacts on soil carbon were much more positive with management adaptation than without. Antle et al. (2006a) also found substantial regional variation in these effects, an indication that generalizations about the effects of land use change on GHG emissions from a small number of sites, as is typically done in large-scale integrated assessments, may be misleading.

3.5 Limitations of Impact Assessments

In addition to their inherent model limitations, none of the impact assessments cited above has considered impacts of climate change on the food transportation, processing, and distribution sectors. In particular, none of the impact assessments has considered the impacts of GHG mitigation policies on production agriculture or on the food processing and distribution systems. Recent experience with higher fossil fuel costs suggests that these impacts may be more important for farmers and food consumers than the impacts of climate on productivity. Thus, by ignoring possible impacts of future climate change mitigation policies, the impact assessments carried out thus far have actually ignored some of the most important long-term implications of climate change. In later sections of this report, some of these issues are explored further.

The impact assessments that have been carried out thus far have a number of other important limitations:

- **Site- and time-specific response of crops to temperature and precipitation.** Crops are known to respond in complex ways to variations in temperature and precipitation. Climate models cannot estimate changes with adequate spatial or temporal resolution, and crop models also have a limited capability to represent the processes involved.
- **CO_2 fertilization.** The crop models used in the impact assessments indicate that the increase in CO_2 concentrations in the atmosphere will increase crop yields substantially for most crops except corn. Recent research on CO_2 fertilization, however, suggests that the positive effect may be much less than modeling studies suggest because factors such as water and nutrients may limit the positive effects of higher CO_2 concentrations (Easterling et al. 2007).
- **Pests and diseases.** Most of the crop models used either do not represent pests and diseases or do so only to a limited degree. In addition, few studies of the effects of climate change on pest and disease populations have been carried out. Finally, higher CO_2

concentrations are likely to increase weed growth, an effect not taken into account in crop modeling studies.

- **Aggregation.** The national studies, such as the U.S. assessment (Reilly et al. 2003), extrapolate from a relatively small number of representative sites to larger regions to estimate impacts on productivity; they also use economic data aggregated to relatively large regions. This type of modeling cannot incorporate the site-specific effects of climate on crop productivity or the site-specific interactions with management decisions. Also, only major crop and livestock systems are represented, with only very simple analyses of major livestock systems. Poultry, aquaculture, fruit, vegetable, and other specialty crops are not represented, nor are smaller, less-specialized farm types. Recent research suggests that horticulture crops may be more sensitive to climate change than grain crops, hence the potential for more adverse regional and localized effects may be high.
- **Adaptation assumptions and costs.** On one hand, the crop modeling studies make limited assumptions about adaptation and assume that adaptation is uniform across large regions, whereas actual adaptive options and capability are likely to vary substantially. Likewise, the aggregated economic models can only represent land-use and management options to a limited degree and thus are likely to underestimate adaptive response. On the other hand, impact assessments largely ignore the costs of adaptation; thus the extent of adaptation is likely to be overestimated and the negative impacts of climate change are likely to underestimated. For example, in the study of central U.S. crop production (Antle et al. 2006a), the shift from hay and pasture crops to grain crops would most likely have impacts on the livestock industry that were not taken into account.
- **Impacts on transportation infrastructure.** None of the studies to date has made any attempt to represent the potential impacts of climate change on transportation or communications infrastructure. For example, changes in sea level may impact ports, and changes in freshwater flows in the Mississippi may impact barge transportation of grains from the Midwest.
- **Technological change.** Virtually no studies have been carried out to predict future changes in technology, either within agriculture or in the broader economy. Technological change has the potential to increase the rate of adaptation within agriculture and to offset the impacts of climate change on the most vulnerable people in society by raising their incomes and thus their ability to adapt.

To illustrate the possible effects of some model limitations on the national impact assessments, it is instructive to compare the results of one of the few field-scale studies to the U.S. assessment (Reilly et al. 2003). The study by Antle et al. (2004) used the Canadian Climate Model to estimate the effects of climate change on winter and spring wheat and barley yields for major land resource areas in Montana; specifically, the study considered (a) the effects of climate change without CO_2 fertilization, (b) the effects of CO_2 fertilization only, and (c) the combined effects of climate change and CO_2. As Table 4 shows, without the effects of CO_2 fertilization, yields are estimated to change by −47 to −9 percent, whereas with CO_2 fertilization and climate change, yields are expected to change in the range of –17 to +25 percent. In contrast, the U.S. assessment's averages for winter wheat and spring wheat are –11 and 14 percent. Economic returns in the Montana study were generally negative without the CO_2 fertilization effect, in the range of –60 to –50 percent without adaptation, and –50 to –30 percent with adaptation. When CO_2 fertilization was included, changes in returns were –25 to 0 percent without adaptation, and –10 to +20 percent with adaptation, implying substantial uncertainty in the impacts. In contrast, the impacts on producer surplus shown in Table 3 are small and negative for the Great Plains region. Thus, the disaggregated results imply a larger range of possible outcomes, with much more adverse outcomes possible if the effects of adaptation and CO_2 fertilization are not fully realized.

Table 4. Montana Agro-ecozone Yield and Net Returns Changes for 2050, Using the Canadian Climate Model (%)

	Climate only	CO_2	Climate + CO_2
MT winter wheat	–27 to –19	+19 to +56	+6 to +25
MT spring wheat	–47 to –44	+48 to +57	–17 to +8
Net returns without adaption	–60 to –49	+37 to +46	–28 to 0
Net returns with adaptation	–45 to –25	+56 to +69	–8 to +18

Notes: Yields are for wheat grown in a fallow rotation. Climate = climate change, CO_2 = CO_2 fertilization.
Source: Antle et al. 2004.

In addition to integrated assessment models, economists have developed other statistical models to analyze climate change impacts and adaptation. Mendelsohn et al. (1994) criticized the use of process-based models, such as the ones used in the U.S. assessment, for what they considered to be a limited ability to model adaptation. They advocated, instead, using a reduced-form econometric modeling approach that uses historical statistical data to estimate observed responses of economic outcomes to historical differences in climate (also see the more recent related research by Deschenes and Greenstone 2007). This style of model has the advantage that it embeds the costs of adjusting to change into the model's parameters. However, this style of model also has disadvantages. One problem is that the approach uses the spatial variation in climate to estimate the economic effects of climate differences, and then uses those estimates to predict effects of changes in climate over time, implying that the statistical relationships across space and across time are the same (Schneider 1997). Another problem is that the econometric models embed behavior that is influenced by policies and technologies that were in place when the historical data were observed, and thus are unlikely to be able to accurately predict responses under changed conditions (this limitation is similar to the one highlighted in the famous "Lucas critique" of econometric models used to predict macroeconomic behavior). Moreover, by not using process-based models to estimate the effect of CO_2 fertilization on productivity, purely statistical models based on historical data cannot represent the effects of CO_2 fertilization that are likely to occur in the future as atmospheric concentrations of CO_2 increase (Antle 1996). Finally, like the integrated assessment models, none of the statistical models measures behavioral responses in the context of the physical and institutional infrastructure that existed when the data were collected. Thus, these models cannot account for costs of adaptation outside of the farm that may occur in response to climate change.

3.6 Conclusions

The impact assessments done thus far indicate that neither the U.S. nor the global food supply are threatened by climate change if current climate predictions are reasonably accurate and if the positive effects of CO_2 fertilization substantially offset some of the negative effects of changes in temperature and precipitation. This conclusion contrasts with frequent statements in the media suggesting possible widespread food shortages and famines.[1] The limited aggregate impacts occur because adverse impacts in some regions, particularly in the tropics, are offset by gains in temperate regions, such as the northern United States. However, these conclusions should be interpreted as highly uncertain because of uncertainties in the rate of climate change and in the magnitude of extreme events as well as the many limitations of the models used to assess these impacts.

Another critical limitation of these impact assessments is the difficulty in quantifying the costs of adaptation. Whereas these studies have attempted to quantify the impacts of climate change on physical quantities of production and their economic value, few, if any, studies have attempted to quantify the costs of adapting to climate change. If the rate of climate change were relatively high, implying that the costs of adaptation were also relatively high, then the net benefits of adaptation would also be lower, and less adaptation would occur. Consequently, contrary to many economists' arguments that adaptation is likely to offset much of the adverse impacts of climate change, it may be that if the costs of adaptation are high, the impact estimates without adaptation may be closer to actual outcomes than the impact estimates that ignore adaptation costs.

4. Vulnerabilities

Vulnerability, a term that has long been used in the analysis of climate change, is often defined as the susceptibility of individuals in a group to an adverse event; it is measured as the likelihood that an individual (or a proportion of individuals in a group) will cross a critical threshold. For example, a crop may be vulnerable to failure (i.e., a zero grain yield) because of drought, heat stress, or frost. Likewise, a farm household may be vulnerable to bankruptcy if its financial resources fall below a critical threshold. However, vulnerability measured with respect to a threshold only captures effects on the lower tail of the distribution. For some purposes, another subset of the population may be relevant. In considering the impacts of climate change on U.S. agriculture, for example, the vulnerability of large, commercial farms that are economically important to the

[1] "Mainstream scientists have warned that unless [climate emissions] are sharply reduced the planet will face rising sea levels, prolonged droughts, widespread famine and other frightening consequences" (The New York Times 2008).

agricultural sector—and politically influential—may be more useful for understanding policy formation than a measure based on the lower tail of the farm size or farm household income distribution.

4.1 Vulnerability to Biophysical Stresses

The growth and productivity of most crops are known to be vulnerable to a number of critical thresholds, including minimum and maximum temperatures, cumulative temperature (degree-days), and water availability. These stresses interact in complex ways with site-specific soil and other environmental conditions (aspect, slope, and elevation), atmospheric CO_2 concentrations, and management (Hatfield et al. 2008). Although agronomic studies have investigated the vulnerability of crops to failure as a result of these stresses, the economic studies based on aggregated data do not effectively quantify these vulnerabilities.

The U.S. assessment indicates that the South and the West are the regions most vulnerable to the adverse impacts of climate change as a result of increased heat stress, drought, and competition for surface and groundwater resources (Reilly et al. 2003, McCarl 2008).

4.2 Economic Vulnerability of Farm Households

The facts about farm structure and income presented in Section 1 have implications for the vulnerability of farm households. Both small and large farms appear likely to be resilient for different reasons. Smaller farms often produce a more diverse mix of crops and livestock, and also depend to a large degree on nonfarm income that is less impacted by climate change. Larger farms tend to be more specialized and thus more vulnerable to climate changes, but are stronger financially, have greater wealth, and receive a larger share of their income from government subsidies. Larger, more specialized farms are also more likely to use market-based risk management tools and to sell in national and international markets that are less vulnerable to local climate variation.

Most of the research on climate change impacts reviewed above has not addressed the vulnerability of U.S. agriculture in the sense of assessing the likelihood of production or incomes falling below critical thresholds. This can be explained in part by the fact that most studies use data aggregated to a regional level, and thus are only able to assess impacts on total production and income, not on the likelihood that production or income falls below a threshold for some individuals in the population.

One study that did address agricultural production vulnerability quantitatively, Antle et al. (2004), used field-level and farm-level data to assess the vulnerability of dryland grain producers in Montana, a semiarid region where the risk of low soil moisture is a key vulnerability. Several measures of vulnerability were used, including the likelihood of crop income falling below a threshold as well as the percentage change in income for all farms. One of the goals of this study was to test the hypothesis, put forth in IPCC assessment reports (IPCC 2001), that vulnerability is inversely related to resource endowments. The results supported the hypothesis that the most adverse changes occur in the areas with the poorest resource endowments and when the mitigating effects of CO_2 fertilization or adaptation are absent. The study also found that the vulnerability of agriculture to climate change depends on how it is measured (in relative versus absolute terms, and with respect to a threshold) and on complex interactions between climate change, CO_2 level, adaptation, and economic conditions. The results showed that relative vulnerability did not increase as resource endowments become poorer and that, without adaptation, there may be either a positive or negative association between endowments and relative vulnerability. However, vulnerability measured in relation to an absolute threshold did vary inversely with resource endowments, and a positive relationship was found between absolute gains from adaptation and the resource endowment of a region.

Financial vulnerability of farm businesses is another relevant consideration that has largely been ignored by the literature on climate change impacts and adaptation. To effectively quantify financial vulnerability, a model of the farm firm is required. Such a model should include financial condition as a function of production income; debt structure; nonfarm income; and the use of financial risk management tools, such as futures markets, crop insurance, and agricultural subsidies. Although in the past, farms faced periodic financial crises when adverse climatic or economic conditions occurred because of high debt-to-asset ratios and imperfect capital markets, this is much less true today for commercial farms. As noted earlier, farm households with commercial farm operations have higher incomes and more wealth than most U.S. households, and are financially sound. Debt-to-equity ratios range from 5 to 20 percent by state, and farm failure rates are far lower than nonfarm failure rates. However, one feature of farm household businesses that may increase their financial vulnerability is that a much larger share of their total wealth is invested in their business than is typical of nonfarm businesses.

4.3 Vulnerability of Ecosystem Services

As noted earlier, in addition to marketed products, agricultural lands produce ecosystem services that are valued by individuals and society. The biophysical and economic vulnerabilities discussed in Section 4.1 have important implications for ecosystem service provision, although these aspects have not been the subject of much research (Buckland et al. 2008). For example, extreme weather events, such as droughts, may lead to overgrazing, making arid pasture lands vulnerable to erosion and the loss of soil organic matter. Both biophysical and economic thresholds may exist, making soil degradation and other losses of natural capital irreversible (Antle et al. 2006b). Also “planned adaptations” by governments may have unintended consequences, as illustrated by the U.S. policy to subsidize corn ethanol. The resulting increase in corn production in the Midwest is likely to increase the application of nutrients, intensifying the problem of hypoxia in the Gulf of Mexico and magnifying other water quality problems associated with intensive agricultural chemical use.

4.4 Food Quality and Safety

The assessments of climate change impacts discussed above suggest that food availability is not threatened by climate change, but there are reasons to believe that food quality and safety may be impacted. Increased CO_2 may increase plant growth but result in lower protein content of grains, for example. In addition, vegetable and fruit quality are highly vulnerable to temperature and water stresses (Hatfield et al. 2008).

Food safety is also likely to be impacted by climate change through several mechanisms (Food and Agriculture Organization of the United Nations 2008). Food-borne pathogens, such as cholera and mycotoxins, are likely to expand their geographic range, and outbreaks are often associated with extreme weather events. Increased stress on water resources is also likely to increase pathogen growth and human infection. Climate change is also likely to increase the occurrence of harmful algal blooms and the contamination of fish and seafood by pathogens and toxins, including through the increased pesticide contamination that is likely to be associated with climate change. Increased disease incidence in livestock is likely to increase the use of veterinary drugs and thus increase the risk of food contamination, antibiotic resistance, and related health issues. Addressing these increased risks will require the adaptation of existing public information, disease surveillance, and intervention practices.

4.5 Market Infrastructure

Another potentially important impact of climate change on agriculture is its impacts on the location and functioning of transportation infrastructure. As noted above, climate change is likely to result in the spatial reorganization of agricultural production such that, for example, maize and soybean production move westward and northward in the United States. These geographic shifts may mean that storage and shipping facilities and rail infrastructure may need to be relocated. The increasing globalization of agriculture and the food system also has increased the amount of traded agricultural commodities, as well as processed products, through rivers and by sea. In the United States, a large share of agricultural commodities in the corn and wheat belts is shipped by barge on the Mississippi River. Competition between upstream and downstream uses of water in the Mississippi watershed is already intense, and is likely to be impacted by climate change. Changes in sea level also could have important implications for the location and operation of storage and shipping facilities at major ports. As yet, these issues have not been investigated systematically to assess the possible costs of changing transportation infrastructure that supports agriculture and the food system. The rate of climate change and sea level risk can be expected to be critical factors in determining these costs.

4.6 The Food Processing and Distribution System

Very little research has addressed the potential vulnerabilities of the food processing and distribution system. Here, a few observations are offered that may be suggestive of possible vulnerabilities.

The meat slaughter industry is one area in which important issues may arise. Regarding food safety in particular, higher temperatures would increase the costs of refrigeration, packaging, handling, and storage of perishable meats that are vulnerable to dangerous pathogens such as Escherichia coli. Changes in the location of livestock production could also necessitate changes in the location of livestock transport, feedlots, and slaughter plants.

Most components of the food processing and distribution system are dependent on fossil fuels for transportation and packaging and on electricity to power processing operations and refrigeration. Thus, policies to reduce GHG emissions that raise fossil fuel costs are likely to have significant impacts across many dimensions of this sector as well as production agriculture. Researchers studying climate change impacts and adaptation have devoted little attention to this issue.

5. Behavioral, Institutional, and Policy Context

This section briefly reviews some issues that may illuminate the capability of the agriculture and food sectors to adapt to climate change.

5.1 Farmers and Adaptation

Farmers routinely make land-use and management decisions to manage climate and market variability. They choose crop varieties for their resilience to drought and pest risk; plant different crops according to slope, aspect, and other highly site-specific conditions; and use different practices, such as tillage, according to the type of crop being grown. Moreover, farmers and ranchers have increasingly made use of technological advances in forward contracting, futures markets, and information technology to manage market risk. These facts suggest that, given sufficient information about changes in climate regimes, well-informed farmers are capable of making appropriate changes to adapt agricultural production to changed climate conditions.

The fact that agricultural production occurs across the United States under a wide array of conditions also suggests that, as climate changes, it will indeed be possible to adapt agricultural production in ways that take advantage of these changed conditions. History shows that, as the continental United States was settled, farmers and ranchers adapted to the wide range of biophysical conditions that existed, and determined which activities and enterprises were economically efficient under each set of location-specific conditions of soils, climate, transportation costs, and other factors.

The conceptual framework presented above identified farmers' perceptions of climate change and their capability of adapting as key factors in their response to climate change. The literature shows that, besides profitability, other key factors affecting farmers' decisions (e.g., to adopt technology and participate in conservation programs) are their perceptions of and attitudes toward risk as well as farm personnel characteristics, such as age, education, experience, and type of economic organization (Sunding and Zilberman 2001; Paustian et al 2006). How these factors affect farmers' perceptions of climate change and their willingness and ability to adapt remain unstudied questions.

5.2 Technological Change

Beginning in the 20th century, agriculture has gone through a rapid technological revolution that required major investments in human and physical capital on farms. These rapid changes continue today, with the introduction of genetically modified crops, and rapid changes in market conditions and government policies (consider the recent policies to subsidize biofuels production). This experience also shows the capability of farmers to innovate in ways that take advantage of regional resource endowments, including those related to climate. Private and public research institutions have similarly shown their capability for such innovation in the context of agricultural research and development (Hayami and Ruttan 1985).

As discussed further below, both private firms and public research institutions play important roles in agricultural technology development. Currently, spending on agricultural research and development is about $8 billion per year, about 40 percent of which is in the public domain.

5.3 Market Institutions

In addition to production risk associated with weather and pests, farmers have historically faced a high degree of market risk associated with highly variable market prices and *monopsonistic* buyers of their products (i.e., a small number of buyers with market power). A number of market institutions have evolved that have served to increase competition and reduce price variability. First and foremost, investment has been made in transportation, storage and communication infrastructure; this lowers transportation costs and allows farmers to be integrated into increasingly larger regional, national, and global markets. Improved storage allows farmers to arbitrage the sale of their products, avoiding low prices at harvest. In addition, the development of futures markets has allowed farmers to hedge against both production and price risk. Modern communications technology allows farmers to know prices over space and time and thus make more effective management and marketing decisions.

5.4 Public Institutions

As noted earlier, the public sector has played a major role in the development of agricultural and food technology through the colleges of agriculture, agricultural experiment stations, and extension services in the land grant universities, and through the Agricultural Research Service of USDA. In the late 19th and first half of the 20th centuries, relatively little private investment was made in agricultural technology or private information services, so public investments were made in basic research as well as applied research and extension services to transfer knowledge to farmers. However, over time these roles have changed, as the more applied technology development and information provision have been increasingly taken over by the private sector. Today, the public sector research and information services focus increasingly on more basic research and information that are public goods, including climatic information.

5.5 Agricultural and Environmental Policy

Like the public sector research institutions, agricultural policy has changed over time in response to the changing realities of U.S. agriculture. Although in some respects agricultural policy retains features of early farm legislation, as it continues to provide subsidies to producers of “program” crops, there has been a progressive shift toward the funding of conservation and environmental programs that address externalities and support the provision of ecosystem services. To the extent that agricultural subsidies tend to encourage some farmers to continue to produce subsidized commodities, it is likely that these policies will tend to inhibit adaptation to climate change. Some conservation programs also may inhibit adaptation, by providing land owners with long-term (i.e., 10-year) contracts to maintain land in conserving uses, such as permanent grass or trees. However, these policies may also have the desirable effect of increasing carbon sequestration.

There is clearly much scope for the reform and redesign of agricultural, conservation, and environmental policies in ways that could enhance both climate change mitigation and adaptation. Commodity-based subsidies could be replaced with programs that support the provision of public goods, including public funding of adaptation research, and with payments for increasing the supply of ecosystem services, including carbon sequestration (Antle 2007). Water law and policies in the western United States could be adapted to increase water allocation efficiency. Crop insurance could be redesigned to be more efficient and reward farmers who invest in risk management capability.

6. Adaptation Policy

The discussion thus far suggests that climate change presents both threats and opportunities for agriculture. Southern parts of the United States will tend to have reduced productivity of crop and livestock agriculture and increased vulnerability to temperature extremes and drought. Northerly regions and dry areas where precipitation increases may experience higher productivity of existing systems and opportunities to shift to more productive and more profitable systems. Climate mitigation policies that effectively raise the cost of fossil fuels will impose costs on some segments of agriculture—particularly large-scale commercial production of grain crops requiring energy-intensive production and marketing—but may benefit smaller-scale producers of crops and livestock that are locally marketed and less dependent on energy-intensive inputs.

In terms of economic vulnerability and adaptive capacity, evidence suggests that most farms are not highly vulnerable to climate change. The relatively small numbers of large commercial farms that produce a large share of agricultural output are vulnerable because they are highly specialized in terms of what they produce. However, most are financially sound and technologically and economically sophisticated. Although these farms are relatively capital intensive, given adequate time, they are capable of adjusting capital and management as the climate changes. The large numbers of smaller farms are less exposed to climate change because they receive most of their income from nonfarm sources, but also may be less able to adapt because of financial constraints and a lack of specialized skills.

Research also suggests that environmental externalities associated with agriculture and ecosystem services could be impacted by climate change because it will induce land-use and management changes. Again, impacts could be positive in some cases and negative in others. Lack of data and appropriate models has prevented regional and national analysis of these issues, but case studies are suggestive of possible impacts.

The food processing and distribution system is not vulnerable to climate in the same way that production agriculture is, but there could be some significant impacts, particularly on the more energy-intensive segments of the sector. Additional investments in food storage and refrigeration may be required with a warmer climate. Food safety also could be impacted by climate change through expansions in the ranges and types of food pathogens that are experienced.

The record shows that U.S. agriculture's success in the 20th century was dependent on complementary investments in physical and human capital and agricultural research and extension, many of them publicly funded through institutions such as the land grant universities. Moreover, complementary policies have fostered the conservation of natural resources and the adoption of more sustainable management practices. This experience suggests that that the U.S. agricultural sector is capable of adapting to a wide range of conditions and adopting new technologies as they become available. As long as the rate of climate change is relatively slow, we can expect the same to be true with future climate change.

The substantial role that the public sector has played in making the complementary investments that led to the success of U.S. agriculture in the 20th century raises a number of questions about appropriate policies in the context of climate change. The justification for public funding of infrastructure, research, and information systems was based on economies of scale as well as the public good aspect of basic research needed to develop agricultural technologies. Although a substantial public role remains in infrastructure, research, and outreach, it has diminished over time as private institutions have become increasingly capable of providing these services. A key question for policy is whether climate change justifies an expanded role in these areas or whether markets can stimulate adequate responses to the adjustments that will be required as the climate changes. There seems to be a particularly compelling case for the provision of public information about climate change, potential impacts, and adaptation strategies.

Agriculture remains an industry with substantial public subsidies to producers of basic grain and fiber commodities, as well as various subsidies and incentives to encourage sustainable land management and to mitigate environmental impacts. Some policies, such as commodity subsidies, create disincentives for farmers to adapt to changing climate and economic conditions, but these subsidies are likely to be under political pressure, both because they increasingly go to large commercial farms and wealthy landowners and because they are incompatible with international trade agreements. Since the 1980s, the subsidy programs have been replaced increasingly by more politically acceptable policies that promote resource conservation and the provision of ecosystem services. These policies are more flexible in the sense that they are not tied to the production of specific commodities, although when they involve the long-term commitment of land to conserving uses, they may also reduce adaptive capacity.

Two other related areas where climate change policy clearly has a potentially significant linkage to agriculture are in GHG mitigation and policies encouraging the use of biofuels. The potential contribution of agriculture to GHG mitigation through land use and biofuels production has been studied in considerable detail (Paustian et al. 2006). Research shows that agriculture can offset GHG emissions at relatively low cost, but the potential quantity that can be offset is a relatively small share of total U.S. emissions. The adoption of practices that sequester carbon can be considered one type of adaptive response; such practices also should be considered in the broader context of the impacts of climate change on agriculture (Antle et al. 2006a). Similarly, policies mandating the use of biofuels, such as ethanol, will have significant impacts on land use and commodity prices, as the commodity price boom in 2008 illustrated, and may ultimately induce changes in land use that largely negate the GHG benefits of biofuel use. Future consideration of policies for agricultural adaptation to climate change will clearly need to take the competition between food and fuel use of agricultural land and other resources into account, together with their impacts on GHG emissions.

7. Conclusions and Implications for Future Research

My review suggests that, despite substantial research on climate change impacts, relatively little research has addressed the likely costs of adaptation in the agricultural sector—or in related sectors, such as transportation—or on appropriate policies to facilitate adaptation. In addition to the policy issues identified in the previous section, this review suggests several directions for further research.

- **Identification of appropriate adaptation strategies: spatial reorganization versus mitigation of extreme events.** The impact assessments carried out thus far have various limitations, as noted above in Section 3.5. These studies have been based largely on changes in mean annual temperature and precipitation from GCMs with coarse spatial and temporal resolution, and thus fail to adequately represent spatial and temporal variability and extreme events. Yet the recent IPCC assessment (Parry et al. 2007, Schneider et al. 2007) emphasizes the importance of vulnerability to extreme events. The modeling exercises indicate that much of the adaptation would take place by changing the types of crops that are grown regionally. In addition to the spatial relocation of crop production, similar logic suggests that a change in the location of livestock production to cooler regions would occur. These changes in the spatial organization of agriculture could imply relatively high costs of adaptation, particularly if the rate of climate change is rapid so that costly changes in farm capital, transportation infrastructure, and processing plants and distribution systems are required. Moreover, if the most significant impacts are in fact associated with extreme events, such as heat waves and droughts, an alternative adaptive strategy could be to develop methods to mitigate the impacts of these extreme events. For example, crops and animals could be bred to tolerate higher temperatures or drought, or structures could be designed or adapted to protect livestock from temperature extremes. This type of strategy might be less costly than relocating private capital and public infrastructure.
- **Estimation of adaptation costs and reassessment of impacts.** The impact assessments carried out thus far have largely ignored the costs of adaptation for the agricultural production sector and for the broader food industry. Some economists have argued that the costs of adaptation are likely to be the most significant impacts of climate change, especially if the rate of change is high (Quiggin and Horowitz 2003). Besides biasing the conclusions of the impact assessments, data on costs of alternative adaptation strategies are needed to inform both private and public decision makers. Costs should be evaluated under alternative scenarios for the rate of climate change, climate variability, and the occurrence of extreme events. Thus far, most of the research effort has been devoted to the impact on grain crops. Much more research on impacts and costs of adaptation in other agricultural

systems is needed, particularly for livestock and other economically important products, such as vegetable and fruit crops.

- **Identifying and estimating the vulnerability of ecosystem services to climate change and adaptive responses.** Agricultural land-use practices are known to have important impacts on the provision of ecosystem services. As yet, the impacts of climate change on ecosystem services have not been quantified systematically on a regional or national basis. Research is needed to identify data and appropriate models that can be linked to site-specific economic models to evaluate the impacts of land-use change on ecosystem services under alternative adaptation strategies.
- **Implications of climate change and mitigation policies for agriculture and the food sector.** As yet, virtually no research has been done on identifying and quantifying potential impacts or adaptation strategies for the food sector. Included in such an analysis would be costs of adapting the food distribution system to a warmer climate and potential impacts on the prevalence and control of food-borne pathogens. The dependence of this sector on fossil fuel–based energy also suggests that GHG mitigation policies could have substantial impacts on the national and global food system as it presently operates. As yet, none of these issues has been addressed in impact assessment studies.

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