Adapting North American agriculture to climate change in review

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Abstract

The adaptability of North American agriculture to climate change is assessed through a review of current literature. A baseline of North American agriculture without climate change suggests that farming faces serious challenges in the future (e.g., declining domestic demand, loss of comparative advantage, rising environmental costs). Climate change adjustments at the farm-level and in government policy, including international trade policy, are inventoried from the literature. The adaptive potential of agriculture is demonstrated historically with situations that are analogous to climate change, including the translocation of crops across natural climate gradients, the rapid introduction of new crops such as soybeans in the US and canola in Canada, and resource substitutions prompted by changes in prices of production inputs. A wide selection of modeling studies is reviewed which, in net, suggests several agronomic and economic adaptation strategies that are available to agriculture. Agronomic strategies include changes in crop varieties and species, timing of operations, and land management including irrigation. Economic strategies include investment in new technologies, infrastructure and labor, and shifts in international trade. Overall, such agronomic strategies were found to offset either partially or completely the loss of productivity caused by climate change. Economic adaptations were found to render the agricultural costs of climate change small by comparison with the overall expansion of agricultural production. New avenues of adaptive research are recommended including the formalization of the incorporation of adaptation strategies into modeling, linkage of adaptation to the terrestrial carbon cycle, anticipation of future technologies, attention to scaling from in situ modeling to the landscape scale, expansion of data sets and the measurement and modeling of unpriced costs. The final assessment is that climate change should not pose an insurmountable obstacle to North American agriculture. The portfolio of assets needed to adapt is large in terms of land, water, energy, genetic diversity, physical infrastructure and human resources, research capacity and information systems, and political institutions and world trade—the research reviewed here gives ample evidence of the ability of agriculture to utilize such assets. In conclusion, the apparent
efficiency with which North American agriculture may adapt to climate changes provides little inducement for diverting agricultural adaptation resources to efforts to slow or halt the climate changes.

1. Introduction

North America, taken here as Canada and the United States, is the world's largest and most productive supplier of food and fiber. It accounted for nearly 12% of the value of global cereal production and nearly 16% of global livestock production in 1991 (US Department of Agriculture (USDA), various years, Agricultural Statistics, US Government Printing Office, Washington, DC). No where else in the world can crops and livestock together be produced as cheaply per unit of input as in Canada and the United States. So dependable is North American agricultural production that it has been a sure supplier of last resort to people in need the world over for several decades.

Will North American agriculture continue its prominent global stature into the first years of the 21st century and beyond? Several economic, social, political and environmental challenges confront North American agriculture. The possibility of future climate change may be one of the most serious challenges.

Rates of climate change from greenhouse warming over the next few decades, were they to occur as expected, are likely to have no precedent in recent history (Schneider and Rosenberg, 1989). Based on current general circulation model (GCM) experiments, the Intergovernmental Panel on Climate Change, IPCC, (Houghton et al., 1990) projected with confidence a global average temperature increase of 1.5–4.5°C from the equivalent radiative forcing of a doubling of all greenhouse gases (e.g. carbon dioxide, methane, chloroflourocarbons) over their preindustrial atmospheric levels (hereafter, $2 \times CO_2$). Though less certain than changes in global average temperature, the IPCC projected a rate of temperature rise of approximately 0.3°C decade$^{-1}$ (with an uncertainty range of 0.2°C to 0.5°C decade$^{-1}$) if greenhouse gas (e.g. carbon dioxide, methane) emissions continue to rise at the present rate. Such a temperature increase would surpass any increase in the last 10,000 years. The IPCC also predicted, though less certain still, that the temperature increases in central North America will be higher than the global mean, accompanied on average by reduced summer precipitation and soil moisture. Furthermore, the uncertainty implied in the range of expected global temperature increase is important in the assessment of the consequences of such. Yohe (1993) points out that such a range introduces an uncertainty multiplier of 'effects' of as little as 0.46 on the low end of expected temperature increase to as much as 15.0 on the high end.

Even if greenhouse gas emissions were drastically reduced overnight the earth likely remains committed to some amount of future warming (NRC/NAS, 1991). The

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1 Mexico, though increasingly engaged in the North American economy, is omitted from consideration here because of dissimilarities with Canada and the United States in terms of production technologies, level of economic development, social institutions and other factors that will regulate its ability to adapt its agriculture to climate change.
The possibility of warming and drying in the major agricultural production region of North America makes a case for examining the potential for adapting agriculture to climate change.

The purpose of this paper is to provide a broad assessment of the adaptability of North American agriculture to climate change and to review major methodological procedures recently developed to conduct such assessment. I begin by defining the terms short-term adjustment or resiliency versus long-term adaptation. Current trends are used to project a plausible scenario of the future of North American agricultural production, climate change apart, in order to establish a baseline against which to measure the consequences of climate change. The historical role of climate in agricultural decision making is examined. Distinctions between current and future climate risk are made. Three major categories of methods aimed at understanding the adaptability of North American agriculture to climate change are examined:

1. analog studies;
2. linked biophysical-economic modeling (agriculture sector only and agriculture sector linked to other sectors) studies; and
3. global assessments, including reduced-form empirical economic models.

I conclude with an assessment of the policy relevance of the various methods and improvements needed to attain the 'next generation' of adaptation assessments, and of what can be said about the adaptability of North American agriculture to climate change vis-à-vis the baseline based on current methods. The two papers that follow this one pursue two alternative new economic modeling approaches to estimating agricultural adaptation to climate change.

It is taken as given, for the sake of argument, that the climate will change in the coming decades, that such change will occur at an unprecedented rate and will be accompanied by steadily rising atmospheric carbon dioxide (CO₂) concentrations. It is also taken as given that farmers and agricultural institutions will make conscious efforts to cope with a steadily worsening climate or to take advantage of new climatic opportunities.

2. Short-term resiliency versus long-term adaptation to climate change

The key question this paper seeks to answer is whether or not North American agriculture can cope with climate changes from greenhouse warming without incurring unacceptable costs. To organize the discussion of this question, agricultural response is divided into short-term resiliency and long-term adaptation.

Kates (1985) distinguishes short-term adjustments to climate change from long-term cumulative adaptations. Borrowing from the field of ecology, Riebsame (1991) amplified this distinction as the difference between the resiliency of a system versus the adaptation of a system, natural or managed. Here resiliency refers to the ability of an

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2 Reduced-form empirical economic models embed statistical associations between proxy economic quantities such as land rents which a priori embody climate and adaptation, often using econometric techniques.
organism, community or ecosystem to absorb infrequent disturbance of varying magnitudes and then return to its pre-disturbance state. Climate fluctuations (e.g. drought episodes, late springs, early freezes) in the Great Plains have periodically temporarily influenced choices of crops to grow, land management practices and use of water, but have done little to change the basic organization of agriculture on the Great Plains (Warrick, 1980).

Long-term adaptation, however, is the ability of an organism or community or system to change form and function in response to repeated disturbance. The notion of adaptation applies to agroecosystems when, for example, a basic production factor becomes more or less scarce over a long period of time prompting a change in the form and function of cropping systems. For example, increasingly scarce irrigation water may cause a change to dryland farming with all of the accompanying shifts in cultural practices, equipment acquisition and marketing infrastructure.

The distinction between resiliency and adaptation is useful in examining the ability of agriculture to deal with climate change in this paper. Short-term adjustments to climate change by farmers, the economy and institutions are efforts to keep the agricultural system in a status quo and, thus, resilient. They are autonomous in the sense that no policy changes or new research are needed in their development or implementation. Short-term adjustments are, in essence, the first line of defense against climate change.

Long-term adaptation of agriculture refers to major changes in infrastructure, production technologies, market mechanisms and government policies in response to some environmental or economic stimulus. Such changes affect fundamental and long-term changes in the resource base and social preferences as reflected in government policies.

3. Major trends affecting US and Canadian agriculture

The Council for Agricultural Science and Technology (CAST, 1992)\textsuperscript{3}, drawing from work by Crosson and Katz (1991), states that a generalized overview of major agricultural trends forms a baseline against which to measure the effects of climate change. Technical, social and economic changes over the last 40 years have greatly transformed North American agriculture. Though the pace and direction of future changes are uncertain, it is important to speculate on what agriculture may look like in the next 3–5 decades since it is likely to take about that much time to realize significant greenhouse gas-induced climate changes. Whether or not climate changes, US and Canadian agriculture face a number of trends in the coming decades that are likely to persist (listed in Table 1).

Domestic demand for food and fiber at the farm gate is not likely to grow by more

\textsuperscript{3}CAST, a nonprofit US organization composed mainly of scientific societies, provides scientific information on key national issues in food and agriculture to policy makers, the media and the public. At the request of the US Department of Agriculture, CAST produced a state-of-the-art appraisal of agricultural response to climate change in the US. The CAST report is a thorough inventory of the assets US agriculture possesses that are needed for adapting to climate change. However, the report draws short of assessing the potential for utilizing such assets based on the current literature, which is the topic of this paper.
Table 1
Trends shaping future North American agriculture

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<th>Trend</th>
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<tr>
<td>1. Slow growth in domestic agricultural demand</td>
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<td>2. Most additional agricultural demand to be foreign</td>
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<td>3. Uncertain rate of productivity growth</td>
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<td>4. Weakening of North American comparative advantage in agriculture</td>
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<td>5. Structural changes in agriculture leading to fewer, larger farms</td>
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<td>6. Decline of rural communities partly offset by technology-driven diffusion of urban amenities to rural areas</td>
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<tr>
<td>7. Protection of environmental values</td>
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<td>8. Increasingly scarce water supplies</td>
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than about 1–1.5% per annum for two main reasons (Duncan, 1989). First, population
growth in North America, a major determinant of demand for agricultural products, has
slowed to about 1% per annum in the 1980s from about 1.75% per annum in the 1950s.
It may go even lower. Second, being reasonably well-fed, the North American consumer
will probably spend less and less additional earned income on food and fiber. The
historical trend of US agricultural demand as reflected in consumption is shown in Fig.
1.

Most of the additional demand US and Canadian farmers will encounter in the future
will come from outside the two countries. Export demand for US agricultural products

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Fig. 1. US consumption and export of wheat, coarse grain and soybeans. Consumed is the annual average for
the 3 years identified by the center or middle year. Production is the sum of export and consumption. Source:
reached a high in the early 1970s (when rapid global economic expansion prompted world trade in wheat and coarse grains to rise at an annual rate of more than 7%) before declining sharply in the mid-1980s (Fig. 2) (Barkema and Drabenstott, 1988). Crosson (1989a), however, posits that world population growth and growth in world per capita income are such that world agricultural demand is likely to be about two to two and one half times larger than present in about 50 years. Most of this new demand will come from developing countries.

North American agricultural productivity and yields are likely to continue to grow but the rate of growth is uncertain. With most good arable land currently in production worldwide, the brightest prospects for increasing world agricultural output lie in technology-driven increases in total farm productivity (total farm productivity is defined as the ratio of total outputs to total inputs). Though the potential for large marginal increases in the harvest index of major grain crops is strongly debated (Khush, 1993), many major physiological controls of crop yields (e.g. photosynthetic efficiency) are nowhere near theoretical limits on yields (McKenney et al., 1992). The USDA (1990) projects that technical progress will lead to a doubling of yields of feed grains, soybeans and wheat from 1980 to 2030. CAST (1992) warns that such projections may be overly optimistic but none-the-less concludes that the abundance of land in the country suggests that projected total production goals will easily be met from the standpoint of the US. The same is also true of Canada.

North American farmers are not likely to enjoy the strong comparative advantage in the future that they possessed over the last 40 years. Major gains in productivity in foreign countries could result in lower production costs in those countries relative to the US and Canada hence eroding US and Canadian market share. Crosson (1989a) argues that several developing countries (for example, Brazil, Argentina, Thailand) have abundant enough land and water resources that they compete favorably with North American farmers. Furthermore, the infusion of human capital, political stability and science-based production technologies could spur emerging countries such as Viet Nam and China also to compete favorably with Canada and the US.
The continuing decline in small farms in the US and Canada will be balanced by an increase in large farms situated in rural areas that have most of the amenities of urban areas. Duncan (1989) concludes that the trend toward consolidation of US agricultural production into larger businesses will continue and will be accompanied by further declines in small communities dependent on farming for support. However, such declines may not be noticed as new technologies such as personal computers, advanced telecommunications and airborne emergency medical systems deliver a suite of once urban amenities to all regions.

Environmental concerns are likely to limit production. Stronger environmental protection policies in the future may cause agricultural production costs to rise and hence erode US and Canadian market share. Phipps et al. (1986) argue that a portion of the gain in North American agricultural productivity since World War II comes at the expense of high environmental costs (e.g. sediment damage, nutrient damage, pesticides in water).

The availability of adequate water supplies for irrigation may seriously challenge agriculture particularly in the semi-arid regions (e.g. southwestern US; western Great Plains) where such is practiced most widely in North America (Frederick, 1991). Frederick (1991) projects that irrigation will continue to expand into regions where there are adequate water resources (e.g. central and eastern Great Plains, Pacific Northwest) and will continue to decline in regions that are faced with increasingly scarce water supplies. CAST (1992) cited the western Great Plains and Arizona Central Valley as two examples of the dramatic preemption of irrigation water by urban uses in recent years.

4. The current role of climate in North American agriculture

4.1. Farmers and perception of climatic risk

How do farmers perceive climate risk in the scheme of all other kinds of farm risks? The answer is useful in showing how farmers may respond to a gradual change in climate normals and variability. Boggess et al. (1985) surveyed farmers in Florida and Alabama and found that weather, specifically rainfall variability, was the most important source of crop risk. Other forms of risk in the survey included pestilence, financial risk, risk of adopting technological innovations and marketing risk.

North American farmers deal with climatic risk in several ways. Boggess et al. (1985) found that southeastern US producers like to maintain animal feed stores and to keep their operations diversified in order to minimize loss from rainfall variability. Sonka and Patrick (1984) confirm the maintenance of feed stores and some forms of diversification (for example, shifting from continuous row crop corn (maize) in Illinois to a row crop–sod crop rotation (corn (maize)–oat–clover)) as ways of minimizing weather-related production risks. They list additional strategies such as selection of technical practices like the investment in extra equipment capacity to manipulate timing of crop exposure to unfavorable weather and adoption of irrigation to supplement natural rainfall in arid and semi-arid environments.
4.2. Agricultural policy and climate risk

Public institutions have made climatic risk a central part of US and Canadian agricultural policy. Their efforts to minimize the disbenefits of climate risk principally fall under the rubrics of disaster payments, crop insurance and subsidized water.

Gardner et al. (1984) and Tyrchiewicz (1986) suggest that the stabilization of agricultural performance has historically been a top priority for US and Canadian agricultural policymakers. Disaster payments are a fundamental part of agricultural stabilization strategy. In Canada, the Western Grain Stabilization Program (begun in 1976) buffers farmers from unforeseen market fluctuations and cost changes (including those climate-induced) by making payments directly to farmers. The US Agriculture and Consumer Protection Act of 1975 established the disaster payments program to compensate farmers for prevented plantings and unusually low yields due to natural disaster, adverse weather and other conditions beyond a farmer’s control. The federal government paid out $4 billion in disaster payments during the drought of 1988 (Riebsame et al., 1991). The disaster payments program has not been without critics. Gardner et al. (1984) argue that disaster payments act as an insurance policy for the farmer and tend to encourage production of high return, high risk crops in marginal areas.

Federally subsidized crop insurance has been available to US farmers in its present form since 1948 and has been fairly widely subscribed. Gudger (1991) points out that all-risk crop insurance in the US is so heavily subsidized that the government absorbs about 30% of the premium cost and pays 100% of losses in excess of premium income. In the 1988 midwestern drought, the US federal crop insurance payout to farmers was $3 billion in addition to the $4 billion in disaster relief mentioned above. Gardner et al. (1984) again point out that crop insurance can have unintentional side effects. They cite a recent survey in Virginia and Montana that found that insured farmers were in a riskier situation than uninsured farmers because they tended to be less diversified, less likely to have irrigation and had less income and savings and greater debt. The point here is, like disaster payments, crop insurance may encourage the taking of imprudent risks by some producers. Such may, in net, increase rather than decrease vulnerability to climatic changes.

The application of irrigation water to crops to supplement precipitation has been a powerful tool for stabilizing crop yields in the face of climatic variability in humid and semi-arid regions alike. The US Reclamation Act of 1902 mandated several federally sponsored irrigation water projects mainly in the form of the construction of large reservoirs (Gardner et al., 1984). Prices for irrigation water have been heavily subsidized, which has tended to hold prices below market values. But overreliance on irrigation has burdened some water supply systems to the extent that irrigation costs have become prohibitive. The High Plains Aquifer has been pumped so heavily in large parts of the southern Plains that groundwater levels have declined precipitously in recent decades (High Plains Associates, 1982). In addition, increased nonagricultural demand for water has threatened the viability of irrigation in some areas. Frederick (1991) observes that states along the mainstem of the Missouri River system have become embroiled in a heated competition for alternative uses of the river’s water (instream environmental values versus irrigation and water-borne transportation). Riebsame (1988)
found that surface water supplies for irrigation in California are strongly competed for by municipal consumers.

5. The problem of climate change

What characteristics differentiate risks with climate change from risks with the current range of climate and weather fluctuations? Smit (1993) summarizes the attributes of natural disturbances that influence the adaptability of human systems; some of them are borrowed here to distinguish climate change from other climatic risks. Such attributes include areal extent, duration and magnitude and frequency, and suddenness. The attribute of synergism with other disturbances is also suggested.

5.1. Areal extent

The scale of climate change will be truly global. No region will be unaffected, though significant regional differences in the pace, direction and extent of change are likely. Easterling et al. (1989) argue that, so long as climate changes do not rapidly reach lethal levels for crops in cold-limited regions, agriculturalists there may be advantaged by climate change while agriculturalists elsewhere may be disadvantaged. There is no way of knowing whether the gains will offset the losses, but the outcome will surely affect world agricultural markets on a long-term basis—something that current climate hazards have not done.

5.2. Duration, magnitude and frequency of extremes

Climate change will be a continually evolving shift away from current climatic normals. For all practical purposes the climate will be in constant, perhaps rapid, transition to new expected weather conditions. Not only will there be a change in average climatic conditions but there also will be a change in the frequency of extreme events (Mearns et al., 1984). It is not known with confidence whether extreme events, such as droughts, will become more or less frequent in major agricultural areas. The IPCC (Houghton et al., 1990) judges that, with increases in mean temperature, there will be more frequent episodes of extreme warm temperatures and less frequent episodes of extreme cold temperatures.

5.3. Suddenness

While there is disagreement over how rapid the climate will change, most of the evidence presented by the IPCC (Houghton et al., 1990) suggests that the change will not deny the agriculture research community a chance to develop new technologies and institutional innovations aimed specifically at dealing with climate change. Rosenberg (1992) suggests there is time “measurable in decades” to develop new adaptive strategies and policies. Most of the climate hazards that currently plague agriculture emerge and then dissipate over time scales ranging from a few minutes or hours to a few
years at most. Though current hazards such as drought, hail, freezes, flooding and the like warrant (and receive) attention of the research establishment, as individual events they have lead times that are too short to respond to individually. Such is not the case with climate change. Crop trials taking place today in Oklahoma, for example, may provide the raw material with which to adapt Nebraska agriculture as Nebraska’s future climate warms to that of Oklahoma now (NRC/NAS, 1991).

5.4. Synergism with other environmental changes

Climate change is not the only global environmental change confronting agriculture. Increased surface receipts of UV-B radiation from stratospheric ozone depletion, acid deposition and landuse change will influence future agricultural performance and will condition agricultural response to climate change. The best example is carbon dioxide itself. Unlike current climate hazards to agriculture, climate change will be accompanied by rising atmospheric concentrations of carbon dioxide. The fact that crops, when exposed to increased concentrations of atmospheric carbon dioxide, respond with greater photosynthetic efficiency and water use efficiency is not questioned (Kimball et al., 1990; Lawlor and Mitchell, 1991; Culotta, 1995). How much the direct effects of higher carbon dioxide concentrations will offset/enhance the potential climate change-induced losses/gains in crop productivity is not known, especially in realistic farming situations where nutrient availability and climatic conditions are less than ideal.

6. Short-term domestic adjustments to climate change

6.1. Farm-level adjustments

The literature reviewed in this paper suggests a large selection of short-term adjustment tactics available to producers for dealing with the effects of climate warming (Table 2). Short-term adjustments to warming and drying \(^4\) include, for example:

1. Changes in planting and harvesting practices. Climate warming will possibly allow farmers to plant earlier in the spring than at present. Earlier planting helps the farmer in several ways. All else equal, crops planted earlier are more likely to have matured past the stage when extreme high temperatures can cause injury—such temperatures are most likely in the middle to late summer. Warmer springs imply a longer growing season. Planting earlier with a longer season (maturation period) cultivar will allow farmers to seek maximum yields, provided moisture is adequate throughout the season and that the risk of heat damage is not too great. For risk averse producers, earlier planting combined with a shorter season cultivar would give the best assurance of

\(^4\) Since it is not known exactly how the climate will change regionally or over time, I focus on adjustments appropriate for the most challenging kind of climate change for agriculture: severe warming accompanied by a decrease in summer precipitation.
Table 2
Short-term adjustments to warming and drying suggested by the literature

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<th>Farm-level adjustments</th>
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<td>Planting and harvesting practices</td>
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<tr>
<td>Earlier planting</td>
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<tr>
<td>Longer-season cultivars</td>
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<tr>
<td>Greater diversity of cultivars</td>
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<tr>
<td>Planting seeds deeper</td>
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<tr>
<td>Earlier harvesting</td>
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<tr>
<td>Eliminate/reduce artificial drying</td>
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<tr>
<td>Tactics to conserve moisture</td>
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<tr>
<td>Conservation tillage</td>
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<tr>
<td>Substitution of less water-intensive crops</td>
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<tr>
<td>Microclimate modification</td>
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<tr>
<td>Irrigation scheduling</td>
</tr>
<tr>
<td>Government programs</td>
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<tr>
<td>Increased flexibility in commodity programs</td>
</tr>
<tr>
<td>Subsidized high efficiency irrigation systems</td>
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<tr>
<td>Trade policies</td>
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avoiding the greatest warmth of the summer, though shorter season cultivars yield less than longer season cultivars when climate is not limiting. Some analysts advocate the planting of a mix of cultivars with different maturation times so as to maximize the probability that a portion of the crop is exposed to favorable climate during a given growing season (Stewart, 1990). Planting deeper gets seeds into the moisture that may be deeper in the soil profile, which makes successful germination more likely.

Earlier planting will, all else equal, allow earlier harvesting. The warmer temperatures will speed up the development of the crop and the drier, warmer conditions will cause grain crops to drydown more rapidly. Earlier harvesting will reduce risks of field losses, but, of course, must be balanced against farmers’ desires to plant longer-season varieties to take full advantage of the longer growing season. Some areas may be able to eliminate or reduce artificial drying in order to attain the desirable moisture content in grains, thus, reducing energy expenditures.

2. Tactics to conserve moisture. Rosenberg (1986) identifies a number of moisture conserving practices that have been used to combat drought. These practices may also be useful in adjusting to climate change. Conservation tillage is the practice of leaving some or all of the previous season’s crop residue on the surface of the field rather than completely ploughing the residue under the surface. Conservation tillage helps protect the field from water and wind erosion and helps the field retain moisture by reducing evaporation and increasing the infiltration of precipitation into the soil. Conservation tillage also decreases soil temperature. Crop substitution (changing from one species such as corn (maize) to another such as wheat) is potentially a means of conserving moisture. Some crops use low amounts of water, are more stress resistant and will tolerate warm, dry weather better than others. For example, wheat and sorghum are more tolerant of warmth and dryness than corn (maize). However, in most farming situations,
drastic crop switches to those not readily grown locally now will probably require investments that go well beyond the concept of simple adjustments discussed so far.

Microclimate modification can be effected by, for example, the use of shelterbelts. Shelterbelt systems are linear configurations of trees surrounding one or more sides of agricultural fields to reduce windspeed. They are particularly effective in windy regions that have little natural vegetation or topography to break the wind. They greatly reduce windspeed across the protected field. Rosenberg (1986) argues that the shelter effect benefits plant growth by conserving moisture, although the trees do compete for moisture with crops at the edge of the field. Shelterbelts and other land management practices can assist water harvesting through, for example, snow trapping and runoff reduction.

Irrigation scheduling is the practice of supplying crops with irrigation water only when they need it. It tunes the proper timing and amount of water to apply to actual field conditions. Irrigation scheduling requires close cooperation between farmers and sources of information about soil moisture conditions. In a study of a sample of four Nebraska counties, Boomstadter et al. (1989) found that irrigation scheduling demonstrations on center pivot systems reduced irrigation water use by 8.9% and saved farmers an average of US $2.10 relative to average total pumping costs of US $30.00 acre⁻¹.

6.2. The role of government programs

Under climate change, current farm programs temporarily would offer several avenues of relief. Disaster payments and subsidized crop insurance programs cater specifically to farmers who have been victimized by weather-related yield losses. G. Barnaby (personal communication, 1990) argues that, as farmers on climatically marginal lands (for example, the western fringe of the Great Plains) see losses begin to mount, they could simply set their land aside in the Conservation Reserve Program and continue receiving revenues from the government. But how long will society continue to wilfully assume a growing financial responsibility to bail farmers out with disaster payments and subsidized crop insurance when there are cheaper alternatives in the form of imports? I consider the potential for adjustments in international trade in the next section.

Even if society is willing to underwrite a portion of agricultural risk under climate change, Lewandrowski and Brazee (1992) argue that current farm programs need to be modified to achieve their goals under a climate change. They mention two examples of such modifications. First, instilling flexibility into commodity programs would allow participants to choose from a range of crops without directly affecting the participant’s level of support in order to facilitate a rapid and efficient change in the participant’s mix of commodities. Participants would not be penalized for giving up the riskier but well-subsidized crops such as corn (maize) in order to grow a more stress-resistant crop such as wheat or sorghum. At present, farmers growing most grain crops must establish a ‘base’ acreage in those crops over a several year period in order to qualify for support payments. Having to reestablish a base acreage in another crop is a strong disincentive to switch crops. Second, reducing the costs to farmers of acquiring high efficiency irrigation systems would give farmers an added hedge against climate change in regions where irrigation withdrawals currently exceed recharge.
7. Interactions between North American agriculture and the global agricultural economy: adjustments involving international trade

North American agriculture is not practiced in isolation from the rest of the world. Kane et al. (1992a) argue persuasively that the functioning of local, regional and international markets for food and fiber will be a key to successful long-term adaptation to climate change. World agricultural trade is the primary means of collecting and distributing supplies of food and fiber. Agricultural prices are set in world markets which in turn govern where and how much food and fiber is allotted to consumers. Were a nation’s agricultural capacity severely damaged by climate change, the most economically efficient solution to the problem of meeting domestic agricultural demand would be to import agricultural commodities which are produced less expensively elsewhere, assuming that climate change does not uniformly disadvantage all nations. How feasible is such a solution with the current functioning of world markets?

CAST (1992) posits that economic growth and trade policy are the two main determinants of trade flows in world agricultural markets. Crosson (1989a) sees no reason why climate change would appreciably affect projected steady growth in future world agricultural demand (economic growth). Thus, policies that affect international agricultural trade are likely to be a more important constraint to effective short-term adjustment to climate change than economic growth.

Crosson (1989a) states that freer trade will be necessary for the movement of agricultural outputs from those nations that are benefitted by climate change to those which are disadvantaged by climate change. Nations which see a loss of comparative advantage in agriculture because of climate change can buy relatively cheaper food and fiber from countries which do not see a loss in comparative advantage; agriculturally disadvantaged countries would be free to reinvest agricultural labor and capital in more profitable sectors than the relatively unproductive agricultural one.

What specifically can be said about North American adjustments to climate change involving international trade? The answer hinges on how climate change differentially affects production in the US, Canada and the rest of the world.

What of the US and Canada? The IPCC (Houghton et al., 1990) concluded with only modest confidence that mid-latitude continental interiors (locations of several important granaries, including those of the US and Canada) may warm more than the global mean and become drier than present. Most of North America’s major agricultural production zone would fall under the provencence of warming and drying. Results of several studies reviewed below (see summary in Table 4) suggest that, after adaptation, warming could benefit production systems that are currently cold-limited (e.g. parts of the northern US and Canada) while such could stress production systems further south (central and southern Midwest), especially if accompanied by drying.

What of the rest of the world? CAST (1992) argues that there is no way of knowing how climate changes will alter future world trade patterns. There will probably be winners and losers among regions. Crosson (1989a) makes two general observations concerning future world production in response to climate change worth noting here. First, he reasons from crop yield studies that by mid-21st century climate change impacts on world agricultural capacity are likely in net to be small (−17% at most) by
comparison with anticipated doubling of capacity from advances in technology. He sees no indication that climate change will pose a major threat to the world's ability to expand agricultural capacity apace with demand. This finding is supported generally by a recent global agriculture study (Rosenzweig and Parry, 1994) reviewed below.

Second, Crosson (1989a) argues that regional distribution of agricultural capacity is likely to change in unforeseen ways. He, too, notes the possibility that cold-limited regions (former Soviet Union, Canada and mountainous areas) may benefit from climate change. On balance, however, changes in the future geographic distribution of comparative advantage uncertain.

Under the above climate scenario Canada and the US could become even stronger trading partners than present. The recently enacted North American Free Trade Agreement (NAFTA) was a significant step toward the easing of barriers to agricultural commodity exchanges between Canada and the US. Were US farmers unable to supply domestic agricultural demand under a steadily worsening climate, not only would US exports fall, if not disappear, but relatively cheaper Canadian imports, provided Canada is less negatively affected by climate change than the US, could help keep agricultural prices acceptably low for US consumers.

What if yields on average decline in the US and Canada. Recent research by Kane et al. (1992b) found that were US crop yields to decline by, for example, 20% while yields in the former USSR, People's Republic of China, Japan, Australia, northern Europe, Brazil and Argentina were to increase by 25% and yields for the rest of the world to decline by 25%, simulated welfare effects as a percentage of 1986 gross domestic product would decrease by about 1%. This finding is probably generally applicable to Canada also though in both cases it is predicated on the assumption that trade flows freely between importing and exporting nations.

The point here is that even were North America to experience a relative loss of comparative advantage in agriculture under climate change, international market adjustments in the form of increased trade with countries benefitted by climate change would likely lessen the impact on the North American agricultural economy.

8. Long-term agricultural adaptation: what historical analogs of climate change can tell us

Recent history has no experience with the magnitudes and rates of anticipated climate changes from which to reason to the future. However, North American agricultural history is replete with examples of long-term adaptation to overcome adversity or to remove an impediment to increased productivity. Glantz (1988) was the first to argue that such examples may be analogs of climate change which may generally provide insight into human and environmental response to the gradual onset of disturbances. Three different situations that are analogs of climate change are considered here:
1. translocation of crops;
2. introduction of a new crop; and
3. resource substitution in response to scarcity.
8.1. The translocation of crops

Expansion of a crop into a new region often requires that the crop be adapted to a new climatic regime. Here I will expand on Rosenberg's (1982) example of such with hard red winter wheat in the US. Expansion of dryland corn (maize) in Canada is given as another example of translocation.

8.1.1. Example 1: expansion of the hard red winter wheat zone north and south

Hard red winter wheat (hereafter in this section, winter wheat) has consistently accounted for about half of all wheat produced annually in the US in this century (Briggle and Curtis, 1987). Rosenberg (1982) shows that the provenance of winter wheat expanded greatly from 1920 to 1980 (Fig. 3). Over the period 1920 to 1980 the northern boundary of the winter wheat production zone shifted to a location which was about 3.5°C cooler and 15% dryer than its location in 1920.

But climate change is more likely to warm the Great Plains than cool it! The southward expansion of winter wheat has not been as extensive as the northward spread. However, average annual temperatures at the current southern boundary of the winter wheat production zone are more than 2°C higher than those of the 1920 southern boundary. Thus, it appears that winter wheat is adaptable to not only cooler climates, but to warmer ones as well.

What sort of changes in wheat culture aided the expansion of the winter wheat zone? Rosenberg (1982) was only able to speculate on such changes in his original work. Dalrymple (1988) has shown the progression over time to a greater diversity of winter
wheat varieties being used by US farmers (Fig. 4). Though not explicitly stated, one implication is that this greater diversity has led to a better adaptation of wheat to growing conditions. In particular, the development and adoption of semi-dwarf varieties in the 1940s (varieties whose stalks can support heavier, grain-laden heads) boosted productivity of wheat (Dalrymple, 1988). Selective breeding for cold-hardy varieties of winter wheat helped the expansion of wheat to the north. Savdie et al. (1991) find that direct, no-till seeding of winter wheat into stubble immediately after harvest of the previous crop (stubble-in) and snow trapping has reduced the risk of winterkill and permitted expansion of the crop northeastward to include most of western Canada's agricultural area. The breeding for disease resistance helped the expansion to the south. Improved farming practices, especially the use of nitrogen fertilizers and better water management practices (for example, fallowing and stubble-mulching) and the use of large self-propelled machinery, also increased productivity. Cox et al. (1986) traced the historical genetic diversity of winter wheat and found that diversity is increasing. They argue that greater genetic diversity provides raw material for further genetic progress.

8.1.2. Example 2: adapting dryland corn (maize) to conditions in southern Alberta

Even more remarkable than the spread of winter wheat culture into the south central Canadian prairie provinces is the recent adaptation of dryland corn (maize) to that same region. Major et al. (1991) found that farming systems in the semi-arid northern Great Plains have historically suffered from overdependence on a narrow range of crops, especially wheat, making the region vulnerable to price fluctuations. Recognition of this
problem caused farmers working in concert with the local agricultural research establishment to seek an alternative crop to the small grains that have typified cropping systems in the region.

This need to diversify cropping systems in southern Alberta led the Lethbridge Research Station to devote 8 years of research to the adaptation of corn (maize) to the climate of the region (Major et al., 1991). Relative to other regions of the US that produce significant quantities of dryland corn (maize), southern Alberta is drier (350–400 mm of precipitation annually), the frost-free season is relatively short (124–129 days), growing degree day accumulations (accumulated positive difference between mean daily temperature and a base of 50°F or 10°C) are low, and photoperiod (length of day) is long. Corn (maize), like all crop plants is limited by photoperiod response and temperature (Major et al., 1991). Photoperiod response may be a crucial limitation to taking full advantage of warming in high latitudes.

Plant breeders at Lethbridge have developed hybrids that have reduced photoperiod sensitivity and a short juvenile phase so the tassel is initiated within a week of plant emergence. Moreover, breeders have successfully selected for varieties with a short interval between anthesis and silking, which appears to give the corn (maize) plants resistance to drought stress.

In dryland trials Major et al. (1991) found that corn (maize) yields were competitive with those of barley and wheat. They found that with current (1991) prices, gross returns per acre (in Canadian dollars) for wheat, barley, and corn (maize) would be $95.45, $99.82, and $162.50, respectively. Total net revenues were not given. They state, however, that although production costs for dryland corn (maize), especially for seed and drying, are higher than for wheat, the economic trends are promising.

8.2. Introduction of new crops: the case of soybeans and canola

Climate change may necessitate widespread and relatively rapid introduction of crops not presently grown in the US and Canada. How easily such a shift could be accomplished will depend on the available pool of crops that will flourish under the changing climate, their production costs (including the cost of new infrastructure), and the markets for them. The expansion of soybeans into US agricultural production, especially since World War II, is one example of the rapidity with which the nation’s production systems can be modified to accommodate a new crop.

Fornari (1979) found that harvested acreage of soybeans rose from 5.8 million acres in 1941 to 58 million acres in 1977. Hart (1986) noted that, in 1920, only 40% of the cropland in the Corn Belt states was planted to corn (maize) with the rest planted to wheat mostly, and there was no measurable acreage planted to soybeans. By 1982, more than half of the region’s cropland was planted to corn (maize) and more than one-third was planted to soybeans (Fig. 5). In less than 30 years soybeans became a major cash crop for US farmers.

The spread of soybeans in the US demonstrates the capacity of the farming system to convert equipment, management, and marketing to grow a new crop in a short period of time. In the case of the south, it also shows the willingness of farmers to experiment with a new crop as their old crop of preference (cotton) became uneconomical.
Fig. 5. Midwestern soybean acreage in 1949 and 1982. Source: Hart (1986).
The introduction and rapid growth of canola production in Canada is another example (NRC/NAS, 1991). Canola production grew from negligible amounts during the early 1940s to nearly 3 million tons year$^{-1}$ in the late 1970s (Fig. 6).

8.3. Substitution of resources in response to scarcity

Climate is an important resource in the growth of a crop. The ‘induced innovation hypothesis,’ developed most fully by Hayami and Ruttan (1985), posits that the development of new agricultural technologies is a dynamic process set in motion by differences in the relative scarcity of agricultural resources, with the differences signaled by changes in relative resource prices. The scarcity differences create incentives among farmers to seek new technologies that substitute more abundant for more scarce resources. In the short-term, the substitution may not require new technological or institutional developments since it may simply involve the use of a larger quantity of less-expensive resources relative to the more expensive ones. Over time, however, extant substitution possibilities are strained or exhausted, which stimulates public and private research institutions to undertake the research needed to provide a new suite of substitution possibilities.

Climate was not considered by Hayami and Ruttan (1985) in their formulation of the induced innovation hypothesis. Climate is not priced\textsuperscript{5}, so it is difficult to provide clear examples of climatic inducements to agricultural research based on price signals. There

\textsuperscript{5}Recent work by Mendelsohn et al. (1994) and others suggest that the economic value of climate may be indirectly reflected in the price of land. Land price encapsulates crop mix and yields, both of which are determined in part by climate.
are other production factors, however, that shape agricultural production whose recent
trends in scarcity can provide a glimpse of how agriculture may respond to enhanced or
interrupted deliveries of climate resources.

8.3.1. Example 1: historical energy prices as driver of agricultural technology

Heady (1984) notes that the persistence of cheap energy prices since the turn of the
century has had an enormous effect on US agricultural technology. In the first 100 years
of this country, the supply of land and labor was large and their prices were low.
Agriculture used prodigious quantities of both. But Heady (1984) describes a remarkable
transformation in agriculture beginning at the end of the 19th century:

"as uncropped land supplies neared exhaustion, emigration laws lessened
labor entrants, and development led to great capital supplies, some
mechanization of agriculture began. This substitution of capital for labor was
encouraged because energy supplies from external sources were favorably
priced... However, at the turn of the century, with land supplies now more
limited, the real price of food in the U.S. began rising. As supplies of fossil
energy greatly expanded and the real price of energy from this source
decreased, fertilizer-responsive crop varieties were developed."

Heady (1984) further noted that the existence of cheap energy was a major catalyst in
the trend toward biological substitutes for land and mechanical substitutes for labor. But
real energy prices have not always been low. In the early 1970s energy prices took a
sharp upturn in response to an embargo on oil exports from the Organization of Oil
Exporting Countries (OPEC) cartel. Darmstadter (1991) finds that energy intensity in US
agricultural production, defined as the ratio of energy inputs measurable in British
Thermal Units (BTUs) to dollars of gross farm product, declined considerably between

Are there lessons from the energy price-induced transformation of US agriculture that
are applicable to the long-term adaptation of agriculture to climate change? A climate
change that benefits agriculture and presents new but untapped opportunities for farmers
would be somewhat similar to the existence of cheap and abundant energy. As with low
real energy prices, a more favorable climate would be a strong inducement to develop
technical and institutional ability to utilize the climate. Similar reasoning may apply to a
climate change that disadvantages agriculture. Again, diminishment of climate resources
constitutes an increase in the 'price' of climate. Such would be a signal to the research
establishment not unlike the signal of higher land prices earlier in this century.

8.3.2. Example 2: adaptation to groundwater is on decline in the High Plains Aquifer

Irrigation water is a substitute for inadequate or unreliable precipitation. Increasingly
scarce irrigation water is essentially the same as scarce precipitation in rain-fed regions.
Glantz and Ausubel (1988) argue that declining irrigation groundwater can serve as a
useful analogy to a gradual climate drying. The rise in pumping costs associated with
declining water tables is no different from a rise in irrigation costs due to long-term
climate drying. Glantz and Ausubel considered the recent agricultural experience with
the High Plains or Ogallala Aquifer in the US Great Plains. The aquifer is a large
geologic formation of porous sand that underlies approximately 225,000 miles² in the
US Great Plains (Fig. 7; Wilhite, 1988). Recharge rates are very low and lateral movement within the aquifer is slow. Groundwater utilization, primarily for irrigation, has steadily risen from 7 million acre-feet in 1950 to 21 million acre-feet in 1980 (Wilhite, 1988). This increase has caused the saturated thickness to decline by as much as 25–50% since the 1940s, especially in the southern Plains (High Plains Associates, 1982; Lehe, 1986). Lehe (1986) concludes that groundwater declines in the aquifer have caused irrigation pumping costs to rise since it takes more fuel to pump water from lower depths.

Glantz and Ausubel (1988) focused mostly on the identification of impacts of groundwater declines as an analogy to climate change impacts; adaptation was nodded to but not handled directly. Here, I incorporate a small number of adaptive studies that bear on the Glantz and Ausubel analysis.

Kromm and White (1986) surveyed water users, primarily agriculturalists, across the High Plains Aquifer region in order to catalog potential adaptations to declining groundwater levels and to rank the adaptations in terms of desirability for adoption (Table 3). They found that the two leading adaptations preferred by water users were to increase irrigation efficiency and practice conservation tillage. Lehe (1986) shows that there has been a dramatic increase in the use of low-pressure irrigation systems in the southern Plains states and that farmers in the region are switching to low water intensity crops such as wheat. A gradual climate drying would also demand stronger water conservation. Nellis (1987) shows that the amount of irrigated acreage in southwestern Kansas declined by 5.5% between 1977 and 1983 (Fig. 8) and that those farmers still using irrigation were switching to low water intensity crops.

A number of studies have called for policy reforms to help farmers and ranchers deal with scarcer groundwater on the High Plains (High Plains Associates, 1982; Supalla et al., 1982; Wilhite, 1988; Glantz and Ausubel, 1988). Keller et al. (1981) found that
Table 3
Groundwater depletion adaptation preferences

<table>
<thead>
<tr>
<th>Categories</th>
<th>Adaptations</th>
</tr>
</thead>
<tbody>
<tr>
<td>Management practices</td>
<td>Improve irrigation efficiency</td>
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<tr>
<td></td>
<td>Employ conservation tillage</td>
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<td></td>
<td>Require tailwater reuse</td>
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<td></td>
<td>Periodically check well efficiency</td>
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<td></td>
<td>Plant shelterbelts</td>
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<td></td>
<td>Grow hybrid plants using less water</td>
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<td></td>
<td>Encourage secondary recovery methods</td>
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<td></td>
<td>Measure soil moisture</td>
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<td></td>
<td>Reduce evapotranspiration</td>
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<td></td>
<td>Rotate fields to be irrigated</td>
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<td></td>
<td>Employ a multi-function irrigation system</td>
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<td></td>
<td>Furrow dike on flat ground</td>
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<td></td>
<td>Prewater to build up soil moisture</td>
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<td></td>
<td>Meter all water use</td>
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<td></td>
<td>Rotate wells pumped</td>
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<td></td>
<td>Use surge flow water application</td>
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<td></td>
<td>Return to dryland</td>
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<tr>
<td>Public policies</td>
<td>Identify intensive control areas</td>
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<td></td>
<td>Give priority to municipal water use</td>
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<tr>
<td></td>
<td>Apportion available water equitably</td>
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<td></td>
<td>Increase spacing between irrigation wells</td>
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<td></td>
<td>Prohibit new irrigation wells</td>
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<td></td>
<td>Give priority to irrigation</td>
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<td></td>
<td>Prohibit irrigation on sandy soils</td>
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<td></td>
<td>Withhold more recent irrigation rights</td>
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<tr>
<td></td>
<td>Limit kinds of crops irrigated</td>
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<tr>
<td></td>
<td>Give priority to industrial water use</td>
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<tr>
<td>Financial incentives and disincentives</td>
<td>Charge for water permits</td>
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<tr>
<td></td>
<td>Tax credit for irrigation fuel</td>
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<tr>
<td></td>
<td>Charge for irrigation water</td>
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<tr>
<td></td>
<td>Tax irrigated acreage</td>
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<tr>
<td></td>
<td>Tax water use by volume</td>
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<tr>
<td></td>
<td>Offer government depletion insurance</td>
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<tr>
<td></td>
<td>Impose a severance tax on groundwater</td>
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<tr>
<td></td>
<td>Government subsidizing of energy costs</td>
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<tr>
<td>Technological fixes</td>
<td>Build reservoirs to store water</td>
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<tr>
<td></td>
<td>Build small recharge dams</td>
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<tr>
<td></td>
<td>Improve weather modification</td>
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<tr>
<td></td>
<td>Transfer water from sources within state</td>
</tr>
<tr>
<td>Other adjustments</td>
<td>Encourage water conservation laws</td>
</tr>
<tr>
<td></td>
<td>Fund water law and use education</td>
</tr>
</tbody>
</table>

Source: after Kromm and White (1986).

Institutional response has typically been organized at the local or regional level and the effectiveness of local policy has varied from state to state. Kansas, on the one hand, passed the Groundwater Management Districts Act in 1972.
which established groundwater management units or districts to regulate the spacing of wells, numbers of wells, metering of water use and to promote water conservation (Nellis, 1987). On the other hand, Texas, a state that could benefit greatly from strong groundwater governance uses the ‘English rule’ in determining ownership of water. (Stepleton, 1986) The English rule states that an owner of a parcel of land owns from the ‘sky above to the depths below’, which includes the water on, above and below the surface. In all other states water is considered a public good. The English rule has proved to be a formidable disincentive for landowners to agree to regulation of their water on the local (e.g. county) level.

What lessons are provided by the High Plains Aquifer experience vis-à-vis adapting to climate change? First, even though farmers experienced hardship as water tables fell, their adaption through reversion to dryland farming has been generally successful (Kromm and White, 1986; Nellis, 1987). Second, the efficacy of institutional response to groundwater scarcity varies widely from state to state.

9. Linked biophysical–economic modeling of agricultural adaptation to climate change

Historical examples of agricultural adaptability can only take us so far in understanding the long-term adaptation of current and future agriculture to climate change. In recent years, researchers have begun to focus on the development of modeling methodologies for anticipating the adaptation of agriculture to possible future climate change. A typical approach is to link crop growth models which simulate agronomic response to climate change with economic models which estimate damage functions based on agronomic response. Most examples of such approaches are organized at the micro- or farm-level where in situ simulations must be scaled up or extrapolated to regional levels.
10. Studies of the agriculture sector

The earliest efforts at linking crop growth and economic models led to a quantum jump in the understanding of adaptation, but were limited by their focus on agriculture, absent connections to other resource sectors (the implications of this are discussed in the next section). In this section I review the major elements of three such recent studies that directly model the adaptation of production agriculture to climate change. The studies will be referred to as:
1. the IIASA (International Institute for Applied Systems Analysis) study (Parry et al., 1988);
2. the EPA (Environmental Protection Agency) study (Smith and Tirpak, 1989); and
3. the Cornell study (Kaiser et al., 1993).

Below, I describe the approach used in each study, summarize the results and analyses and interpret insights gained concerning adaptation.

10.1. The IIASA study

10.1.1. Research approach

Martin Parry led a study based at IIASA that examined the impacts of climate variation and change on agriculture in a number of locations worldwide (Parry et al., 1988). The research approach involved the use of a partially integrated hierarchy of models. Climate scenarios based on the instrumental record and GCM experiments were inserted into biophysical models of first-order impacts (effects of climatic variation on agronomic and animal productivity) to estimate climate impacts on crop yield, livestock production, and livestock health. Economic models were used to examine farm profitability, regional employment, and gross domestic product. Short term adjustments to climate change were examined at two levels:
1. farm-level adjustments such as crop changes, increased irrigation and changes in fertilization; and
2. policy responses from the local to international level.

The study locations were divided into two groups:
1. cool temperate and cold regions (Saskatchewan, Iceland, Finland and the Leningrad, Central and Cherdyn regions of what was the northern USSR, and northern Japan); and
2. semi-arid regions (Central Sierra of Ecuador, Northeast Brazil, Central and Eastern Kenya, dry, tropical India, the Stavropol and Saratov regions of the southern USSR, and Southeast Australia).

These regions were selected because they are at the margins of climatic tolerance for the crops currently grown there.

10.1.2. Results and analysis

I only will describe the results of experiments for the cool temperate and cold regions since the production systems in these regions are more similar to North American production systems than the systems of the semi-arid regions.
<table>
<thead>
<tr>
<th>Study</th>
<th>Type of adaptation</th>
<th>Location</th>
<th>Climate scenario</th>
<th>Specific application and result</th>
</tr>
</thead>
<tbody>
<tr>
<td>IIASA Study</td>
<td>Switch types of varieties</td>
<td>Saskatchewan, Canada</td>
<td>Historical drought of 1936</td>
<td>Switch spring to winter wheat on 10% of farm area: reduced net farm revenue loss by Can$1800 per farm</td>
</tr>
<tr>
<td>(Parry et al., 1988)</td>
<td></td>
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<tr>
<td></td>
<td>Switch to varieties with higher thermal requirements</td>
<td>Cherdyn, USSR</td>
<td>GISS 2×CO₂</td>
<td>Change in spring wheat yields relative to baseline: +16% with +50 growing degree days (GDDs); +26% with +100 GDDs</td>
</tr>
<tr>
<td></td>
<td>Switch to varieties giving less variable yields</td>
<td>Hokkaido, Japan</td>
<td>GISS 2×CO₂</td>
<td>Switch late maturing rice varieties relative to baseline varieties and climate: +25% yield</td>
</tr>
<tr>
<td></td>
<td>Increased fertilizer application</td>
<td>Leningrad, USSR</td>
<td>GISS 2×CO₂</td>
<td>50% more fertilizer relative to baseline fertilizer and climate: +15% winter rye yields</td>
</tr>
<tr>
<td></td>
<td>Improvement in soil drainage</td>
<td>Leningrad, USSR</td>
<td>GISS 2×CO₂</td>
<td>Marginal positive effect on winter rye relative to baseline drainage and climate: +14% production of total grain</td>
</tr>
<tr>
<td></td>
<td>Change in farm expenditures for capital and labor</td>
<td>Central region, Moscow, USSR</td>
<td>GISS 2×CO₂</td>
<td>Longer season dryland and irrigated maize relative to baseline varieties and GFDL 2×CO₂ climate: small effect in yield reduction</td>
</tr>
<tr>
<td>EPA Study</td>
<td>Crop variety shift</td>
<td>Fort Wayne, IN, USA</td>
<td>GFDL 2×CO₂</td>
<td>Average yields relative to baseline for 12 locations: +18% dryland wheat (range = 0.30%–152%); +28% irrigated wheat (range = −34%–257%); −13.5% dryland maize (range = −32%–0.1%)</td>
</tr>
<tr>
<td>(Smith and Tirpak, 1989)</td>
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<td></td>
<td>Combined shift in planting date and crop variety to optimize climate change</td>
<td>US Southern Great Plains</td>
<td>GISS 2×CO₂</td>
<td>Projection of historical yield trend as proxy for technology-driven future productivity gains: 2% reduction in economic surplus relative to 6% reduction with current technology</td>
</tr>
<tr>
<td></td>
<td>Future technology— driven increases in productivity</td>
<td>USA</td>
<td>GISS 2×CO₂</td>
<td></td>
</tr>
</tbody>
</table>
Table 4 (continued)

<table>
<thead>
<tr>
<th>Study</th>
<th>Type of adaptation</th>
<th>Location</th>
<th>Climate scenario</th>
<th>Specific application and result</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cornell study</td>
<td>Combined shift in crop varieties, crop types, timing of field operations</td>
<td>Minnesota, USA</td>
<td>GISS transient: A = 'severe'; B = 'mild'</td>
<td>Change in net farm revenue relative to baseline: A, +33% by 2060; B, +87% by 2070 A, −40% by 2060; B, −15% by 2070</td>
</tr>
<tr>
<td>(Kaiser et al., 1993)</td>
<td></td>
<td>Nebraska, USA</td>
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<tr>
<td>MINK study</td>
<td>Adjustments with current technology: combined shift in crop varieties, crop types,</td>
<td>Missouri, Iowa, Nebraska,</td>
<td>1930s droughts ('Dust Bowl')</td>
<td>Changes in value of production of major crops relative to baseline: −3.3%</td>
</tr>
<tr>
<td>(Easterling et al., 1993)</td>
<td>furrow diking, timing of field operations</td>
<td>Kansas, USA</td>
<td></td>
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<tr>
<td>Global EPA study</td>
<td>Level 1 (see text): combined shift in planting date (± 1 month) additional irrigation application, change in variety</td>
<td>Developed countries</td>
<td></td>
<td>Change in grain yield relative to baseline:</td>
</tr>
<tr>
<td>(Rosenzweig and Parry, 1994)</td>
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<td></td>
<td></td>
<td>UKMO 2×CO₂</td>
<td>+4%</td>
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<td></td>
<td></td>
<td></td>
<td>GISS 2×CO₂</td>
<td>+14%</td>
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<td></td>
<td></td>
<td>GFDL 2×CO₂</td>
<td>+8%</td>
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<tr>
<td></td>
<td></td>
<td></td>
<td>UKMO 2×CO₂</td>
<td>−12%</td>
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<td></td>
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<td>Developing countries</td>
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<td></td>
<td>GISS 2×CO₂</td>
<td>−11%</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>GFDL 2×CO₂</td>
<td>−9%</td>
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<td></td>
<td>UKMO 2×CO₂</td>
<td>+1%</td>
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<td>developed countries</td>
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<tr>
<td></td>
<td>Level 2 (see text): combined large shift in planting date (&gt; ± 1 month) increased fertilization application, installation of irrigation, new crop varieties</td>
<td></td>
<td>UKMO 2×CO₂</td>
<td>11%</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>GISS 2×CO₂</td>
<td>+3%</td>
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<td></td>
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<td></td>
<td>GFDL 2×CO₂</td>
<td>−6%</td>
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<tr>
<td></td>
<td></td>
<td>Developing countries</td>
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<td></td>
<td>GISS 2×CO₂</td>
<td>−7%</td>
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<td></td>
<td></td>
<td></td>
<td>GFDL 2×CO₂</td>
<td>−5%</td>
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Table 4 (continued)

<table>
<thead>
<tr>
<th>Study</th>
<th>Type of adaptation</th>
<th>Location</th>
<th>Climate scenario</th>
<th>Specific application and result</th>
</tr>
</thead>
<tbody>
<tr>
<td>Economic combined increased investment in agriculture, reallocation of agricultural resources according to returns, reclamation of arable land in response to higher commodity prices</td>
<td>World</td>
<td>Change in agricultural prices (b) relative to baseline:</td>
<td></td>
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<td>With Level 1 adaptations:</td>
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<td></td>
<td></td>
<td>UKMO (2 \times \text{CO}_2) + 100%</td>
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<td></td>
<td>GISS (2 \times \text{CO}_2) + 10%</td>
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<td>GFDL (2 \times \text{CO}_2) + 20%</td>
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<td>With Level 2 adaptations:</td>
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<td></td>
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<td>UKMO (2 \times \text{CO}_2) + 35%</td>
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<tr>
<td></td>
<td></td>
<td>GISS (2 \times \text{CO}_2) - 5%</td>
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<tr>
<td></td>
<td></td>
<td>GFDL (2 \times \text{CO}_2) + 1%</td>
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</tr>
</tbody>
</table>

\(a\) Direct effects of \(\text{CO}_2\) on plants, where considered, are factored into adaptation result listed.

\(b\) Percentage change in the number of people at risk of hunger, explained in the tests closely tracks these prices.

The specific short-term adjustments that were examined are shown in Table 4. In Saskatchewan, Canada, switching 10% of the cropped area from spring to winter wheat would, in a normal year, reduce farm profits but in an abnormal year such as a recurrence of the drought of 1936, would reduce losses in net farm revenues by nearly Can$1800 per farm. For the \(2 \times \text{CO}_2\) Goddard Institute for Space Studies (GISS) scenario in central and southern Finland, where climate warming could be beneficial, a change to spring wheat varieties with higher thermal requirements (120 growing degree days higher) increased yields by an average of 15% (Fig. 9).

Parry et al. (1988) demonstrate that changes in farm expenditures can enhance the beneficial effects of climate change in the central USSR. For example, the investment of an extra US$30 million in extra on-farm infrastructure under current conditions would increase harvested grain production by about 3% although costs per unit of production would rise slightly. With a 1°C warming, the same US$30 million investment would increase production by about 14% and per unit costs would actually decline.

10.1.3. Insights into adaptation

The IIASA study was the first large modeling effort to examine systematically the effectiveness of short-term adjustments to climate change. Furthermore, the short-term adjustments were examined in a variety of climatically marginal regions and over several different cropping systems. The authors conclude that short-term adjustments will facilitate the transition of agriculture to a changed climate. The results of the cool temperate and cold region studies are more applicable to those regions of North America
Fig. 9. Effects of climate scenarios on mean marketable spring wheat yields: (a) yields under average 1959–1983 climate (kg ha−1); (b) yields under the GISS 2×CO₂ scenario with variety having thermal requirement of 120 GDD greater than present varieties (expressed as a percent of average, a); (c) yields under a warm scenario (observed climate of 1966–1973) with present-day varieties (expressed as percent of average, a); and (d) yields under a cool scenario (observed climate for 1974–1982) with present-day varieties (expressed as percent of average, a). Source: after Parry et al. (1988).

where production is currently cold-limited than regions where production is not cold-limited. Short-term adjustments in those studies, therefore, were aimed at taking advantage of the warmer climate. In the US, climate changes that will disadvantage agriculture are likely across large regions. Short-term adjustments there will be needed not to enhance a good situation but rather to offset the negative effects of climate change on productivity.

A common thread to all of the modeling studies reviewed in this paper including the IIASA study, is the ad hoc protocol of incorporating adaptation strategies into the models. Only a few simple illustrative examples of such strategies were modeled, giving the adaptation analysis a stylistic quality. The significance of such is discussed in a later section. In conclusion, though the IIASA study was a groundbreaking investigation of short-term adjustment to climate change, the study was silent on the method by which
the adjustments would likely come into practice. Furthermore, the geographic focus of
the cool temperate studies was too narrow to give complete insight across the whole of
the US and Canada.

10.2. The EPA study

10.2.1. Research approach

In the latter part of the 1980s the US Environmental Protection Agency (EPA)
commissioned a major study of the potential effects of climate change on the US (Smith
and Tirpak, 1989). Four regional case studies were conducted:
1. the Southeast;
2. the Great Lakes;
3. California; and
4. the southern Great Plains.

Systems that were identified for examination included forests, agriculture, sea level rise,
biodiversity, water resources, electricity demand, air quality, human health, and urban
infrastructure. Except in the case of the California study, agriculture was examined in
isolation from the other aforementioned sectors.

Climate change scenarios were generated by three different GCMs: GISS (Hansen et
al., 1988); Geophysical Fluid Dynamics Laboratory (GFDL) (Manabe and Wetherald,
1987); and Oregon State University (OSU) (Schlesinger and Zhao, 1988). Each of the
models was used to generate $2 \times CO_2$ equilibrium climate change scenarios. The global
mean annual temperature increases from $2 \times CO_2$ were $4.2^\circ C$ for the GISS model, $4.0^\circ C$
for the GFDL model, and $2.8^\circ C$ for the OSU model.

Crop simulation models (CERES-Maize, CERES-Wheat, and SOYGRO) were used
to estimate the potential impacts of the various scenarios of climate change on crop
productivity. Agronomic adjustments to the impacts of climate change were not uni-
formly considered in each of the regional agricultural studies. However, a few simple
short-term adjustments (earlier planting, increasing irrigation, changing to cultivars with
different thermal requirements) were considered in the Great Lakes and the two Great
Plains studies (Rosenzweig, 1989; Allen and Gichuki, 1989; Ritchie et al., 1989). In a
study which focused on the nation as a whole, Adams et al. (1989) used a partial
equilibrium model to examine the economic effects of climate change on US agriculture.
Though short-term adjustments and long-term adaptations to the climate changes were
not explicitly considered, Adams et al. (1989) did take account of the potentially
ameliorative effects of technology-induced increases in future agricultural productivity.

10.2.2. Results and analysis

Rosenzweig (1989) found that altering planting dates for dryland corn (maize) in the
southern Plains offsets the yield reduction caused by the GISS $2 \times CO_2$ scenario at only
one of 12 locations (Table 4). The other 11 locations continued to show yield reductions
ranging from $-4.2\%$ to $-32\%$. The most dramatic effects of short-term adjustments
were in dryland and irrigated wheat. After altering planting dates and switching to
cultivars with lower vernalization requirements and lower photoperiod sensitivity, wheat
yields in the GISS $2 \times CO_2$ climate were higher than the baseline at nine of 14 dryland locations and at eight of 12 irrigated locations.

Easterling et al. (1989) assayed short-term adjustment strategies for Illinois corn (maize) producers through interviews with agricultural experts. Though none of the strategies were explicitly tested, he found most experts generally confident that farmers could successfully deal with climate change through changes in planting decisions and land management to conserve water.

Adams et al. (1989) took account of the presumed positive effects of new technologies in projecting crop yields 70 years into the future. They assumed that by 2060 yield increases relative to current normals will range from 41.2% for cotton to 128.8% for corn (maize). When those yield increases are included in the equilibrium model of the US economy in 2060, the net social value of agricultural output rises 34%, or $32$ billion. The effect of the GISS $2 \times CO_2$ climate is a $2.1$ billion year$^{-1}$ loss in potential agricultural production (defined as the difference in projected value of agricultural output with new technologies but no climate change and the projected value of agricultural output with new technologies and climate change). However, the absolute level of economic surplus is still $30$ billion higher than the base case despite the climate change. Thus, the technology effect swamps the climate change effect on future agricultural surplus. The same is true for the GFDL $2 \times CO_2$ climate, although the greater severity of the GFDL climate resulted in a lower agricultural surplus ($12$ billion) than the GISS case. Adams et al. (1989) found that the effect of the GFDL climate change is approximately equal to about 50 years of technical progress in crop productivity.

10.2.3. Insights into adaptation

The main significance of the agriculture component of the EPA study is two-fold. First, it confirms the findings of the IIASA study that agronomic adjustments and adaptations are important and must be taken into account when modeling the impacts of climate change on yields. Based on model results, it appears that in some cases proper agronomic adaptations can transform yield losses into yield gains, at least in the case of wheat. Second, Adams et al. (1989), helped demonstrate convincingly that technical change will continue to modify agricultural production into the foreseeable future and such will condition the response of agriculture to climate change. These two contributions are significant.

The major limitations of the overall approach of the EPA study with respect to adaptation were the ad hoc nature of the agronomic adaptations, as explained in the IIASA study above, and the lack of explicit consideration of climate change effects outside of the US.

10.3. The Cornell study

A US Department of Agriculture-sponsored study at Cornell University aimed to model the climatic, biotic, and economic interactions that will determine the adaptability of individual farms to a gradually unfolding climate change (Kaiser et al., 1993).
10.3.1. Research approach

A multidisciplinary team (economists, climatologists, crop scientists) linked a stochastic climate model to a crop growth simulation model which was in turn linked to a farm-level dynamic programming economic model to address the question of how adaptable farming will be to climate change. The so-called "transient GCM Scenarios A and B" of Hansen et al. (1988) were used to generate time-dependent (in decadal time-steps) scenarios of future climate change. Climatic variability on several time scales was adjusted stochastically. Three scenarios of climate were examined: no change, a gradual warming and drying (Scenario A), and a gradual warming and moistening (Scenario B). A crop simulation model developed by Buttler and Riha (1989) was used to estimate crop yield response to the gradual climate changes. A discrete stochastic sequential programming model was used to evaluate and determine farm-level decisions in response to various 'states of nature' (yield responses to climate change).

Fig. 10. Choice of corn (A) and soybeans (B) by climate scenario for the risk-neutral case, 1980–2070. Source: Kaiser et al. (1993).
Change in crop mix was the primary adaptation response tactic examined, although minor year to year adjustments in planting dates, amount of time allocated to field work and harvest practices (i.e. grain drying) also were examined. The initial study area was a hypothetical farm in southern Minnesota and crops considered for substitution were corn (maize), soybeans, and sorghum. An additional example of a Nebraska farm was included.

10.3.2. Results and analysis

The results indicated that, in a risk-neutral situation (defined as profit maximizing), sorghum will never be planted under either a warmer/wetter or warmer/dryer climate in southern Minnesota. The percent of area in corn (maize) is predicted to always exceed that of soybeans because of price inducements and longer growing season (Fig. 10). Indeed the authors suggest that a gradual shift toward longer season corn (maize) varieties is warranted by both climate change scenarios. Effects of adaptations on net revenues are shown in Table 4. While adaptations are efficient on the Minnesota farm, there is a large loss of net revenue on the Nebraska farm even after adaptation.

10.3.3. Insights into adaptation

The study is sketchy on points like: (a) the handling of climate change effects outside the southern Minnesota and eastern Nebraska region especially as such will influence prices; (b) the direct effects of CO₂ on crop productivity; and (c) the role of gradual changes in resource endowments and technologies that impinge on agriculture. Like the IIASA and EPA studies above, adaptations appeared to be implemented ad hoc. However, the use of a time-dependent scenario of climate change gives insight into the incremental nature of short-term adjustments and the structured farm level decision model is a strong tool for the normative analysis of farm decision making under climate change.

11. Regional studies of the agriculture sector with linked sectors

The effects of climate change on agricultural production will extend to other economic sectors, both forwardly to purchasers of agricultural goods and backwardly to suppliers of basic agricultural production inputs. In adapting to climate changes, agriculture will rely on exchanges of resources and services with nonagricultural sectors, most of which themselves will be affected directly by climate change. Water resources are, of course, an obvious example. Such makes a strong case for examining agricultural adaptation to climate change within the broader context of all sectors comprising a regional economy. One recent study that takes such a regional approach to examining the potential for agricultural adaptation is the ‘MINK’ study (Rosenberg and Crosson, 1991).

11.1. The MINK study

11.1.1. Research approach

In late 1988, the US Department of Energy commissioned Resources for the Future to develop and test a methodology for the integrated study of the response of a region's
natural resource base and associated economy to climate change (Rosenberg and Crosson, 1991). The farm-level agriculture component is reported fully in a special issue of *Agricultural and Forest Meteorology* (Easterling et al., 1992) and the full regional assessment in a special issue of *Climatic Change* (Easterling et al., 1993; Rosenberg et al., 1993).

The four-state region of Missouri–Iowa–Nebraska–Kansas (MINK) was chosen to develop and test the methodology because of the importance of climate-sensitive natural resources to the regional economy. The notoriously hot and dry weather of the 1930s served as an analog of climate change. Average annual temperatures across the MINK region during that period ranged from 0.7 to 1.0°C warmer than the 1951–1980 normal and average annual precipitation ranged from 28 to 102 mm less.

The study proceeded in a sequence of four tasks. Task A was a complete baseline description of the region as it currently functions. Task B imposed the climate change on the region as it functions today. Task C was the projection of a new baseline description of the region as it might be in the future, absent climate change. Task D is the imposition of climate change on the region as it might be in the future.

The farm-level analysis utilized the Erosion Productivity Impact Calculator (EPIC), a semi-mechanistic crop simulation model, to estimate the effects of climate change on crop productivity (Williams et al., 1984). The model was modified to represent the direct effects of increased atmospheric CO$_2$ concentrations on crops and was programmed to represent 50 different ‘representative farms’ across the region.

Based on a literature review and sensitivity analysis, earlier planting, use of longer season cultivars and furrow diking in warm season crops to conserve water were selected as currently available short-term adjustments. A small set of technological breakthroughs that are likely, whether or not the climate changes, were identified through conversations with experts and a review of the literature. An additional set of technologies which might be specifically developed to deal with the future climate change through directed agricultural research was identified. These technical breakthroughs, listed in Table 4, were represented mechanistically in the EPIC model in order to simulate agricultural production in the year 2030, both without and with climate change (McKenney et al., 1992).

11.1.2. Results and analysis

Control yields were computed by simulating crop growth under the climate of the 1951–1980 period with 350 ppm CO$_2$. Simulated dryland corn (maize) yields, with climate change and current technology, were 17% lower than control values; soybean yields were reduced by 15%, sorghum and wheatgrass by 11%, irrigated corn (maize) and sorghum were reduced by 2% and 11%, respectively. Wheat yields actually rose above control levels by 10%. The application of the short-term adjustments (earlier planting, longer season varieties and use of furrow diking) to MINK farms caused yields of all crops but dryland corn (maize) and soybeans to meet or exceed current yields (Fig. 11). Table 4 shows that with on-farm adjustments and the higher CO$_2$ levels, the total agricultural production decline in the MINK region was $0.5 billion or 3.3% of $15.2 billion (Crosson and Katz, 1991).

The future technologies caused crops to yield an average of 72% higher than current
normals, except for wheat which averaged 88% higher. These higher yields became the control values of the future. When the climate change was imposed, yields simulated with those technologies showed little increased resistance to the climate change. However, with the new technologies and long-term adaptive strategies (increased drought resistance and irrigation efficiency) and short-term adjustments in place, the climate change prompted all crops but dryland corn (maize) to yield higher than the new baseline (Fig. 12), account taken of higher CO₂ effect. Soybean yields were improved by 1%, sorghum by 9%, dryland wheat by 20%, alfalfa by 23%, irrigated corn (maize) by 10%, irrigated sorghum by 18%, and irrigated wheat by 18%. With these adaptations total agricultural production would be $6.45 million (3%) higher than had the climate of 2030 not changed (Table 4).

11.1.3. Insights into adaptation

The MINK study was the first to explore broadly the potential for farmers and institutions to adjust and adapt to climate change as a necessary condition for the accurate estimation of impacts. A wide range of potential short-term adjustment tactics was tested for agronomic and economic efficiency in dealing with the effects of climate change. For example, the MINK study found that certain short-term adjustments reaped substantial yield benefits (e.g. increased irrigation) but were too costly to make economic sense. Furthermore, the MINK study was the first to examine the combined effect of increased atmospheric CO₂ and adaptations.
A fundamental contribution of the MINK study is the modification of the EPIC crop model to represent future agricultural technology. Instead of extrapolating past trends into the future, the impact of new technologies or 'breakthroughs' was represented mechanistically in the model.

The MINK study had several limitations. First, the climate of the 1930s was not as severe a departure from current normals as the climate changes projected at the time by most of the GCMs for 2030. Drought was not uniformly severe across the MINK region. The eastern half of the region was less severely affected than the western half. Second, crude assumptions about the influence of climate changes on production outside of the region were made. Clearly, a weakness of the MINK study was the lack of explicitness of how, globally, climate change would affect the demand and prices for MINK products which will be strongly influenced by global forces. Third, the farm-level economic analysis of adaptations was not formalized in a model. Though concerted effort was given to the identification of region-specific adaptation strategies, model limitations precluded examination of the full range of strategies. Fourth, unpriced environmental costs of adaptation were not considered and may detract from the optimistic conclusions of the authors.

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\[ \text{It is highly unlikely that regions will experience no change in climate at all under greenhouse warming as was the case of a few locations in the MINK area vis-à-vis the 1930s droughts.} \]
12. Global studies of agricultural adaptation: toward integrated assessment

Considerable interest has arisen recently in the development of a modeling framework that extends the linkage of biophysical and socioeconomic models to incorporate analytical capabilities to examine mitigation of carbon emissions and adaptation to climate change simultaneously. Such a framework is called an "integrated assessment" which Robinson (1985) defines as one that internalizes causal linkages between biophysical and socioeconomic processes in order to represent whole systems. In other words, a single model would represent:

1. strategies to mitigate greenhouse gas emissions;
2. effects of such strategies on the global economy and on greenhouse gas atmospheric concentrations, account taken of natural processes of net carbon exchange between the oceans, terrestrial ecosystems and the atmosphere;
3. the response of the climate system to different greenhouse gas concentrations; and finally
4. the damages of climate change to sensitive ecosystems and economic sectors, account taken of adaptation.

Very little is left exogenous to the model and, in its purest form, is truly global in scale but can be decomposed into different sized regions.

Nordhaus (1992) is credited with developing an initial prototype of such a model. His model, DICE, is a reduced-form general equilibrium representation of the global economy which computes optimal greenhouse gas emissions paths within a tradeoff among capital investment, carbon emissions limitations, and consumption of goods and services. The model has internal representations of carbon emissions and climate system response to such emissions, and a damage function for assessing the impacts of climate change on the global economy. Mendelsohn and Rosenberg (1994) argue that global integrated assessment methodologies are too poorly developed at present to recommend any one for general use. Furthermore, they and Nordhaus (1992) point out that the least developed component of such assessments is measurement of the impacts of climate change on natural and managed ecosystems. Thus, as a tool for examining the adaptability of systems such as agriculture to climate change, integrated assessment methodology is in its infancy. Eventually it will be a powerful policy tool since the greenhouse problem can be explained in its entirety. The two papers that follow this one (Antle, 1996; Mendelsohn et al., 1996) offer two alternative approaches to computing the economic damage function of climate change for agricultural systems, with explicit attention to adaptation.

A major hurdle to the proper computation of economic costs/loss to North American agriculture imposed by climate change is the weak understanding of how agriculture in the rest of the world will be affected by such change. As pointed out earlier, successful agricultural adaptation to climate change in a specific region will be strongly influenced

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Mendelsohn and Rosenberg (1994) allude to major global integrated assessment modeling projects currently underway at MIT, Batelle, and Carnegie-Mellon. Such projects are in their earliest development stages and, so far as I am aware, there is little published on them in the peer-reviewed literature yet.
by the summation of climate change impacts in all other regions globally. The aforementioned modeling studies either ignore extraregional influences of climate change or vastly oversimplify them. One study that was recently concluded provides the first step toward an integrated global assessment of agricultural response to climate change and is referred to here as the "EPA Global Agriculture" study (Rosenzweig and Parry, 1994).

12.1. EPA Global Agriculture study

As the abovementioned limitations of the (US-focused) EPA study became apparent, a follow-on study (cosponsored by EPA and the US Agency for International Development) was conducted that was expanded to become truly global in scope (Rosenzweig and Parry, 1994).

12.1.1. Research approach

A set of crop growth models was deployed to 112 sites in order to simulate 70–75% of current world wheat, corn (maize), and soybean production—48% of current rice production was represented. Climate change scenarios used in the crop models were generated by the GISS, GFDL, and United Kingdom Meteorological Office (UKMO) models. Atmospheric CO\textsubscript{2} was raised from its current 340 ppmv concentration to 630 ppmv in the GISS model, 600 ppmv in the GFDL model, and 640 ppmv in the UKMO model. In the elevated CO\textsubscript{2} experiments, the GISS, GFDL, and UKMO models predicted global average annual temperature increases of 4.2°C, 4.0°C and 5.2°C, respectively. They predicted global average annual precipitation increases of 11%, 8%, and 15%, respectively.

Two categories of farm-level adaptation were examined within the crop models. The first category (Level 1) consisted of relatively simple, low-cost adjustments that are generally available to all farmers such as, for example, changes to planting dates, variety and crop choices and irrigation and fertilization application. The second category (Level 2) consisted of more elaborate and costly adaptations, some of which would require policy or research assistance such as, for example, installation of irrigation systems or development and distribution of new crop varieties. Both levels of adaptation were examined in concert with increased atmospheric CO\textsubscript{2} concentrations.

Simulated response of production to climate change, with either category of adaptation, was inserted into a world food trade model described by Fischer et al. (1988) as the "basic linked system (BLS)." The model actually consisted of a series of 16 like-structured national models, 14 regional models, and four national models with unique structure. The 20 national models cover approximately 80% of world agricultural production, with the remaining 20% covered by the 14 regional models. Among the BLS model estimates that indicated sensitivity to climate change were world cereal production and cereal prices. Also, the BLS computed the population at "risk of hunger" based on estimated available food energy relative to nutritional requirements.

12.1.2. Results and analysis

The GISS and GFDL climate changes, with elevated CO\textsubscript{2} levels but no adaptations, resulted in positive yield changes in middle and high latitudes and negative yield
changes in low latitudes (yields ranged from + to −30%). The UKMO climate change scenario caused almost uniformly negative yield changes, with Pakistan showing −50% yields.

Level 1 adaptations (simple, low-cost ones) were found to compensate unevenly for yield decreases caused by GISS- and GFDL-simulated climate changes across developing countries (Table 4). Level 2 adaptations fully compensated for yield decreases everywhere with those changes (Table 4). Neither Level 1 nor 2 adaptations fully compensated for yield decreases caused by the relatively more severe UKMO climate changes.

The BLS model was used to simulate a reference scenario of world agricultural trade in the absence of climate change, inclusive of new technology that is assumed to increase production over time but at a slower rate than the historical trend. The model was then used to simulate world trade under climate changes suggested by the three GCMs with: (a) no rise in CO₂ and no adaptations; (b) rising CO₂ and Level 1 adaptations; and (c) rising CO₂ and Level 2 adaptations.

The reference scenario projected the future growth of food production to exceed future growth in population. However, simulated real food prices rose in the first part of the period (1980 to 2020) due to the assumed continued existence of trade barriers. In the latter half of the period (2020 to 2060), prices fell due to efficiencies created by the removal of trade barriers. Also, the percentage of the world population at risk of hunger is projected to fall from ca. 10% to ca. 6% by 2060.

Climate changes accompanied by current CO₂ levels and no adaptation caused a large upswing, relative to the reference scenario, in agricultural prices (24–145%) over the three climate model scenarios. Similarly, the number of people at risk of hunger increased by a range of 10%–60%. Level 1 adaptations (with higher CO₂ levels) were found to work well in offsetting production losses in developed countries but not so well in developing countries. Prices remained higher (10–100%, depending on the climate scenario) than the reference case (Table 4). Level 1 adaptations were unable to prevent a 6–50% increase in the number of people at risk of hunger over the reference case.

Level 2 adaptations completely offset climate-induced global yield reductions under the GISS and GFDL climate changes, and offset yield reductions under the UKMO climate changes to about a third of the reference case (Table 4). These adaptations actually reduce prices relative to the reference scenario with mild climate change and hold prices to an increase of 35% with extreme climate change. Level 2 adaptations also modestly reduced the number of people at risk of hunger (−2%) under the GISS climate change; slightly more people were at risk of hunger under the GFDL climate, and 20% more were at risk of such under the UKMO climate. More importantly, regardless of choice of climate model, Level 2 adaptations were unable to offset rising numbers of people at risk of hunger in developing countries. Moreover, the above results are highly

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8 The reader is reminded that holding CO₂ levels constant is an analytical convention intended to illustrate different impacts of climate change on crops, even though the climate model scenarios of climate change were initially generated by increased CO₂ and other greenhouse gas concentrations in the atmosphere.
dependent on the unrestricted availability of irrigation water which inflates the net effectiveness of adaptation strategies.

12.1.3. Insights into adaptation

The EPA Global Agriculture study was a noteworthy contribution to the understanding of agricultural adaptability to climate change for several reasons. It was the first attempt to build a geographically representative global agricultural assessment based on a spatial hierarchy of linked biophysical and economic models. The crop simulation modeling was coordinated such that investigators working within their own countries or regions were provided with appropriate models and climate change scenarios. The national economic models had a common structure that melded easily into the BLS trade model. Such permitted a logical method of simulating global agricultural capacity. Anticipated increases in future agricultural productivity were also incorporated into the estimation of future agricultural capacity. The computation of changes in numbers of people at risk of hunger from climate change was new. The comparative assessment of developed and developing countries pointed out the continuing vulnerability of poorer regions to climate change. However, like the previously discussed studies, the choice of adaptation strategies was ad hoc and limited to a few examples, with little or no tailoring to specific countries. Such tends to weaken the basis used to distinguish adaptability between classes of countries.

The EPA Global Agriculture study, impressive in breadth as it was, might be termed a ‘partial integrated assessment’ since it was focused on questions of impacts and adaptation with no direct linkage to net carbon exchange processes (this point is discussed further below). The study pointed the way to some important next steps, including: (a) the linkage of agricultural systems with other sectors that, as the investigators point out, may limit adaptability (e.g. water, energy); (b) linkage of adaptation and mitigation strategies involving agriculture; and (c) examination of environmental consequences of adaptation. The EPA Global Agriculture study was a major step toward a truly integrated global assessment of the consequences of climate change for agriculture at a variety of spatial scales, but, based on criticisms of the previous paragraph, should not preclude further regionally focused assessments.

13. Applicability of adaptation methodology to policy analysis

Each modeling study reviewed above was funded directly or indirectly by a government agency interested in the policy implications of global warming. Chief among government concerns is whether or not deliberate government intervention to limit the amount of anticipated warming and to assist in the adaptation to any warming that is unavoidable is warranted. Thus, the applicability of adaptation methodologies lies largely in their policy relevance. Questions of limiting future warming apart, how useful are extant methodologies for guiding the formulation of policies to facilitate agricultural adaptation to climate change in North America?

Crosson (1989a) posits that climate change will raise policy questions to mid-latitude governments when two necessary conditions are met:
1. high social costs are imposed; and
2. existing market forces and policies are unlikely to keep such costs within socially acceptable limits. Adaptation methodologies should shed light on these necessary conditions as a starting point for policy analysis.

13.1. Characterizing social costs of agricultural adaption

Social costs of climate change include those which are *priced* (i.e. the goods and services affected have clear and enforceable property rights) and those which are *unpriced* (i.e. the goods and services affected are owned individually or collectively but with no exclusivity of property rights for which there is a measurable demand). Priceable costs include, for example, climate change effects on the value of crops and livestock while unpriced costs include, for example, effects on environmental quality or human health.

Methodologies for quantifying the social costs of climate change have progressed considerably since the 1970s and early 1980s. The earliest climate change agricultural impact studies (e.g. Thompson, 1969; Bach, 1979; Newman, 1982) provide a benchmark against which to measure such progress. Such studies were based on simple empirical relationships between weather and crop yields. Weather and crop yield relationships were expressed as regression coefficients (slope and intercept) and climate change scenarios were inserted into the regression models in order to obtain predicted crop yield response. Deficiencies of regression-based analysis with respect to the estimation of the effects of climate change on crop productivity are well-known:
1. high temporal and spatial uniqueness and low temporal and spatial resolution of model estimates;
2. inability to account for adaptation strategies;
3. failure to account for economic, technological and other non-agronomic factors, which are equally as important as purely agronomic factors in the calculus of impacts; and
4. absence or simplistic representation of the direct effects of rising atmospheric carbon dioxide concentrations on photosynthetic and water use efficiencies.

The usefulness of such models as policy tools was undermined by the above deficiencies; the models inherently overestimated the negative impacts of climate change and thus defined a 'worst-case' scenario. What progress has been made in overcoming those early deficiencies? What deficiencies remain?

13.1.1. Temporal and spatial uniqueness and resolution

Regression-based crop-climate models have all but been replaced in current impact assessments by mostly process-based plant growth simulation models in order to estimate the effects of weather on crop yields. Examples of such models include the Erosion Productivity Impact Calculator or EPIC (Williams et al., 1984), the CERES...
family of models for simulating corn (maize), wheat (Jones and Kiniry, 1986), and soybeans (Jones et al., 1988), and GAPS (Buttler and Riha, 1989). Such models attempt to simulate physiological and phenological processes of crop growth mechanistically, though some parts of the models remain empirical. Within reason, process simulation models are transportable to any location so long as their appetite for extensive and detailed local data inputs can be satisfied. Their daily or, in some cases, even hourly time-steps of operation permit these models to simulate the effects of climate on many aspects of plant growth. The effects of management strategies, for example, irrigation, nutrient and pesticide application, and tillage operations, on such aspects are often explicit. Such models have a much higher degree of realism than crop–climate regression approaches and, hence, have enriched the understanding of the biological response of crops to weather and climate variation. Each of the major modeling studies reviewed above incorporated process-based crop growth models.

13.1.2. Taking account of adaptation

That farmers and agricultural institutions will take action to either offset the negative effects of climate change or seize the benefits of positive effects of climate change is not questioned. Full or partial account of the attempts of agriculturalists to adapt to climate change is explicitly taken in virtually all current impact assessments. It must be in order to obtain realistic assessments of the full impacts of climate change on agriculture. As the central thesis of this paper suggests, there is still much to be learned about the capacity of production agriculture to adapt to climate change, but the essential tools to conduct adaptation assessments are gradually adding realism.

13.1.3. Incorporating the social and economic dimensions of climate change

In the 1980s, agricultural impact assessment methodologies began formal linkage of crop model simulations of agricultural production with regional and national economic models. In the first EPA study reviewed above, a partial equilibrium model of the US agricultural economy was linked with model simulations of crop response to a set of GCM simulations of $2 \times CO_2$ climate change. In the MINK study, model simulations of the response of water resources, forests and crops to a return to the Dust Bowl droughts in the midwestern US were linked with a regional input–output economic model to estimate the economic impact of such a climate change on the overall regional economy. The main deficiency of these above examples, as pointed out above, was the lack of explicit consideration of global economic forces that will play a large role in shaping the economic consequences of climate change in the study regions.

13.1.4. Inclusion of $CO_2$ direct effects

The accumulation of research on the direct effects of atmospheric carbon dioxide on plants over the last decade is supportive that such effects must be taken into account in determining the full impacts of climate change on crop productivity (Culotta, 1995).

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10 There is a rich tradition of research on the economic impacts of climate change, including, for example, the work of Ausubel and Biswas (1980) and Schelling (1983). The IIASA study reviewed above gave considerable attention to the estimation of economic impacts of climate change on agriculture. The major breakthrough referred to here is the linkage of biophysical models with economic models.
Though the magnitude and precise nature of such effects on actual farming operations (where conditions are much less controlled than the experimental situations referenced above) remain open questions, the general consensus is that higher CO$_2$ levels will offset some of the deleterious effects of climate change on crops. In the earliest agricultural impact studies, CO$_2$ direct effects, if considered at all, were accounted for by making a ‘bottom line’ crop yield adjustment. Beginning with the MINK study and followed by the EPA global agriculture study, mechanistic algorithms of CO$_2$ effects on water use and photosynthetic efficiency from existing experimental studies were incorporated into crop simulation models, thus enabling continuous analysis of incremented change in atmospheric CO$_2$ concentrations.

13.2. Improving policy relevance of future adaptation research

The remarkable progress in ridding agricultural impacts research of the above deficiencies has given way to a set of new research directions that will lend even greater policy relevance. The listing below is by no means inclusive, but hopefully captures the major new thrusts that are needed:

13.2.1. Converting opinions into modeling

Each of the modeling studies reviewed above incorporated a range of adaptative strategies. How did the investigators decide which adaptations to represent and how to represent them? I suspect that in some cases the initial choices were ad hoc—the product of the informed judgments of the investigators constrained by the capabilities of the models. In other cases, systematic identification of adaptation strategies was undertaken through literature reviews and discussions with local experts.

As with any modeling study, the choice of what to include will condition the predictions of the model and the interpretations of those predictions. In the studies reviewed above, methodological limitations and shortage of time and resources dictated simplicity in the treatment of adaptations in the models. Small sets of adaptations were modeled uniformly across regions and farming systems. In reality, however, adaptations are bound to be more complex than heretofore modeled stylistically. They will vary widely across regions and farming systems and over time. Thus, these existing studies portray special cases of adaptation.

Are the above modeling studies any more than orderly opinion surveys? All models, save ones purely of closed systems governed by fully described physical laws, are ultimately expressions of human choices. I argue that the above modeling studies have utility beyond opinion surveys because they provide an objective means of hypothesis testing and sensitivity analysis. Their results are insightful of the vulnerabilities of agriculture to climate change and can give first approximations of adaptability, but they are not predictions of the future. More research is needed to increase understanding of how agricultural adaptation strategies are likely to vary spatially among different farming systems and economic, social, cultural and environmental conditions. Compilations of such research would be useful in guiding modeling studies.

13.2.2. Linking adaptation with the carbon cycle

The linkage of agricultural adaptation in response to climate change with processes that regulate greenhouse gas emissions needs to be made explicit. Houghton (1994)
states that human land use changes occurring over the past few hundred years (especially the conversion of Northern Hemisphere forests to agriculture and, more recently, tropical deforestation) have greatly exceeded natural forcing of the terrestrial carbon cycle. Several of the studies reviewed above allude to land use changes (e.g. switching crop species, increased irrigation) as adaptive strategies. In net, these land use changes are likely to have a measurable effect on terrestrial carbon cycling. In particular, research is needed on how agricultural adaptation may influence soil organic matter accumulation, surface hydrology, livestock management, energy use, and other factors which regulate net exchanges of carbon between regional agroecosystems and the atmosphere. Furthermore, the findings of such research need to supplement projections of greenhouse gas emissions inventories (such inventories are reviewed by Graedal et al., 1994).

13.2.3. Anticipation of future technologies

The technological regime 30–40 years into the future is bound to differ substantially from that of today, climate change or not. Casual observation of technologies that are already on the drawing board and expected to be economical to farmers within the next decade will render adaptation assessments based on current technologies overly pessimistic. Some of the latter modeling studies reviewed above have taken simple first steps toward the anticipation of new technologies (e.g. McKenney et al., 1992; Rosenzweig and Parry, 1994). Much new information could be produced by the conduct of model-based sensitivity analysis of future technologies inferred by recent technology projections (e.g. Office of Technology Assessment, 1992).

Basic insights are needed into the very nature of innovation induced by climate. How does the research and policy establishment perceive the possibility of future climate change and how does such perception translate into the development of technological and institutional innovations that will facilitate agricultural adaptability? Retrospective empirical studies are needed to shed light on the manner in which climatic limitations (either over time in the form of persistent droughts and other anomalies or across spatial climatic gradients) to agricultural production have been overcome by new technology.

13.2.4. Methods of scaling

Assessments of the impact of and adaptation to climate change are conducted on numerous spatial and temporal scales. Often, features of climate change are modeled on scales of thousands of kilometers while typical impact and adaptation assessments are modeled on scales as small as a single hectare or even a single plant. The validity of extrapolating in situ impact and adaptation research to the regional scale is not known. Research is needed to determine appropriate spatial and temporal scales of climate change scenarios in order to capture impacts and adaptations reliability.

The development of sound methods for down-scaling climate change scenarios and up-scaling impact and adaptation assessments is a critical research need. As a minimum, new data sets organized at increasing and/or decreasing spatial scales and the application of geographic information system technologies are needed to accomplish this task.

Many of the studies reviewed above rely on climate change scenarios generated by GCM experiments. Such scenarios are resolvable only to grid cells thousands of
kilometers across while many agricultural processes vary on much finer spatial scales. Promising work that 'nests' meso-scale climate models within GCMs to produce fine-resolution climate change scenarios (e.g. Giorgi and Mearns, 1991) should be evaluated in light of adaptation analysis.

13.2.5. Expanded data sets

The data requirements for conducting adaptation assessments are large and the availability of such data, at least for agricultural modeling simulations, is poor. Particular attention must be paid to the collection and archiving of climate and climate-related data on spatial and temporal scales appropriate for agricultural analysis. The development of social and economic data bases is sorely needed in this regard. The development of such data bases needs to be done in concert with research that identifies specific data needs. The absence of a coherent and dynamic data base for conducting adaptation research is a major incongruence with other aspects of global change research. Efforts are underway by the Consortium for Interdisciplinary Earth Science Information Network (CIESIN) of the National Aeronautical and Space Agency (NASA) to develop a prototype of such a data base. More efforts along those lines are needed.

13.2.6. Measuring and modeling unpriced costs

Agricultural adaptation to climate change is bound to affect environmental quality in most cases. Any increase in use of irrigation, particularly, will influence such quality. Were the total costs of adapting agriculture to climate change to exclude these environmental damages, they would be unrealistically low. Little or no research has examined explicitly the possible environmental consequences of adapting agriculture to climate change. In particular, research should focus on such consequences for air and water quality, wildlife habitat (including riparian systems, wetlands and uplands) and soil erosion. It is especially important that economists and other social scientists collaborate on the development of difficult to quantify social costs. Similar collaboration is needed between economists and environmental scientists.

14. Summary and conclusions

Can North American agriculture adapt to relatively rapid future changes in climate without losing comparative advantage? The answer depends on a number of factors. Climate change apart, over the next few decades North American farmers can expect:

1. most new demand for their products to come from outside Canada and the US;
2. new land and labor saving technologies to account for most of the increase in productivity needed to keep pace with rising demand;
3. their share of foreign markets for agricultural commodities to be challenged by rising competitors such as Vietnam, Brazil, China, and Thailand;
4. the inclusion of environmental damages from farming in their costs of production; and
5. to run their operations like any other production business with sophisticated production and marketing processes in rural areas possessing many amenities once the
provenance of urban areas only.

Crosson (1989a) argues that climate change is not likely to change demand for food and fiber and it is also doubtful that climate change will alter the transition of US agriculture to larger, more sophisticated operations. Climate change will, however, affect the ability of farmers to keep pace with rising agricultural demand and the relative position of Canada and the US in world agricultural markets. It will also affect the level of environmental damage from agriculture especially as farmers try to adjust to the change.

Drabenstott (1992), expanding on his CAST (1992) contribution, proposed a ‘portfolio’ of ten assets available to US agriculture in preparing for climate change. Each asset, its value for adapting to climate change and policy steps needed to increase flexibility in its use are reproduced in Table 5. Drabenstott’s (1992) portfolio is discussed here in light of the foregoing review in order to reach an assessment of the adaptability of North American agriculture to climate change. Some assets in the portfolio are combined for succinctness.

14.1. Land

North America has a large endowment of cropland, $188 \times 10^6$ ha in the US alone, that traverses a variety of climates. The aforementioned wheat and corn (maize) translocation examples showed the ease with which those crops were adapted to progressively different climates over time periods of the same magnitude of anticipated climate change. Each of the modeling studies reviewed above found that varietal and/or species shifts either fully or partially offset the deleterious effects of climate change (Table 4). Such studies suggest that the great extent of North American cropland will provide ample potential for adapting cropping systems by shifting crops and technologies from currently warmer regions to regions that will become like them under climate change. Also, they show that the research establishment will provide new means of utilizing these extensive cropland resources, if historical research performance is only modestly repeated.

14.2. Water

The NRC/NAS (1991) report lists water as a major limitation to agricultural adaptation to climate change. Virtually all modeling studies reviewed above called for increased irrigation application or, in some instances, conversion of dryland agriculture into irrigation. Increased water conservation will be a key to successful agricultural adaptation to climate change, especially in those areas where irrigation water is already in short supply. Water conservation as an adjustment strategy was shown to be currently profitable through techniques such as irrigation scheduling, manipulation of crop species planted to maximize water use efficiency and land management (e.g. furrow diking). The reversion of irrigated to dryland agriculture on portions of the High Plains Aquifer that experienced severe groundwater declines recently is suggestive of successful adaptation when irrigation costs become prohibitive. These examples give some optimism about the prospects of success on conserving water under climate change.
Table 5
Portfolio of assets to prepare for climate change

<table>
<thead>
<tr>
<th>Asset</th>
<th>Value for adapting to climate change</th>
<th>Policy steps to increase flexibility</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Land</td>
<td>Extensive cropland across diverse climates provides diversity for adaptation</td>
<td>Reform agricultural policy to encourage flexible land use</td>
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<tr>
<td>2. Water</td>
<td>Water, which already limits farming in some regions, is crucial for adaptation if climate becomes more dry</td>
<td>Reform water markets to encourage more prudent use of water</td>
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<tr>
<td>3. Energy</td>
<td>Reliable energy supply is essential for many adaptations to new climate</td>
<td>Improve the efficiency of energy in food production</td>
</tr>
<tr>
<td>4. Physical infrastructure</td>
<td>Facilitates trade and input flows when market signals change</td>
<td>Explore new biological fuels and ways to stash more carbon in trees and soil</td>
</tr>
<tr>
<td>5. Genetic diversity</td>
<td>Provides source of genes to adapt crops and animals to new climates</td>
<td>Assemble, preserve, and characterize plant and animal genes</td>
</tr>
<tr>
<td>6. Research capacity</td>
<td>Provides source of knowledge and technology for adaptation to climate change</td>
<td>Broaden research agenda to encompass</td>
</tr>
<tr>
<td>adapting to climate change</td>
<td></td>
<td>Encourage private research on adaptation</td>
</tr>
<tr>
<td>7. Information systems</td>
<td>Provide information needed to track climate change and adapt to it</td>
<td>Find farming systems that can be sustained in new climates</td>
</tr>
<tr>
<td>8. Human resources</td>
<td>Provide pool of skills enabling farmers and researchers to adapt to climate change</td>
<td>Enhance the nation’s systems that exchange information</td>
</tr>
<tr>
<td>9. Political institutions</td>
<td>Determine the policies and rules that facilitate or hinder adaptation to new climates</td>
<td>Encourage the exchange of agricultural research information</td>
</tr>
<tr>
<td>10. World market</td>
<td>Enables trade to mediate shifts in farm production and sends price signals that eventually adjust production to new climates</td>
<td>Make flexible skills the hallmark of agriculture’s human resources</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Strengthen rural education systems, particularly continuing education</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Harmonize agricultural institutions and policies</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Promote freer trade and avoid protectionism</td>
</tr>
</tbody>
</table>


14.3. Energy

The recent decline in the energy intensity of US agriculture noted by Darmstadter (1991) demonstrates the ingenuity of farmers with respect to energy conservation in the
face of high energy prices. Why should climate change-induced increases in energy prices, were they to occur, be any different, at least initially, from historical price increases such as those precipitated by the energy shocks of the 1970s and early 80s?

14.4. Physical infrastructure and human resources

The maintenance of physical infrastructure adequate to support the future movement of agricultural products to and from markets will be critical to adaptation. The existence of a pool of skilled and informed farmers is also critical. Parry et al. (1988) demonstrated the improvement in Russian grain production under climate change achieved by increased investment in agricultural capital and labor. However, returns on such investment are bound not to be as great in North America as in Russia since North American infrastructure and labor skills are already in relatively good shape.

14.5. Genetic diversity

As noted earlier, genetic diversity will provide important basic material for adapting crop species to changing climatic conditions. Genetic diversity of winter wheat was found to be increasing not decreasing over time. Other major crops were not examined in this regard, but the growing emphasis on biotechnology research is bound to create new genetic material for a variety of crops in the future.

14.6. Research capacity and information systems

The NRC/NAS (1991) noted that agricultural research investment by the US federal government has been declining in real terms for the last 3 decades. Some of the shortfall in research funding is being subsumed by the private sector, but in net, there has been a decline, especially in basic research. Funding of cooperative extension, a major information delivery system to farmers, has also been declining. Such trends do not bode well for sustained streams of new technologies needed to keep pace with climate changes. Research is the 'gilt-edge' investment on which agricultural adaptability to climate change hinges (CAST, 1992; Drabenstott, 1992). Recent trends suggest that an increasing share of the burden of adaptive research will fall on the private sector.

14.7. Political institutions and world markets

The interplay of government policy and international trade will strongly determine the success of efforts to adapt North American agriculture to climate change. Lewandrowski and Brazee (1992) noted that current government programs inhibit easy changes in crop mixes. Government-imposed international trade barriers would disrupt the free exchange of food and fiber between climate change-advantaged and -disadvantaged nations, directly through tariffs on imports and indirectly through price-distorting subsidy payments to farmers, were such to continue in force. Crosson (1989a), like several analysts (e.g. Drabenstott, 1992), do not anticipate that current trade barriers will continue to disrupt world agricultural trade in the future, in part because continuance of such barriers makes poor economic sense. Recent progress in international trade agreements (e.g. the Uruguay Round of the General Agreement on Trade and Tariffs,
North American agriculture faces serious social and economic challenges in the coming decades. Warming and drying across major portions of the North American granary will add another one. The challenge of warming and drying to North American agriculturalists will be exacerbated if, in net, agricultural production elsewhere is either unaffected or favored by climate change. It is not yet clear how much climate change-induced yield loss will be offset by accompanying increases in atmospheric CO₂ concentrations. Yet, the studies reviewed above point toward North American agriculture being able either fully or partially to offset climate change-induced losses. Furthermore, several studies suggested that were the rate of expansion of future agricultural capacity only to be modest by comparison with past trends, the losses of capacity imposed by climate change will quickly become small as a percentage of total capacity. Though some loss of comparative advantage in North American agriculture because of climate change cannot be ruled out, it does not appear that climate change, by itself, will present an insurmountable obstacle to North American agriculture.

Finally, does the foregoing discussion shed light on the complex question of should society forego additional investment in adapting North American agriculture to climate change in favor of investment in slowing or halting the warming itself, and if so, when? The answer cannot be given justice in this brief concluding section. However, a few general comments are in order. Crosson (1989b) argues that the nations of the world probably would agree that unimpeded global warming would impose unfair intergenerational costs and loss of national income to present and future generations. But he also notes that any national attempts now at halting warming will likely involve a tradeoff with increased costs and even less national income for the present generation.

Using simple analytical reasoning, Crosson (1989b) demonstrates that the ability of individual nations to adjust efficiently to the warming is a strong inducement to delay efforts to halt the warming. Furthermore, Schelling (1983) points out that most of the loss of income caused by warming will be in agriculture. Agricultural income is a small proportion of total world income and it is an even smaller proportion of total income in developed nations such as the US and Canada.

Thus, the loss of North American agricultural income alone from unimpeded warming, not even accounting for efficiency of adaptation, does not appear to provide a strong inducement for North Americans to undertake drastic measures to halt the warming now. The foregoing review suggests that North American agriculture is likely to be able to adapt to the warming with only minimal costs, which further weakens the inducement to slow or halt warming based solely on agricultural costs. Such inducement probably will have to come from costs of warming other than agricultural ones (i.e. sea level rise). This line of reasoning leads to the conclusion that investment in North American agricultural adaptation to warming is the best course for the present.

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